Renewable Energy Sources and Climate Change Mitigation

Special Report of the Intergovernmental Panel on Climate Change

Climate change is one of the great challenges of the 21st century. Its most severe impacts may still be avoided if efforts are made to transform current energy systems. Renewable energy sources have a large potential to displace emissions of greenhouse gases from the combustion of fossil fuels and thereby to mitigate climate change. If implemented properly, renewable energy sources can contribute to social and economic development, to energy access, to a secure and sustainable energy supply, and to a reduction of negative impacts of energy provision on the environment and human health.

This Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) impartially assesses the scientific literature on the potential role of renewable energy in the mitigation of climate change for policymakers, the private sector, academic researchers and civil society. It covers six renewable energy sources – bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy and wind energy – as well as their integration into present and future energy systems. It considers the environmental and social consequences associated with the deployment of these technologies, and presents strategies to overcome technical as well as non-technical obstacles to their application and diffusion. The authors also compare the levelized cost of energy from renewable energy sources to recent non-renewable energy costs.

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. It was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to provide the world with a clear scientific view on the current state of knowledge on climate change and its potential environmental and socio-economic impacts.

Renewable Energy Sources and Climate Change Mitigation

Special Report of the Intergovernmental Panel on Climate Change

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Foreword and Preface

Foreword

The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) provides a comprehensive review concerning these sources and technologies, the relevant costs and benefits, and their potential role in a portfolio of mitigation options.

For the first time, an inclusive account of costs and greenhouse gas emissions across various technologies and scenarios confirms the key role of renewable sources, irrespective of any tangible climate change mitigation agreement.

As an intergovernmental body established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), the IPCC has successfully provided policymakers over the ensuing period with the most authoritative and objective scientific and technical assessments, which, while clearly policy relevant, never claimed to be policy prescriptive. Moreover, this Special Report should be considered especially significant at a time when Governments are pondering the role of renewable energy resources in the context of their respective climate change mitigation efforts.

The SRREN was made possible thanks to the commitment and dedication of hundreds of experts from various regions and disciplines. We would like to express our deep gratitude to Prof. Ottmar Edenhofer, Dr. Ramon Pichs-Madruga, and Dr. Youba Sokona, for their untiring leadership throughout the SRREN development process, as well as to all Coordinating Lead Authors, Lead Authors, Contributing Authors, Review Editors and Reviewers, and to the staff of the Working Group III Technical Support Unit.

We greatly value Germany's generous support and dedication to the SRREN, as evidenced in particular by its hosting of the Working Group III Technical Support Unit. Moreover, we wish to express our appreciation to the United Arab Emirates, for hosting the plenary session which approved the report; as well as to Brazil, Norway, the United Kingdom and Mexico, which hosted the successive Lead Authors meetings; to all sponsors which contributed to the IPCC work through their financial and logistical support; and finally to the IPCC Chairman, Dr. R. K. Pachauri, for his leadership throughout the SRREN development process.

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Secretary General
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Preface

The Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) of the IPCC Working Group III provides an assessment and thorough analysis of renewable energy technologies and their current and potential role in the mitigation of greenhouse gas emissions. The results presented here are based on an extensive assessment of scientific literature, including specifics of individual studies, but also an aggregate across studies analyzed for broader conclusions. The report combines information on technology specific studies with results of large-scale integrated models, and provides policy-relevant (but not policy-prescriptive) information to decision makers on the characteristics and technical potentials of different resources; the historical development of the technologies; the challenges of their integration and social and environmental impacts of their use; as well as a comparison in levelized cost of energy for commercially available renewable technologies with recent non-renewable energy costs. Further, the role of renewable energy sources in pursuing GHG concentration stabilization levels discussed in this report and the presentation and analysis of the policies available to assist the development and deployment of renewable energy technologies in climate change mitigation and/or other goals answer important questions detailed in the original scoping of the report.

The process

This report has been prepared in accordance with the rules and procedures established by the IPCC and used for previous assessment reports. After a scoping meeting in Lübeck, Germany from the 20th to the 25th of January, 2008, the outline of the report was approved at the 28th IPCC Plenary held in Budapest, Hungary on the 9th and 10th of April, 2008. Soon afterward, an author team of 122 Lead Authors (33 from developing countries, 4 from EIT countries, and 85 from industrialized countries), 25 Review Editors and 132 contributing authors was formed.

The IPCC review procedure was followed, in which drafts produced by the authors were subject to two reviews. 24,766 comments from more than 350 expert reviewers and governments and international organizations were processed. Review Editors for each chapter have ensured that all substantive government and expert review comments received appropriate consideration.

The Summary for Policy Makers was approved line-by-line and the Final Draft of the report was accepted at the 11th Session of the Third Working Group held in Abu Dhabi, United Arab Emirates from the 5th to the 8th of May, 2011. The Special Report was accepted in its entirety at the 33rd IPCC Plenary Session held also in Abu Dhabi from the 10th to the 13th of May, 2011.

Structure of the Special Report

The SRREN consists of three categories of chapters: one introductory chapter; six technology specific chapters (Chapters 2-7); and four chapters that cover integrative issues across technologies (Chapters 8-11).

Chapter 1 is the introductory chapter designed to place renewable energy technologies within the broader framework of climate change mitigation options and identify characteristics common to renewable energy technologies.

Each of the technology chapters (2-7) provides information on the available resource potential, the state of technological and market development and the environmental and social impacts for each renewable energy source including bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy and wind energy. In addition, prospects for future technological innovation and cost reductions are discussed, and the chapters end with a discussion on possible future deployment.

Chapter 8 is the first of the integrative chapters and discusses how renewable energy technologies are currently integrated into energy distribution systems, and how they may be integrated in the future. Development pathways for the strategic use of renewable technologies in the transport, buildings, industry and agricultural sectors are also discussed.

Renewable energy in the context of sustainable development is covered in Chapter 9. This includes the social, environmental and economic impacts of renewable energy sources, including the potential for improved energy access and a secure supply of energy. Specific barriers for renewable energy technologies are also covered.

In a review of over 160 scenarios, Chapter 10 investigates how renewable energy technologies may contribute to varying greenhouse gas emission reduction scenarios, ranging from business-as-usual scenarios to those reflecting ambitious GHG concentration stabilization levels. Four scenarios are analyzed in depth and the costs of extensive deployment of renewable energy technologies are also discussed.

The last chapter of the report, Chapter 11, describes the current trends in renewable energy support policies, as well as trends in financing and investment in renewable energy technologies. It reviews current experiences with RE policies, including effectiveness and efficiency measures, and discusses the influence of an enabling environment on the success of policies.

While the authors of the report included the most recent literature available at the time of publication, readers should be aware that topics covered in this Special Report may be subject to further rapid development. This includes state of development of some renewable energy technologies, as well as the state of knowledge of integration challenges, mitigation costs, co-benefits, environmental and social impacts, policy approaches and financing options. The boundaries and names shown and the designations used on any geographic maps in this report do not imply official endorsement or acceptance by the United Nations. In the geographic maps developed for the SRREN, the dotted line in Jammu and Kashmir represents approximately the Line of Control agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

Acknowledgements

Production of this Special Report was a major enterprise, in which many people from around the world were involved, with a wide variety of contributions. We wish to thank the generous contributions by the governments and institutions involved, which enabled the authors, Review Editors and Government and Expert Reviewers to participate in this process.

We are especially grateful for the contribution and support of the German Government, in particular the Bundesministerium für Bildung und Forschung (BMBF), in funding the Working Group III Technical Support Unit (TSU). Coordinating this funding, Gregor Laumann and Christiane Textor of the Deutsches Zentrum für Luft- und Raumfahrt (DLR) were always ready to dedicate time and energy to the needs of the team. We would also like to express our gratitude to the Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). In addition, the Potsdam Institute for Climate Impact Research (PIK) kindly hosted and housed the TSU offices.

We would very much like to thank the governments of Brazil, Norway, the United Kingdom and Mexico, who, in collaboration with local institutions, hosted the crucial lead author meetings in São José dos Campos (January 2009), Oslo (September 2009), Oxford (March 2010) and Mexico City (September 2010). In addition, we would like to thank the government of the United States and the Institute for Sustainability, with the Founder Society Technologies for Carbon Management Project for hosting the SRREN Expert Review meeting in Washington D.C.(February 2010). Finally, we

express our appreciation to PIK for welcoming the SRREN Coordinating Lead Authors on their campus for a concluding meeting (January 2011).

This Special Report is only possible thanks to the expertise, hard work and commitment to excellence shown throughout by our Coordinating Lead Authors and Lead Authors, with important assistance by many Contributing Authors. We would also like to express our appreciation to the Government and Expert Reviewers, acknowledging the time and energy invested to provide constructive and useful comments to the various drafts. Our Review Editors were also critical in the SRREN process, supporting the author team with processing the comments and assuring an objective discussion of relevant issues.

It is a pleasure to acknowledge the tireless work of the staff of the Working Group III Technical Support Unit, Patrick Matschoss, Susanne Kadner, Kristin Seyboth, Timm Zwickel, Patrick Eickemeier, Gerrit Hansen, Steffen Schloemer, Christoph von Stechow, Benjamin Kriemann, Annegret Kuhnigk, Anna Adler and Nina Schuetz, who were assisted by Marilyn Anderson, Lelani Arris, Andrew Ayres, Marlen Goerner, Daniel Mahringer and Ashley Renders. Brigitte Knopf, in her role as Senior Advisor to the TSU, consistently provided valuable input and direction. Graphics support by Kay Schröder and his team at Daily-Interactive.com Digitale Kommunikation is gratefully appreciated, as is the layout work by Valarie Morris and her team at Arroyo Writing, LLC.

The Working Group III Bureau – consisting of Antonina Ivanova Boncheva (Mexico), Carlo Carraro (Italy), Suzana Kahn Ribeiro (Brazil), Jim Skea (UK), Francis Yamba (Zambia), and Taha Zatari (Saudi Arabia) and prior to his elevation to IPCC Vice Chair, Ismail A.R. Elgizouli (Sudan) – provided continuous and constructive support to the Working Group III Co-Chairs throughout the SRREN process.

We would like to thank the Renate Christ, Secretary of the IPCC, and the Secretariat staff Gaetano Leone, Mary Jean Burer, Sophie Schlingemann, Judith Ewa, Jesbin Baidya, Joelle Fernandez, Annie Courtin, Laura Biagioni, Amy Smith Aasdam, and Rockaya Aidara, who provided logistical support for government liaison and travel of experts from developing and transitional economy countries.

Our special acknowledgement to Dr. Rajendra Pachauri, Chairman of the IPCC, for his contribution and support during the preparation of this IPCC Special Report.



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This report is dedicated to

Wolfram Krewitt, Germany
Coordinating Lead Author in Chapter 8

Wolfram Krewitt passed away October 8th, 2009. He worked at the Deutsches Zentrum für Luft- und Raumfahrt (DLR) in Stuttgart, Germany.

Raymond Wright, Jamaica
Lead Author in Chapter 10

Raymond Wright passed away July 7th, 2011. He worked at the Petroleum Corporation of Jamaica (PCJ) in Kingston, Jamaica.

Wolfram Krewitt made a significant contribution to this Special Report and his vision for Chapter 8 (Integration of Renewable Energy into Present and Future Energy Systems) remains embedded in the text for which he is acknowledged. Raymond Wright was a critical member of the Chapter 10 (Mitigation Potential and Costs) author team who consistently offered precise insights to the Special Report, ensuring balance and credibility. Both authors were talented, apt and dedicated members of the IPCC author team - their passing represents a deep loss for the international scientific communities working in climate and energy issues. Wolfram Krewitt and Raymond Wright are dearly remembered by their fellow authors.

II

Summaries

SPM

Summary for Policymakers

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Table of Contents

1. Introduction

The Working Group III Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) presents an assessment of the literature on the scientific, technological, environmental, economic and social aspects of the contribution of six renewable energy (RE) sources to the mitigation of climate change. It is intended to provide policy relevant information to governments, intergovernmental processes and other interested parties. This Summary for Policymakers provides an overview of the SRREN, summarizing the essential findings.

The SRREN consists of 11 chapters. Chapter 1 sets the context for RE and climate change; Chapters 2 through 7 provide information on six RE technologies, and Chapters 8 through 11 address integrative issues (see Figure SPM.1).

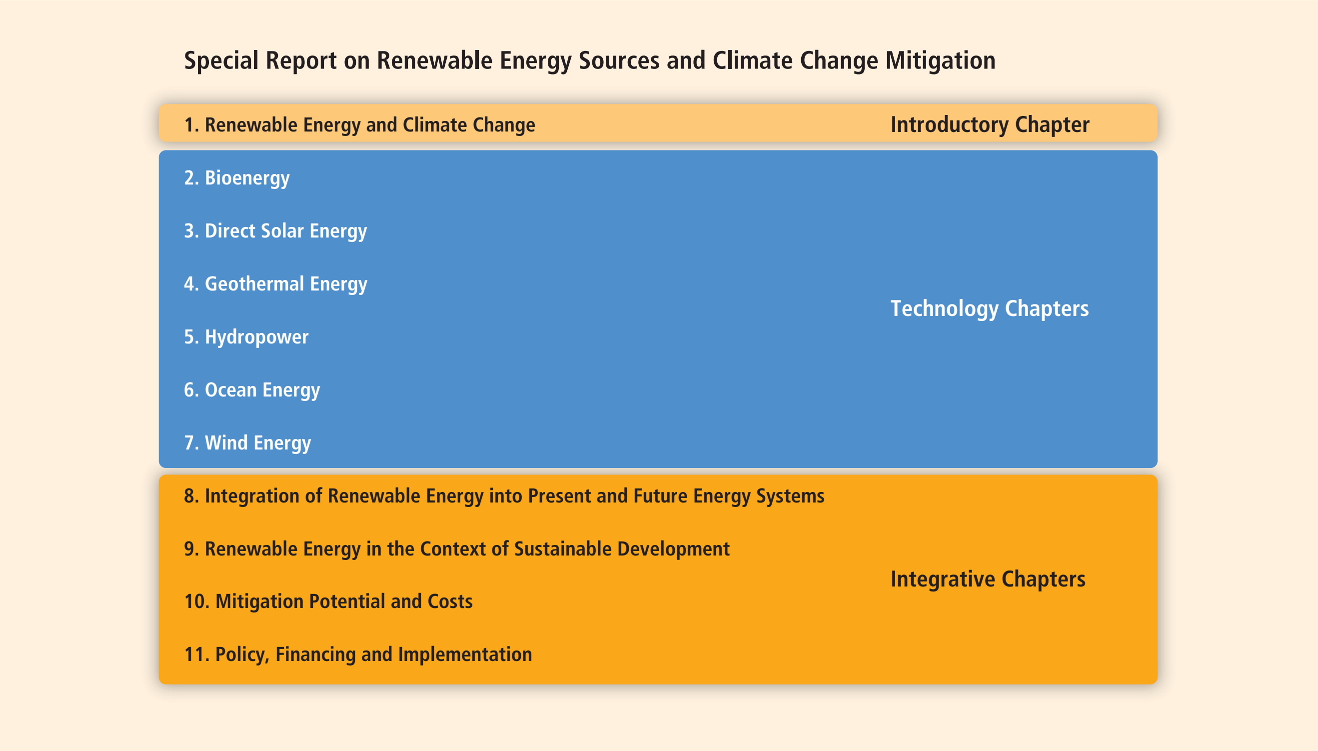


Figure SPM.1 | Structure of the SRREN. [Figure 1.1, 1.1.2]

References to chapters and sections are indicated with corresponding chapter and section numbers in square brackets. An explanation of terms, acronyms and chemical symbols used in this SPM can be found in the glossary of the SRREN (Annex I). Conventions and methodologies for determining costs, primary energy and other topics of analysis can be found in Annex II and Annex III. This report communicates uncertainty where relevant.[1]

1 This report communicates uncertainty, for example, by showing the results of sensitivity analyses and by quantitatively presenting ranges in cost numbers as well as ranges in the scenario results. This report does not apply formal IPCC uncertainty terminology because at the time of the approval of this report, IPCC uncertainty guidance was in the process of being revised.

2. Renewable energy and climate change

Demand for energy and associated services, to meet social and economic development and improve human welfare and health, is increasing. All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility and communication) and to serve productive processes. [1.1.1, 9.3.2] Since approximately 1850, global use of fossil fuels (coal, oil and gas) has increased to dominate energy supply, leading to a rapid growth in carbon dioxide (CO_2) emissions. [Figure 1.6]

Greenhouse gas (GHG) emissions resulting from the provision of energy services have contributed significantly to the historic increase in atmospheric GHG concentrations. The IPCC Fourth Assessment Report (AR4) concluded that "Most of the observed increase in global average temperature since the mid-20th century is very likely[2] due to the observed increase in anthropogenic greenhouse gas concentrations."

Recent data confirm that consumption of fossil fuels accounts for the majority of global anthropogenic GHG emissions.[3] Emissions continue to grow and CO_2 concentrations had increased to over 390 ppm, or 39% above preindustrial levels, by the end of 2010. [1.1.1, 1.1.3]

There are multiple options for lowering GHG emissions from the energy system while still satisfying the global demand for energy services. [1.1.3, 10.1] Some of these possible options, such as energy conservation and efficiency, fossil fuel switching, RE, nuclear and carbon capture and storage (CCS) were assessed in the AR4. A comprehensive evaluation of any portfolio of mitigation options would involve an evaluation of their respective mitigation potential as well as their contribution to sustainable development and all associated risks and costs. [1.1.6] This report will concentrate on the role that the deployment of RE technologies can play within such a portfolio of mitigation options.

As well as having a large potential to mitigate climate change, RE can provide wider benefits. RE may, if implemented properly, contribute to social and economic development, energy access, a secure energy supply, and reducing negative impacts on the environment and health. [9.2, 9.3]

Under most conditions, increasing the share of RE in the energy mix will require policies to stimulate changes in the energy system. Deployment of RE technologies has increased rapidly in recent years, and their share is projected to increase substantially under most ambitious mitigation scenarios [1.1.5, 10.2]. Additional policies would be required to attract the necessary increases in investment in technologies and infrastructure. [11.4.3, 11.5, 11.6.1, 11.7.5]

3. Renewable energy technologies and markets

RE comprises a heterogeneous class of technologies (Box SPM.1). Various types of RE can supply electricity, thermal energy and mechanical energy, as well as produce fuels that are able to satisfy multiple energy service needs [1.2]. Some RE technologies can be deployed at the point of use (decentralized) in rural and urban environments, whereas others are primarily deployed within large (centralized) energy networks [1.2, 8.2, 8.3, 9.3.2]. Though a growing number of RE technologies are technically mature and are being deployed at significant scale, others are in an earlier phase of technical maturity and commercial deployment or fill specialized niche markets [1.2]. The energy output of

2 According to the formal uncertainty language used in the AR4, the term 'very likely' refers to a >90% assessed probability of occurrence.

3 The contributions of individual anthropogenic GHGs to total emissions in 2004, reported in AR4, expressed as CO_2eq were: CO_2 from fossil fuels (56.6%), CO_2 from deforestation, decay of biomass etc. (17.3%), CO_2 from other (2.8%), methane (14.3%), nitrous oxide (7.9%) and fluorinated gases (1.1%) [Figure 1.1b, AR4, WG III, Chapter 1. For further information on sectoral emissions, including forestry, see also Figure 1.3b and associated footnotes.]

RE technologies can be (i) variable and—to some degree—unpredictable over differing time scales (from minutes to years), (ii) variable but predictable, (iii) constant, or (iv) controllable. [8.2, 8.3]

Box SPM.1 | Renewable energy sources and technologies considered in this report.

Bioenergy can be produced from a variety of biomass feedstocks, including forest, agricultural and livestock residues; short-rotation forest plantations; energy crops; the organic component of municipal solid waste; and other organic waste streams. Through a variety of processes, these feedstocks can be directly used to produce electricity or heat, or can be used to create gaseous, liquid, or solid fuels. The range of bioenergy technologies is broad and the technical maturity varies substantially. Some examples of commercially available technologies include small- and large-scale boilers, domestic pellet-based heating systems, and ethanol production from sugar and starch. Advanced biomass integrated gasification combined-cycle power plants and lignocellulose-based transport fuels are examples of technologies that are at a pre-commercial stage, while liquid biofuel production from algae and some other biological conversion approaches are at the research and development (R&D) phase. Bioenergy technologies have applications in centralized and decentralized settings, with the traditional use of biomass in developing countries being the most widespread current application.[4] Bioenergy typically offers constant or controllable output. Bioenergy projects usually depend on local and regional fuel supply availability, but recent developments show that solid biomass and liquid biofuels are increasingly traded internationally. [1.2, 2.1, 2.3, 2.6, 8.2, 8.3]

Direct solar energy technologies harness the energy of solar irradiance to produce electricity using photovoltaics (PV) and concentrating solar power (CSP), to produce thermal energy (heating or cooling, either through passive or active means), to meet direct lighting needs and, potentially, to produce fuels that might be used for transport and other purposes. The technology maturity of solar applications ranges from R&D (e.g., fuels produced from solar energy), to relatively mature (e.g., CSP), to mature (e.g., passive and active solar heating, and wafer-based silicon PV). Many but not all of the technologies are modular in nature, allowing their use in both centralized and decentralized energy systems. Solar energy is variable and, to some degree, unpredictable, though the temporal profile of solar energy output in some circumstances correlates relatively well with energy demands. Thermal energy storage offers the option to improve output control for some technologies such as CSP and direct solar heating. [1.2, 3.1, 3.3, 3.5, 3.7, 8.2, 8.3]

Geothermal energy utilizes the accessible thermal energy from the Earth's interior. Heat is extracted from geothermal reservoirs using wells or other means. Reservoirs that are naturally sufficiently hot and permeable are called hydrothermal reservoirs, whereas reservoirs that are sufficiently hot but that are improved with hydraulic stimulation are called enhanced geothermal systems (EGS). Once at the surface, fluids of various temperatures can be used to generate electricity or can be used more directly for applications that require thermal energy, including district heating or the use of lower-temperature heat from shallow wells for geothermal heat pumps used in heating or cooling applications. Hydrothermal power plants and thermal applications of geothermal energy are mature technologies, whereas EGS projects are in the demonstration and pilot phase while also undergoing R&D. When used to generate electricity, geothermal power plants typically offer constant output. [1.2, 4.1, 4.3, 8.2, 8.3]

Hydropower harnesses the energy of water moving from higher to lower elevations, primarily to generate electricity. Hydropower projects encompass dam projects with reservoirs, run-of-river and in-stream projects and cover a continuum in project scale. This variety gives hydropower the ability to meet large centralized urban needs as well as decentralized rural needs. Hydropower technologies are mature. Hydropower projects exploit a resource that varies temporally. However, the controllable output provided by hydropower facilities that have reservoirs can be used to meet peak electricity demands and help to balance electricity systems that have large amounts of variable RE generation. The operation of hydropower reservoirs often reflects their multiple uses, for example, drinking water, irrigation, flood and drought control, and navigation, as well as energy supply. [1.2, 5.1, 5.3, 5.5, 5.10, 8.2]

4 Traditional biomass is defined by the International Energy Agency (IEA) as biomass consumption in the residential sector in developing countries and refers to the often unsustainable use of wood, charcoal, agricultural residues, and animal dung for cooking and heating. All other biomass use is defined as modern [Annex I].

Ocean energy derives from the potential, kinetic, thermal and chemical energy of seawater, which can be transformed to provide electricity, thermal energy, or potable water. A wide range of technologies are possible, such as barrages for tidal range, submarine turbines for tidal and ocean currents, heat exchangers for ocean thermal energy conversion, and a variety of devices to harness the energy of waves and salinity gradients. Ocean technologies, with the exception of tidal barrages, are at the demonstration and pilot project phases and many require additional R&D. Some of the technologies have variable energy output profiles with differing levels of predictability (e.g., wave, tidal range and current), while others may be capable of near-constant or even controllable operation (e.g., ocean thermal and salinity gradient). [1.2, 6.1, 6.2, 6.3, 6.4, 6.6, 8.2]

Wind energy harnesses the kinetic energy of moving air. The primary application of relevance to climate change mitigation is to produce electricity from large wind turbines located on land (onshore) or in sea- or freshwater (offshore). Onshore wind energy technologies are already being manufactured and deployed on a large scale. Offshore wind energy technologies have greater potential for continued technical advancement. Wind electricity is both variable and, to some degree, unpredictable, but experience and detailed studies from many regions have shown that the integration of wind energy generally poses no insurmountable technical barriers. [1.2, 7.1, 7.3, 7.5, 7.7, 8.2]

On a global basis, it is estimated that RE accounted for 12.9% of the total 492 Exajoules (EJ)[5] of primary energy supply in 2008 (Box SPM.2 and Figure SPM.2). The largest RE contributor was biomass (10.2%), with the majority (roughly 60%) being traditional biomass used in cooking and heating applications in developing countries but with rapidly increasing use of modern biomass as well.[6] Hydropower represented 2.3%, whereas other RE sources accounted for 0.4%. [1.1.5] In 2008, RE contributed approximately 19% of global electricity supply (16% hydropower, 3% other RE) and biofuels contributed 2% of global road transport fuel supply. Traditional biomass (17%), modern biomass (8%), solar thermal and geothermal energy (2%) together fuelled 27% of the total global demand for heat. The contribution of RE to primary energy supply varies substantially by country and region. [1.1.5, 1.3.1, 8.1]

Deployment of RE has been increasing rapidly in recent years (Figure SPM.3). Various types of government policies, the declining cost of many RE technologies, changes in the prices of fossil fuels, an increase of energy demand and other factors have encouraged the continuing increase in the use of RE. [1.1.5, 9.3, 10.5, 11.2, 11.3] Despite global financial challenges, RE capacity continued to grow rapidly in 2009 compared to the cumulative installed capacity from the previous year, including wind power (32% increase, 38 Gigawatts (GW) added), hydropower (3%, 31 GW added), grid-connected photovoltaics (53%, 7.5 GW added), geothermal power (4%, 0.4 GW added), and solar hot water/heating (21%, 31 GW_{th} added). Biofuels accounted for 2% of global road transport fuel demand in 2008 and nearly 3% in 2009. The annual production of ethanol increased to 1.6 EJ (76 billion litres) by the end of 2009 and biodiesel to 0.6 EJ (17 billion litres). [1.1.5, 2.4, 3.4, 4.4, 5.4, 7.4]

Of the approximate 300 GW of new electricity generating capacity added globally over the two-year period from 2008 to 2009, 140 GW came from RE additions. Collectively, developing countries host 53% of global RE electricity generation capacity [1.1.5]. At the end of 2009, the use of RE in hot water/heating markets included modern biomass (270 GW_{th}), solar (180 GW_{th}), and geothermal (60 GW_{th}). The use of decentralized RE (excluding traditional biomass) in meeting rural energy needs at the household or village level has also increased, including hydropower stations, various modern biomass options, PV, wind or hybrid systems that combine multiple technologies. [1.1.5, 2.4, 3.4, 4.4, 5.4]

5 1 Exajoule = 10^{18} joules = 23.88 million tonnes of oil equivalent (Mtoe).

6 In addition to this 60% share of traditional biomass, there is biomass use estimated to amount to 20 to 40% not reported in official primary energy databases, such as dung, unaccounted production of charcoal, illegal logging, fuelwood gathering, and agricultural residue use. [2.1, 2.5]

Box SPM.2 | Accounting for primary energy in the SRREN.

There is no single, unambiguous accounting method for calculating primary energy from non-combustible energy sources such as non-combustible RE sources and nuclear energy. The SRREN adopts the 'direct equivalent' method for accounting for primary energy supply. In this method, fossil fuels and bioenergy are accounted for based on their heating value while non-combustible energy sources, including nuclear energy and all non-combustible RE, are accounted for based on the secondary energy that they produce. This may lead to an understatement of the contribution of non-combustible RE and nuclear compared to bioenergy and fossil fuels by a factor of roughly 1.2 up to 3. The selection of the accounting method also impacts the relative shares of different individual energy sources. Comparisons in the data and figures presented in the SRREN between fossil fuels and bioenergy on the one hand, and non-combustible RE and nuclear energy on the other, reflect this accounting method. [1.1.9, Annex II.4]

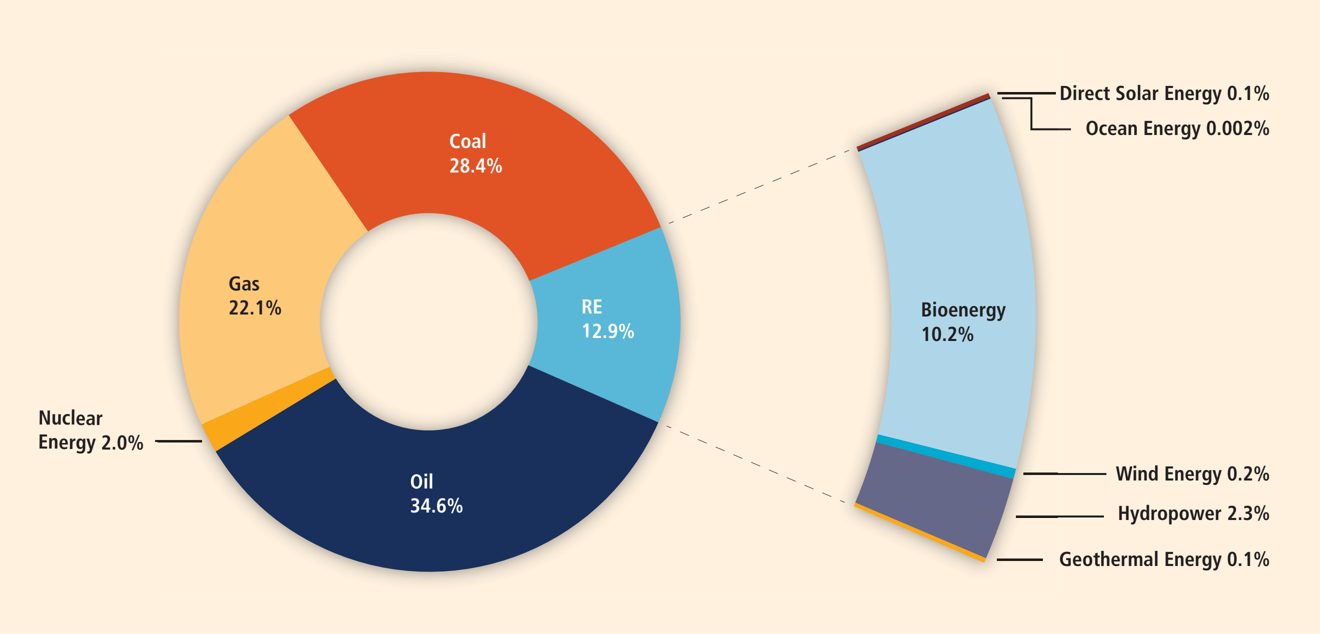


Figure SPM.2 | Shares of energy sources in total global primary energy supply in 2008 (492 EJ). Modern biomass contributes 38% of the total biomass share. [Figure 1.10, 1.1.5]

Note: Underlying data for figure have been converted to the 'direct equivalent' method of accounting for primary energy supply. [Box SPM.2, 1.1.9, Annex II.4]

The global technical potential[7] of RE sources will not limit continued growth in the use of RE. A wide range of estimates is provided in the literature, but studies have consistently found that the total global technical potential for RE is substantially higher than global energy demand (Figure SPM.4) [1.2.2, 10.3, Annex II]. The technical potential for solar energy is the highest among the RE sources, but substantial technical potential exists for all six RE sources. Even in regions with relatively low levels of technical potential for any individual RE source, there are typically significant opportunities for increased deployment compared to current levels. [1.2.2, 2.2, 2.8, 3.2, 4.2, 5.2, 6.2, 6.4, 7.2, 8.2, 8.3, 10.3] In the longer term and at higher deployment levels, however, technical potentials indicate a limit to the

7 Definitions of technical potential often vary by study. 'Technical potential' is used in the SRREN as the amount of RE output obtainable by full implementation of demonstrated technologies or practices. No explicit reference to costs, barriers or policies is made. Technical potentials reported in the literature and assessed in the SRREN, however, may have taken into account practical constraints and when explicitly stated they are generally indicated in the underlying report. [Annex I]

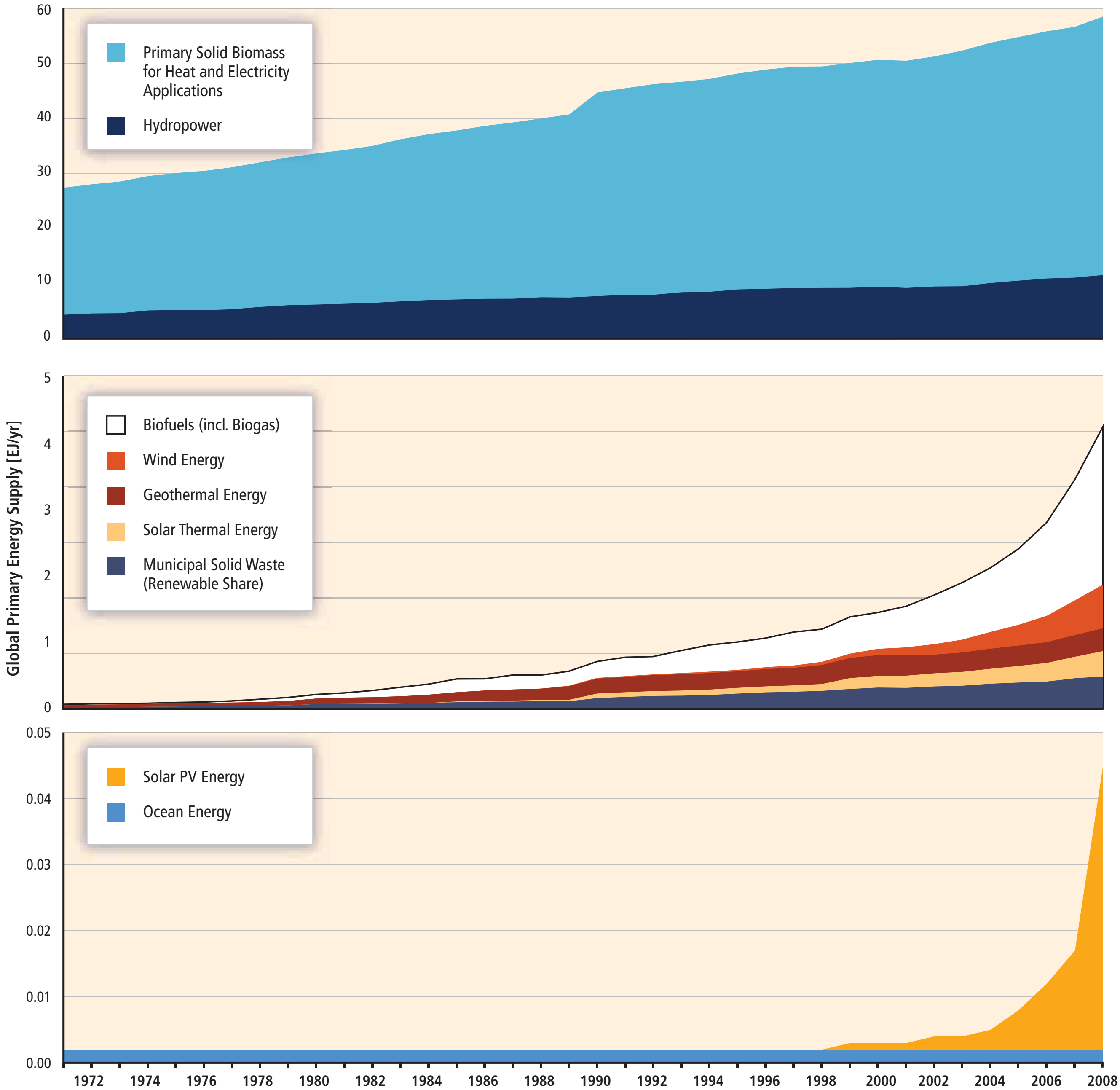
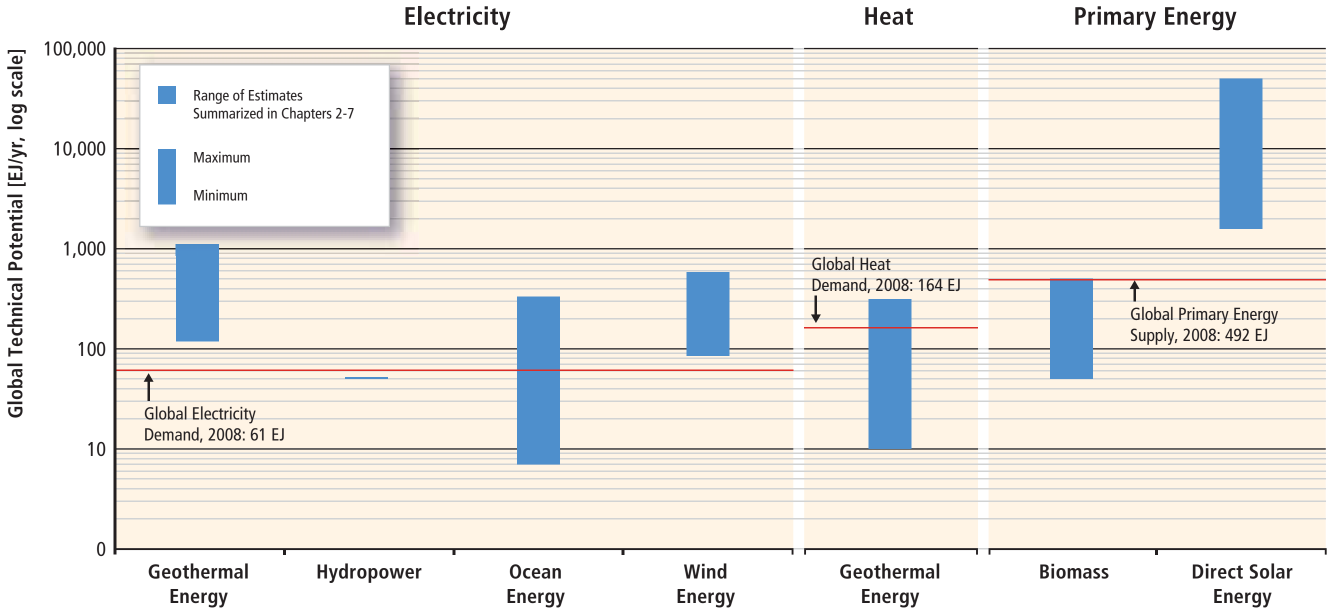


Figure SPM.3 | Historical development of global primary energy supply from renewable energy from 1971 to 2008. [Figure 1.12, 1.1.5]

Notes: Technologies are referenced to separate vertical units for display purposes only. Underlying data for figure has been converted to the 'direct equivalent' method of accounting for primary energy supply [Box SPM.2, 1.1.9, Annex II.4], except that the energy content of biofuels is reported in secondary energy terms (the primary biomass used to produce the biofuel would be higher due to conversion losses. [2.3, 2.4])

contribution of some individual RE technologies. Factors such as sustainability concerns [9.3], public acceptance [9.5], system integration and infrastructure constraints [8.2], or economic factors [10.3] may also limit deployment of RE technologies.

Climate change will have impacts on the size and geographic distribution of the technical potential for RE sources, but research into the magnitude of these possible effects is nascent. Because RE sources are, in many cases, dependent on the climate, global climate change will affect the RE resource base, though the precise nature and magnitude of these impacts is uncertain. The future technical potential for bioenergy could be influenced by climate change through impacts on biomass production such as altered soil conditions, precipitation, crop productivity and other factors. The overall impact of a global mean temperature change of less than 2°C on the technical potential of bioenergy is expected to be relatively small on a global basis. However, considerable regional differences could be expected and uncertainties are larger and more difficult to assess compared to other RE options due to the large number of feedback mechanisms involved. [2.2, 2.6] For solar energy, though climate change is expected to influence the distribution and variability of cloud cover, the impact of these changes on overall technical potential is expected to be small [3.2]. For hydropower the overall impacts on the global technical potential is expected to be slightly positive. However, results also indicate the possibility of substantial variations across regions and even within countries. [5.2] Research to date suggests that climate change is not expected to greatly impact the global technical potential for wind energy development but changes in the regional distribution of the wind energy resource may be expected [7.2]. Climate change is not anticipated to have significant impacts on the size or geographic distribution of geothermal or ocean energy resources. [4.2, 6.2]



Range of Estimates of Global Technical Potentials

Max (in EJ/yr)	1109	52	331	580	312	500	49837
Min (in EJ/yr)	118	50	7	85	10	50	1575

Figure SPM.4 | Ranges of global technical potentials of RE sources derived from studies presented in Chapters 2 through 7. Biomass and solar are shown as primary energy due to their multiple uses; note that the figure is presented in logarithmic scale due to the wide range of assessed data. [Figure 1.17, 1.2.3]

Notes: Technical potentials reported here represent total worldwide potentials for annual RE supply and do not deduct any potential that is already being utilized. Note that RE electricity sources could also be used for heating applications, whereas biomass and solar resources are reported only in primary energy terms but could be used to meet various energy service needs. Ranges are based on various methods and apply to different future years; consequently, the resulting ranges are not strictly comparable across technologies. For the data behind Figure SPM.4 and additional notes that apply, see Chapter 1 Annex, Table A.1.1 (as well as the underlying chapters).

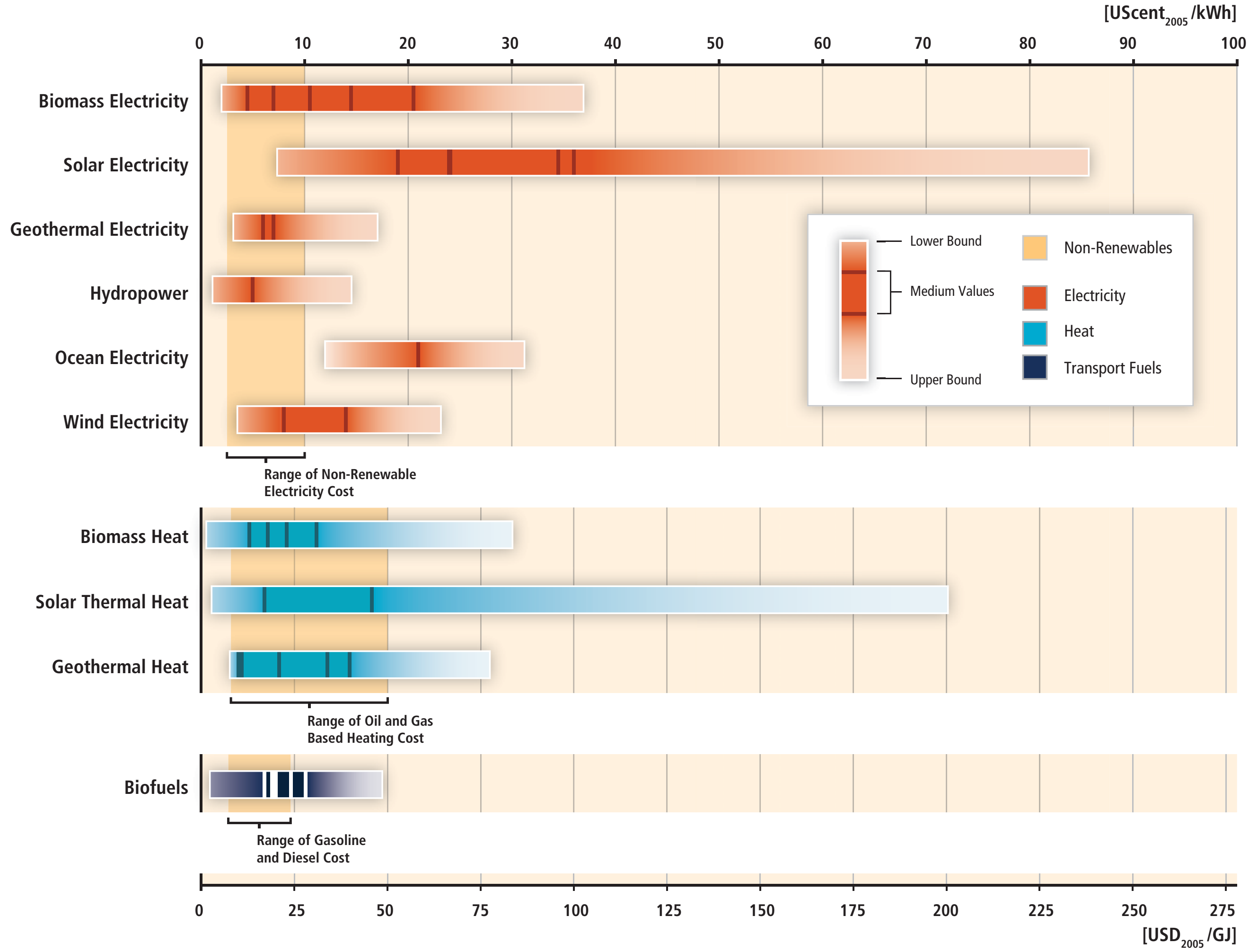
The levelized cost of energy[8] for many RE technologies is currently higher than existing energy prices, though in various settings RE is already economically competitive. Ranges of recent levelized costs of energy for selected commercially available RE technologies are wide, depending on a number of factors including, but not limited to, technology characteristics, regional variations in cost and performance, and differing discount rates (Figure SPM.5). [1.3.2, 2.3, 2.7, 3.8, 4.8, 5.8, 6.7, 7.8, 10.5, Annex III] Some RE technologies are broadly competitive with existing market energy prices. Many of the other RE technologies can provide competitive energy services in certain circumstances, for example, in regions with favourable resource conditions or that lack the infrastructure for other low-cost energy supplies. In most regions of the world, policy measures are still required to ensure rapid deployment of many RE sources. [2.3, 2.7, 3.8, 4.7, 5.8, 6.7, 7.8, 10.5]

Monetizing the external costs of energy supply would improve the relative competitiveness of RE. The same applies if market prices increase due to other reasons (Figure SPM.5). [10.6] The levelized cost of energy for a technology is not the sole determinant of its value or economic competitiveness. The attractiveness of a specific energy supply option depends also on broader economic as well as environmental and social aspects, and the contribution that the technology provides to meeting specific energy services (e.g., peak electricity demands) or imposes in the form of ancillary costs on the energy system (e.g., the costs of integration). [8.2, 9.3, 10.6]

The cost of most RE technologies has declined and additional expected technical advances would result in further cost reductions. Significant advances in RE technologies and associated long-term cost reductions have been demonstrated over the last decades, though periods of rising prices have sometimes been experienced (due to, for example, increasing demand for RE in excess of available supply) (Figure SPM.6). The contribution of different drivers (e.g., R&D, economies of scale, deployment-oriented learning, and increased market competition among RE suppliers) is not always understood in detail. [2.7, 3.8, 7.8, 10.5] Further cost reductions are expected, resulting in greater potential deployment and consequent climate change mitigation. Examples of important areas of potential technological advancement include: new and improved feedstock production and supply systems, biofuels produced via new processes (also called next-generation or advanced biofuels, e.g., lignocellulosic) and advanced biorefining [2.6]; advanced PV and CSP technologies and manufacturing processes [3.7]; enhanced geothermal systems (EGS) [4.6]; multiple emerging ocean technologies [6.6]; and foundation and turbine designs for offshore wind energy [7.7]. Further cost reductions for hydropower are expected to be less significant than some of the other RE technologies, but R&D opportunities exist to make hydropower projects technically feasible in a wider range of locations and to improve the technical performance of new and existing projects. [5.3, 5.7, 5.8]

A variety of technology-specific challenges (in addition to cost) may need to be addressed to enable RE to significantly upscale its contribution to reducing GHG emissions. For the increased and sustainable use of bioenergy, proper design, implementation and monitoring of sustainability frameworks can minimize negative impacts and maximize benefits with regard to social, economic and environmental issues [SPM.5, 2.2, 2.5, 2.8]. For solar energy, regulatory and institutional barriers can impede deployment, as can integration and transmission issues [3.9]. For geothermal energy, an important challenge would be to prove that enhanced geothermal systems (EGS) can be deployed economically, sustainably and widely [4.5, 4.6, 4.7, 4.8]. New hydropower projects can have ecological and social impacts that are very site specific, and increased deployment may require improved sustainability assessment tools, and regional and multi-party collaborations to address energy and water needs [5.6, 5.9, 5.10]. The deployment of ocean energy could benefit from testing centres for demonstration projects, and from dedicated policies and regulations that encourage early deployment [6.4]. For wind energy, technical and institutional solutions to transmission constraints and operational integration concerns may be especially important, as might public acceptance issues relating primarily to landscape impacts. [7.5, 7.6, 7.9]

8 The levelized cost of energy represents the cost of an energy generating system over its lifetime; it is calculated as the per-unit price at which energy must be generated from a specific source over its lifetime to break even. It usually includes all private costs that accrue upstream in the value chain, but does not include the downstream cost of delivery to the final customer; the cost of integration, or external environmental or other costs. Subsidies and tax credits are also not included.



Notes: Medium values are shown for the following subcategories, sorted in the order as they appear in the respective ranges (from left to right):

Electricity	Heat	Transport Fuels
Biomass: 1. Cofiring 2. Small scale combined heat and power, CHP (Gasification internal combustion engine) 3. Direct dedicated stoker & CHP 4. Small scale CHP (steam turbine) 5. Small scale CHP (organic Rankine cycle) **Solar Electricity:** 1. Concentrating solar power 2. Utility-scale PV (1-axis and fixed tilt) 3. Commercial rooftop PV 4. Residential rooftop PV **Geothermal Electricity:** 1. Condensing flash plant 2. Binary cycle plant **Hydropower:** 1. All types **Ocean Electricity:** 1. Tidal barrage **Wind Electricity:** 1. Onshore 2. Offshore	**Biomass Heat:** 1. Municipal solid waste based CHP 2. Anaerobic digestion based CHP 3. Steam turbine CHP 4. Domestic pellet heating system **Solar Thermal Heat:** 1. Domestic hot water systems in China 2. Water and space heating **Geothermal Heat:** 1. Greenhouses 2. Uncovered aquaculture ponds 3. District heating 4. Geothermal heat pumps 5. Geothermal building heating	**Biofuels:** 1. Corn ethanol 2. Soy biodiesel 3. Wheat ethanol 4. Sugarcane ethanol 5. Palm oil biodiesel

The lower range of the levelized cost of energy for each RE technology is based on a combination of the most favourable input-values, whereas the upper range is based on a combination of the least favourable input values. Reference ranges in the figure background for non-renewable electricity options are indicative of the levelized cost of centralized non-renewable electricity generation. Reference ranges for heat are indicative of recent costs for oil and gas based heat supply options. Reference ranges for transport fuels are based on recent crude oil spot prices of USD 40 to 130/barrel and corresponding diesel and gasoline costs, excluding taxes.

Figure SPM.5 | Range in recent levelized cost of energy for selected commercially available RE technologies in comparison to recent non-renewable energy costs. Technology subcategories and discount rates were aggregated for this figure. For related figures with less or no such aggregation, see [1.3.2, 10.5, Annex III].

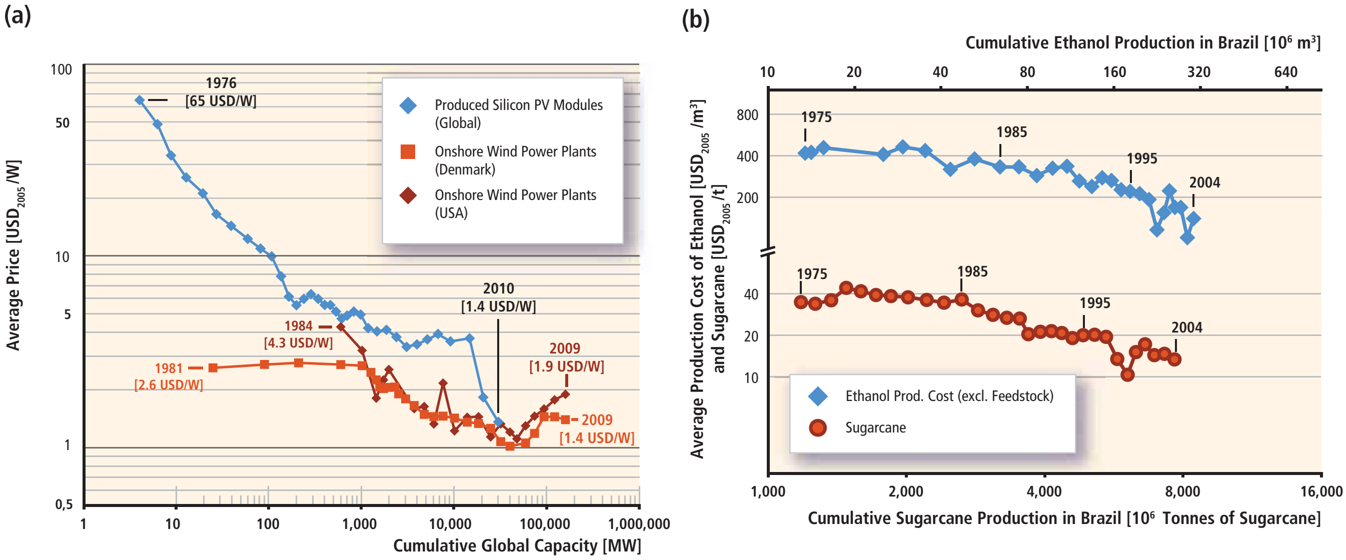


Figure SPM.6 | Selected experience curves in logarithmic scale for (a) the price of silicon PV modules and onshore wind power plants per unit of capacity; and (b) the cost of sugarcane-based ethanol production [data from Figure 3.17, 3.8.3, Figure 7.20, 7.8.2, Figure 2.21, 2.7.2].

Notes: Depending on the setting, cost reductions may occur at various geographic scales. The country-level examples provided here derive from the published literature. No global dataset of wind power plant prices or costs is readily available. Reductions in the cost or price of a technology per unit of capacity understate reductions in the levelized cost of energy of that technology when performance improvements occur. [7.8.4, 10.5]

4. Integration into present and future energy systems

Various RE resources are already being successfully integrated into energy supply systems [8.2] and into end-use sectors [8.3] (Figure SPM.7).

The characteristics of different RE sources can influence the scale of the integration challenge. Some RE resources are widely distributed geographically. Others, such as large-scale hydropower, can be more centralized but have integration options constrained by geographic location. Some RE resources are variable with limited predictability. Some have lower physical energy densities and different technical specifications from fossil fuels. Such characteristics can constrain ease of integration and invoke additional system costs particularly when reaching higher shares of RE. [8.2]

Integrating RE into most existing energy supply systems and end-use sectors at an accelerated rate—leading to higher shares of RE—is technologically feasible, though will result in a number of additional challenges. Increased shares of RE are expected within an overall portfolio of low GHG emission technologies [10.3, Tables 10.4-10.6]. Whether for electricity, heating, cooling, gaseous fuels or liquid fuels, including integration directly into end-use sectors, the RE integration challenges are contextual and site specific and include the adjustment of existing energy supply systems. [8.2, 8.3]

The costs and challenges of integrating increasing shares of RE into an existing energy supply system depend on the current share of RE, the availability and characteristics of RE resources, the system characteristics, and how the system evolves and develops in the future.

- RE can be integrated into all types of *electricity* systems, from large inter-connected continental-scale grids [8.2.1] down to small stand-alone systems and individual buildings [8.2.5]. Relevant system characteristics include the generation mix and its flexibility, network infrastructure, energy market designs and institutional rules, demand location, demand profiles, and control and communication capability. Wind, solar PV energy and CSP without

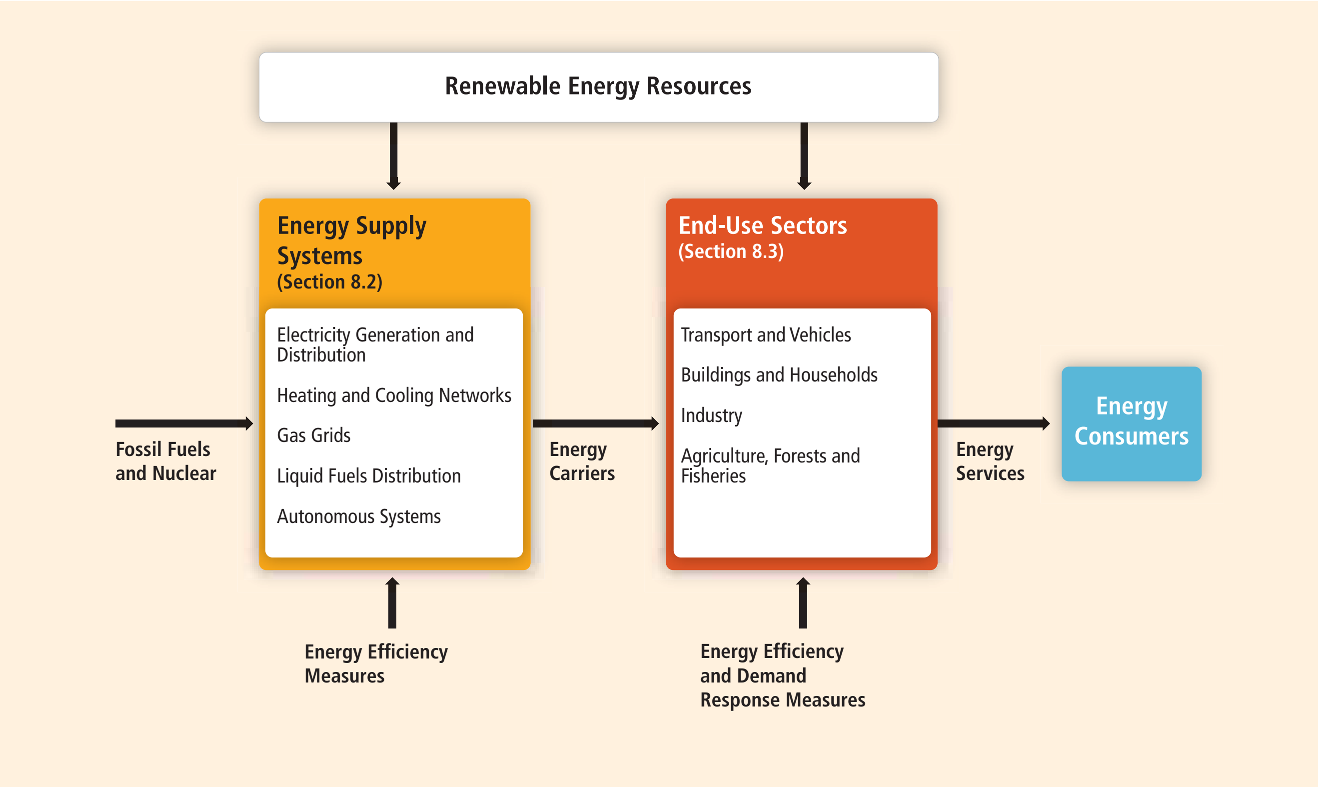


Figure SPM.7 | Pathways for RE integration to provide energy services, either into energy supply systems or on-site for use by the end-use sectors. [Figure 8.1, 8.1]

storage can be more difficult to integrate than dispatchable[9] hydropower, bioenergy, CSP with storage and geothermal energy.

As the penetration of variable RE sources increases, maintaining system reliability may become more challenging and costly. Having a portfolio of complementary RE technologies is one solution to reduce the risks and costs of RE integration. Other solutions include the development of complementary flexible generation and the more flexible operation of existing schemes; improved short-term forecasting, system operation and planning tools; electricity demand that can respond in relation to supply availability; energy storage technologies (including storage-based hydropower); and modified institutional arrangements. Electricity network transmission (including interconnections between systems) and/or distribution infrastructure may need to be strengthened and extended, partly because of the geographical distribution and fixed remote locations of many RE resources. [8.2.1]

- *District heating systems* can use low-temperature thermal RE inputs such as solar and geothermal heat, or biomass, including sources with few competing uses such as refuse-derived fuels. *District cooling* can make use of cold natural waterways. Thermal storage capability and flexible cogeneration can overcome supply and demand variability challenges as well as provide demand response for electricity systems. [8.2.2]

9 Electricity plants that can schedule power generation as and when required are classed as dispatchable [8.2.1.1, Annex I]. Variable RE technologies are partially dispatchable (i.e., only when the RE resource is available). CSP plants are classified as dispatchable when heat is stored for use at night or during periods of low sunshine.

- In *gas distribution grids*, injecting biomethane, or in the future, RE-derived hydrogen and synthetic natural gas, can be achieved for a range of applications but successful integration requires that appropriate gas quality standards are met and pipelines upgraded where necessary. [8.2.3]

- *Liquid fuel systems* can integrate biofuels for transport applications or for cooking and heating applications. Pure (100%) biofuels, or more usually those blended with petroleum-based fuels, usually need to meet technical standards consistent with vehicle engine fuel specifications. [8.2.4, 8.3.1]

There are multiple pathways for increasing the shares of RE across all end-use sectors. The ease of integration varies depending on region, characteristics specific to the sector and the technology.

- For *transport*, liquid and gaseous biofuels are already and are expected to continue to be integrated into the fuel supply systems of a growing number of countries. Integration options may include decentralized on-site or centralized production of RE hydrogen for fuel cell vehicles and RE electricity for rail and electric vehicles [8.2.1, 8.2.3] depending on infrastructure and vehicle technology developments. [8.3.1] Future demand for electric vehicles could also enhance flexible electricity generation systems. [8.2.1, 8.3.1]

- In the *building* sector, RE technologies can be integrated into both new and existing structures to produce electricity, heating and cooling. Supply of surplus energy may be possible, particularly for energy efficient building designs. [8.3.2] In developing countries, the integration of RE supply systems is feasible for even modest dwellings. [8.3.2, 9.3.2]

- Agriculture as well as food and fibre process *industries* often use biomass to meet direct heat and power demands on-site. They can also be net exporters of surplus fuels, heat, and electricity to adjacent supply systems. [8.3.3, 8.3.4] Increasing the integration of RE for use by industries is an option in several sub-sectors, for example through electro-thermal technologies or, in the longer term, by using RE hydrogen. [8.3.3]

The costs associated with RE integration, whether for electricity, heating, cooling, gaseous or liquid fuels, are contextual, site-specific and generally difficult to determine. They may include additional costs for network infrastructure investment, system operation and losses, and other adjustments to the existing energy supply systems as needed. The available literature on integration costs is sparse and estimates are often lacking or vary widely.

In order to accommodate high RE shares, energy systems will need to evolve and be adapted. [8.2, 8.3] Long-term integration efforts could include investment in enabling infrastructure; modification of institutional and governance frameworks; attention to social aspects, markets and planning; and capacity building in anticipation of RE growth. [8.2, 8.3] Furthermore, integration of less mature technologies, including biofuels produced through new processes (also called advanced biofuels or next-generation biofuels), fuels generated from solar energy, solar cooling, ocean energy technologies, fuel cells and electric vehicles, will require continuing investments in research, development and demonstration (RD&D), capacity building and other supporting measures. [2.6, 3.7, 11.5, 11.6, 11.7]

RE could shape future energy supply and end-use systems, in particular for electricity, which is expected to attain higher shares of RE earlier than either the heat or transport fuel sectors at the global level [10.3]. Parallel developments in electric vehicles [8.3.1], increased heating and cooling using electricity (including heat pumps) [8.2.2, 8.3.2, 8.3.3], flexible demand response services (including the use of smart meters) [8.2.1], energy storage and other technologies could be associated with this trend.

As infrastructure and energy systems develop, in spite of the complexities, there are few, if any, fundamental technological limits to integrating a portfolio of RE technologies to meet a majority share of total

energy demand in locations where suitable RE resources exist or can be supplied. However, the actual rate of integration and the resulting shares of RE will be influenced by factors such as costs, policies, environmental issues and social aspects. [8.2, 8.3, 9.3, 9.4, 10.2, 10.5]

5. Renewable energy and sustainable development

Historically, economic development has been strongly correlated with increasing energy use and growth of GHG emissions, and RE can help decouple that correlation, contributing to sustainable development (SD). Though the exact contribution of RE to SD has to be evaluated in a country-specific context, RE offers the opportunity to contribute to social and economic development, energy access, secure energy supply, climate change mitigation, and the reduction of negative environmental and health impacts. [9.2] Providing access to modern energy services would support the achievement of the Millennium Development Goals. [9.2.2, 9.3.2]

- **RE can contribute to social and economic development.** Under favorable conditions, cost savings in comparison to non-RE use exist, in particular in remote and in poor rural areas lacking centralized energy access. [9.3.1, 9.3.2.] Costs associated with energy imports can often be reduced through the deployment of domestic RE technologies that are already competitive. [9.3.3] RE can have a positive impact on job creation although the studies available differ with respect to the magnitude of net employment. [9.3.1]

- **RE can help accelerate access to energy, particularly for the 1.4 billion people without access to electricity and the additional 1.3 billion using traditional biomass.** Basic levels of access to modern energy services can provide significant benefits to a community or household. In many developing countries, decentralized grids based on RE and the inclusion of RE in centralized energy grids have expanded and improved energy access. In addition, non-electrical RE technologies also offer opportunities for modernization of energy services, for example, using solar energy for water heating and crop drying, biofuels for transportation, biogas and modern biomass for heating, cooling, cooking and lighting, and wind for water pumping. [9.3.2, 8.1] The number of people without access to modern energy services is expected to remain unchanged unless relevant domestic policies are implemented, which may be supported or complemented by international assistance as appropriate. [9.3.2, 9.4.2]

- **RE options can contribute to a more secure energy supply, although specific challenges for integration must be considered.** RE deployment might reduce vulnerability to supply disruption and market volatility if competition is increased and energy sources are diversified. [9.3.3, 9.4.3] Scenario studies indicate that concerns regarding secure energy supply could continue in the future without technological improvements within the transport sector. [2.8, 9.4.1.1, 9.4.3.1, 10.3] The variable output profiles of some RE technologies often necessitate technical and institutional measures appropriate to local conditions to assure energy supply reliability. [8.2, 9.3.3]

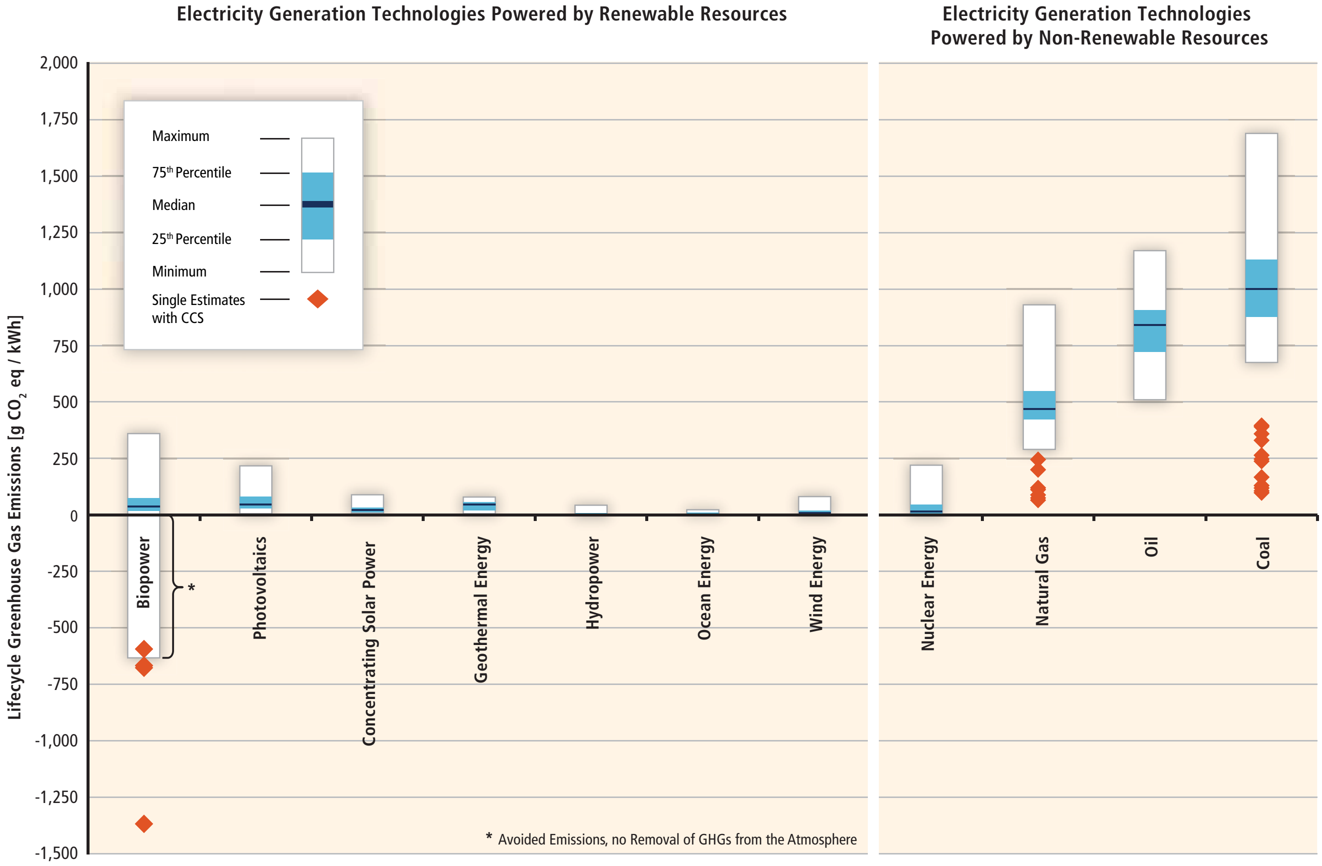
- **In addition to reduced GHG emissions, RE technologies can provide other important environmental benefits. Maximizing these benefits depends on the specific technology, management, and site characteristics associated with each RE project.**

  - **Lifecycle assessments (LCA) for electricity generation indicate that GHG emissions from RE technologies are, in general, significantly lower than those associated with fossil fuel options, and in a range of conditions, less than fossil fuels employing CCS.** The median values for all RE range from 4 to 46 g CO_2eq/kWh while those for fossil fuels range from 469 to 1,001 g CO_2eq/kWh (excluding land use change emissions) (Figure SPM.8).

  - **Most current bioenergy systems, including liquid biofuels, result in GHG emission reductions, and most biofuels produced through new processes (also called advanced biofuels or next-generation biofuels) could provide higher GHG mitigation. The GHG balance may be affected by land use**

changes and corresponding emissions and removals. Bioenergy can lead to avoided GHG emissions from residues and wastes in landfill disposals and co-products; the combination of bioenergy with CCS may provide for further reductions (see Figure SPM.8). The GHG implications related to land management and land use changes in carbon stocks have considerable uncertainties. [2.2, 2.5, 9.3.4.1]

- **The sustainability of bioenergy, in particular in terms of lifecycle GHG emissions, is influenced by land and biomass resource management practices.** Changes in land and forest use or management that, according to a considerable number of studies, could be brought about *directly* or *indirectly* by biomass production for use as fuels, power or heat, can decrease or increase terrestrial carbon stocks. The same studies also



	Biopower	Photovoltaics	Concentrating Solar Power	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
Count of Estimates	222(+4)	124	42	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	13	6	11	5	49	32	36(+4)	10	50(+10)

Figure SPM.8 | Estimates of lifecycle GHG emissions (g CO_2eq/kWh) for broad categories of electricity generation technologies, plus some technologies integrated with CCS. Land use-related net changes in carbon stocks (mainly applicable to biopower and hydropower from reservoirs) and land management impacts are excluded; negative estimates[10] for biopower are based on assumptions about avoided emissions from residues and wastes in landfill disposals and co-products. References and methods for the review are reported in Annex II. The number of estimates is greater than the number of references because many studies considered multiple scenarios. Numbers reported in parentheses pertain to additional references and estimates that evaluated technologies with CCS. Distributional information relates to estimates currently available in LCA literature, not necessarily to underlying theoretical or practical extrema, or the true central tendency when considering all deployment conditions. [Figure 9.8, 9.3.4.1]

10 'Negative estimates' within the terminology of lifecycle assessments presented in the SRREN refer to avoided emissions. Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHGs from the atmosphere.

show that indirect changes in terrestrial carbon stocks have considerable uncertainties, are not directly observable, are complex to model and are difficult to attribute to a single cause. Proper governance of land use, zoning, and choice of biomass production systems are key considerations for policy makers. [2.4.5, 2.5.1, 9.3.4, 9.4.4] Policies are in place that aim to ensure that the benefits from bioenergy, such as rural development, overall improvement of agricultural management and the contribution to climate change mitigation, are realized; their effectiveness has not been assessed. [2.2, 2.5, 2.8]

- **RE technologies, in particular non-combustion based options, can offer benefits with respect to air pollution and related health concerns.** [9.3.4.3, 9.4.4.1] Improving traditional biomass use can significantly reduce local and indoor air pollution (alongside GHG emissions, deforestation and forest degradation) and lower associated health impacts, particularly for women and children in developing countries. [2.5.4, 9.3.4.4]

- **Water availability could influence choice of RE technology.** Conventional water-cooled thermal power plants may be especially vulnerable to conditions of water scarcity and climate change. In areas where water scarcity is already a concern, non-thermal RE technologies or thermal RE technologies using dry cooling can provide energy services without additional stress on water resources. Hydropower and some bioenergy systems are dependent on water availability, and can either increase competition or mitigate water scarcity. Many impacts can be mitigated by siting considerations and integrated planning. [2.5.5.1, 5.10, 9.3.4.4]

- **Site-specific conditions will determine the degree to which RE technologies impact biodiversity.** RE-specific impacts on biodiversity may be positive or negative. [2.5, 3.6, 4.5, 5.6, 6.5, , 9.3.4.6]

- **RE technologies have low fatality rates.** Accident risks of RE technologies are not negligible, but their often decentralized structure strongly limits the potential for disastrous consequences in terms of fatalities. However, dams associated with some hydropower projects may create a specific risk depending on site-specific factors. [9.3.4.7]

6. Mitigation potentials and costs

A significant increase in the deployment of RE by 2030, 2050 and beyond is indicated in the majority of the 164 scenarios reviewed in this Special Report.[11] In 2008, total RE production was roughly 64 EJ/yr (12.9% of total primary energy supply) with more than 30 EJ/yr of this being traditional biomass. More than 50% of the scenarios project levels of RE deployment in 2050 of more than 173 EJ/yr reaching up to over 400 EJ/yr in some cases (Figure SPM.9). Given that traditional biomass use decreases in most scenarios, a corresponding increase in the production level of RE (excluding traditional biomass) anywhere from roughly three-fold to more than ten-fold is projected. The global primary energy supply share of RE differs substantially among the scenarios. More than half of the scenarios show a contribution from RE in excess of a 17% share of primary energy supply in 2030 rising to more than 27% in 2050. The scenarios with the highest RE shares reach approximately 43% in 2030 and 77% in 2050. [10.2, 10.3]

RE can be expected to expand even under baseline scenarios. Most baseline scenarios show RE deployments significantly above the 2008 level of 64 EJ/yr and up to 120 EJ/yr by 2030. By 2050, many baseline scenarios reach RE deployment levels of more than 100 EJ/yr and in some cases up to about 250 EJ/yr (Figure SPM.9). These baseline deployment levels result from a range of assumptions, including, for example, continued demand growth for energy services throughout the century, the ability of RE to contribute to increased energy access and the limited long-term

11 For this purpose a review of 164 global scenarios from 16 different large-scale integrated models was conducted. Although the set of scenarios allows for a meaningful assessment of uncertainty, the reviewed 164 scenarios do not represent a fully random sample suitable for rigorous statistical analysis and do not represent always the full RE portfolio (e.g., so far ocean energy is only considered in a few scenarios) [10.2.2]. For more specific analysis, a subset of 4 illustrative scenarios from the set of 164 was used. They represent a span from a baseline scenario without specific mitigation targets to three scenarios representing different CO_2 stabilization levels. [10.3]

availability of fossil resources. Other assumptions (e.g., improved costs and performance of RE technologies) render RE technologies increasingly economically competitive in many applications even in the absence of climate policy. [10.2]

RE deployment significantly increases in scenarios with low GHG stabilization concentrations. Low GHG stabilization scenarios lead on average to higher RE deployment compared to the baseline. However, for any given long-term GHG concentration goal, the scenarios exhibit a wide range of RE deployment levels (Figure SPM.9). In scenarios that stabilize the atmospheric CO_2 concentrations at a level of less than 440 ppm, the median RE deployment level in 2050 is 248 EJ/yr (139 in 2030), with the highest levels reaching 428 EJ/yr by 2050 (252 in 2030). [10.2]

Many combinations of low-carbon energy supply options and energy efficiency improvements can contribute to given low GHG concentration levels, with RE becoming the dominant low-carbon energy supply option by 2050 in the majority of scenarios. This wide range of results originates in assumptions about factors such as developments in RE technologies (including bioenergy with CCS) and their associated resource bases and costs; the comparative attractiveness of other mitigation options (e.g., end-use energy efficiency, nuclear energy, fossil energy with CCS); patterns of consumption and production; fundamental drivers of energy services demand (including future population and economic growth); the ability to integrate variable RE sources into power grids; fossil fuel resources; specific policy approaches to mitigation; and emissions trajectories towards long-term concentration levels. [10.2]

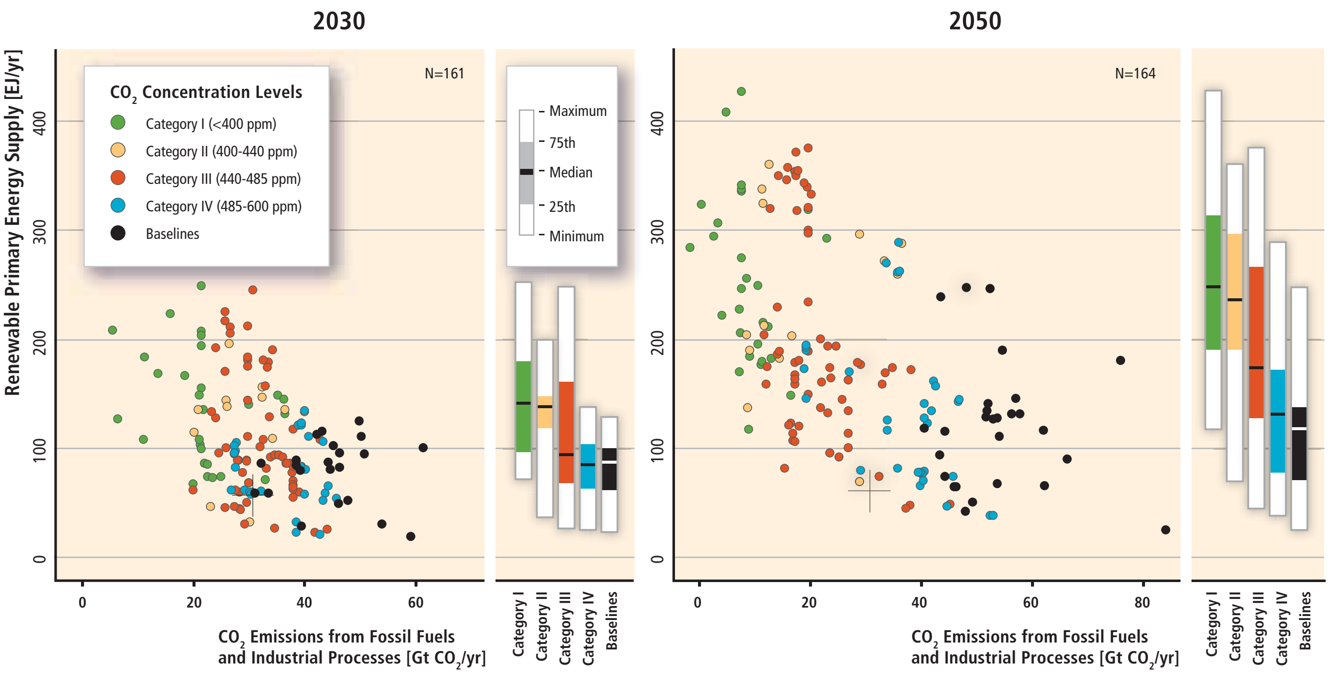


Figure SPM.9 | Global RE primary energy supply (direct equivalent) from 164 long-term scenarios versus fossil and industrial CO_2 emissions in 2030 and 2050. Colour coding is based on categories of atmospheric CO_2 concentration stabilization levels that are defined consistently with those in the AR4. The panels to the right of the scatterplots show the deployment levels of RE in each of the atmospheric CO_2 concentration categories. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. The grey crossed lines show the relationship in 2007. [Figure 10.2, 10.2.2.2]

Notes: For data reporting reasons only 161 scenarios are included in the 2030 results shown here, as opposed to the full set of 164 scenarios. RE deployment levels below those of today are a result of model output and differences in the reporting of traditional biomass. For details on the use of the 'direct equivalent' method of accounting for primary energy supply and the implied care needed in the interpretation of scenario results, see Box SPM.2. Note that categories V and above are not included and category IV is extended to 600 ppm from 570 ppm, because all stabilization scenarios lie below 600 ppm CO_2 in 2100 and because the lowest baseline scenarios reach concentration levels of slightly more than 600 ppm by 2100.

The scenario review in this Special Report indicates that RE has a large potential to mitigate GHG emissions. Four illustrative scenarios span a range of global cumulative CO_2 savings between 2010 and 2050, from about 220 to 560 Gt CO_2 compared to about 1,530 Gt cumulative fossil and industrial CO_2 emissions in the IEA World Energy Outlook 2009 Reference Scenario during the same period. The precise attribution of mitigation potentials to RE depends on the role scenarios attribute to specific mitigation technologies, on complex system behaviours and, in particular, on the energy sources that RE displaces. Therefore, attribution of precise mitigation potentials to RE should be viewed with appropriate caution. [10.2, 10.3, 10.4]

Scenarios generally indicate that growth in RE will be widespread around the world. Although the precise distribution of RE deployment among regions varies substantially across scenarios, the scenarios are largely consistent in indicating widespread growth in RE deployment around the globe. In addition, the total RE deployment is higher over the long term in the group of non-Annex I countries[12] than in the group of Annex I countries in most scenarios (Figure SPM.10). [10.2, 10.3]

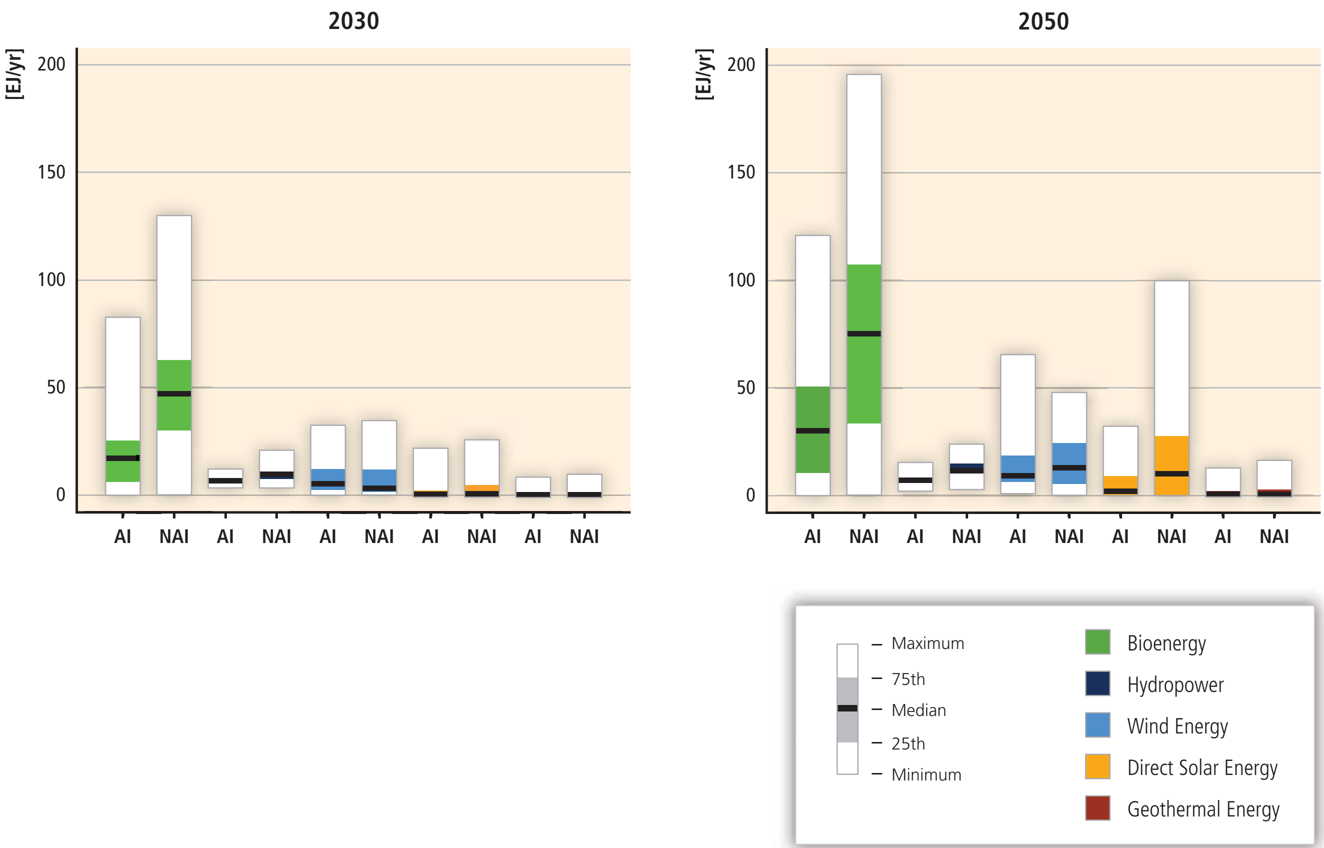


Figure SPM.10 | Global RE primary energy supply (direct equivalent) by source in the group of Annex I (AI) and the group of Non-Annex I (NAI) countries in 164 long-term scenarios by 2030 and 2050. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. [Figure 10.8, 10.2.2.5]

Notes: For details on the use of the 'direct equivalent' method of accounting for primary energy supply and the implied care needed in the interpretation of scenario results, see Box SPM.2. More specifically, the ranges of secondary energy provided from bioenergy, wind energy and direct solar energy can be considered of comparable magnitude in their higher penetration scenarios in 2050. Ocean energy is not presented here as only very few scenarios consider this RE technology.

12 The terms 'Annex I' and 'non-Annex I' are categories of countries that derive from the United Nations Framework Convention on Climate Change (UNFCCC).

Scenarios do not indicate an obvious single dominant RE technology at a global level; in addition, the global overall technical potentials do not constrain the future contribution of RE. Although the contribution of RE technologies varies across scenarios, modern biomass, wind and direct solar commonly make up the largest contributions of RE technologies to the energy system by 2050 (Figure SPM.11). All scenarios assessed confirm that technical potentials will not be the limiting factors for the expansion of RE at a global scale. Despite significant technological and regional differences, in the four illustrative scenarios less than 2.5% of the global available technical RE potential is used. [10.2, 10.3]

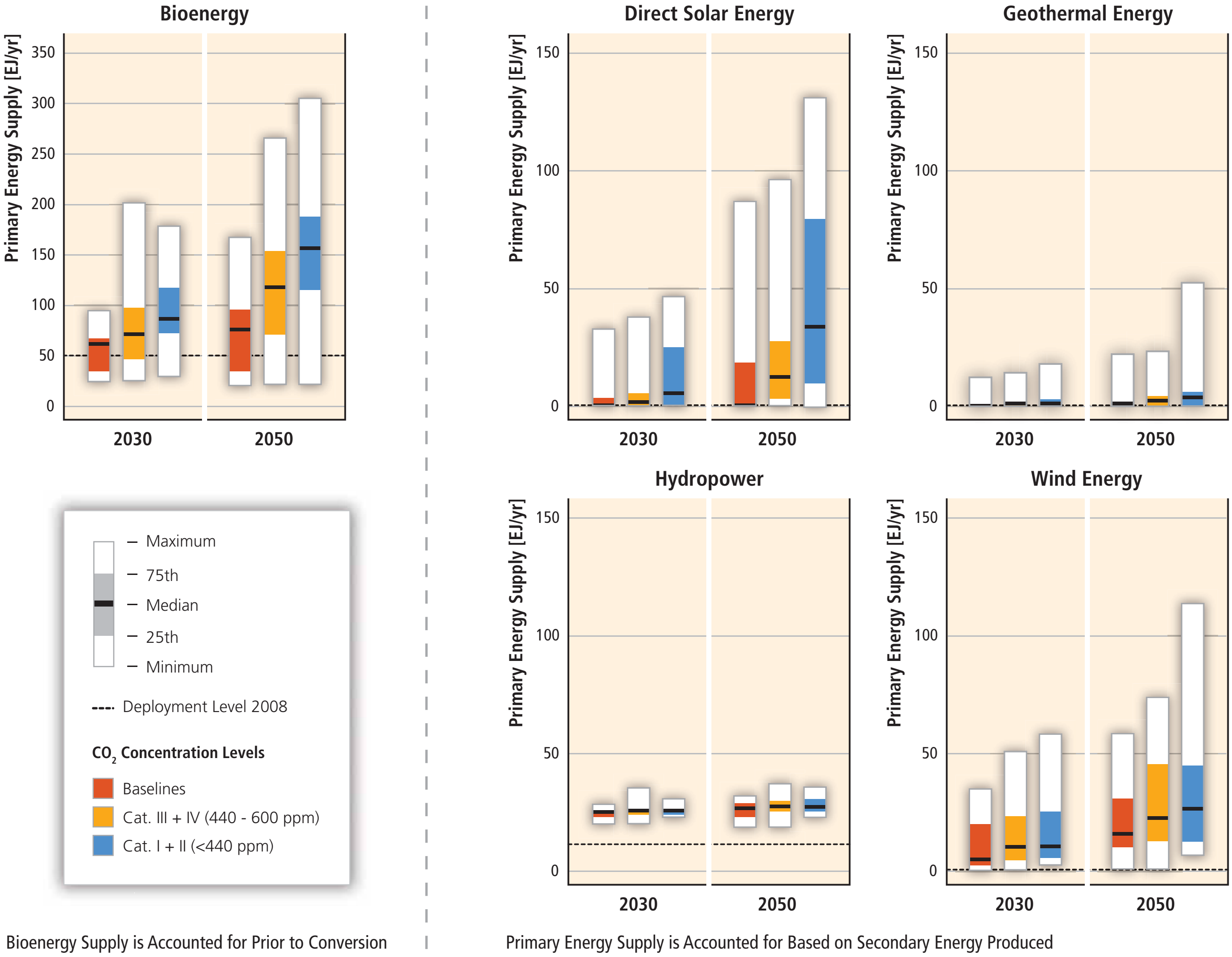


Figure SPM.11 | Global primary energy supply (direct equivalent) of bioenergy, wind, direct solar, hydro, and geothermal energy in 164 long-term scenarios in 2030 and 2050, and grouped by different categories of atmospheric CO_2 concentration level that are defined consistently with those in the AR4. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. [Excerpt from Figure 10.9, 10.2.2.5]

Notes: For details on the use of the 'direct equivalent' method of accounting for primary energy supply and the implied care needed in the interpretation of scenario results, see Box SPM.2. More specifically, the ranges of secondary energy provided from bioenergy, wind energy and direct solar energy can be considered of comparable magnitude in their higher penetration scenarios in 2050. Ocean energy is not presented here as only very few scenarios consider this RE technology. Note that categories V and above are not included and category IV is extended to 600 ppm from 570 ppm, because all stabilization scenarios lie below 600 ppm CO_2 in 2100 and because the lowest baselines scenarios reach concentration levels of slightly more than 600 ppm by 2100.

Individual studies indicate that if RE deployment is limited, mitigation costs increase and low GHG concentration stabilizations may not be achieved. A number of studies have pursued scenario sensitivities that assume constraints on the deployment of individual mitigation options, including RE as well as nuclear and fossil energy with CCS. There is little agreement on the precise magnitude of the cost increase. [10.2]

A transition to a low-GHG economy with higher shares of RE would imply increasing investments in technologies and infrastructure. The four illustrative scenarios analyzed in detail in the SRREN estimate global cumulative RE investments (in the power generation sector only) ranging from USD_{2005} 1,360 to 5,100 billion for the decade 2011 to 2020, and from USD_{2005} 1,490 to 7,180 billion for the decade 2021 to 2030. The lower values refer to the IEA World Energy Outlook 2009 Reference Scenario and the higher ones to a scenario that seeks to stabilize atmospheric CO_2 (only) concentration at 450 ppm. The annual averages of these investment needs are all smaller than 1% of the world's gross domestic product (GDP). Beyond differences in the design of the models used to investigate these scenarios, the range can be explained mainly by differences in GHG concentrations assessed and constraints imposed on the set of admissible mitigation technologies. Increasing the installed capacity of RE power plants will reduce the amount of fossil and nuclear fuels that otherwise would be needed in order to meet a given electricity demand. In addition to investment, operation and maintenance (O&M) and (where applicable) feedstock costs related to RE power plants, any assessment of the overall economic burden that is associated with their application will have to consider avoided fuel and substituted investment costs as well. Even without taking the avoided costs into account, the lower range of the RE power investments discussed above is lower than the respective investments reported for 2009. The higher values of the annual averages of the RE power sector investment approximately correspond to a five-fold increase in the current global investments in this field. [10.5, 11.2.2]

7. Policy, implementation and financing

An increasing number and variety of RE policies—motivated by many factors—have driven escalated growth of RE technologies in recent years. [1.4, 11.2, 11.5, 11.6] Government policies play a crucial role in accelerating the deployment of RE technologies. Energy access and social and economic development have been the primary drivers in most developing countries whereas secure energy supply and environmental concerns have been most important in developed countries [9.3, 11.3]. The focus of policies is broadening from a concentration primarily on RE electricity to include RE heating and cooling and transportation. [11.2, 11.5]

RE-specific policies for research, development, demonstration and deployment help to level the playing field for RE. Policies include regulations such as feed-in-tariffs, quotas, priority grid access, building mandates, biofuel blending requirements, and bioenergy sustainability criteria. [2.4.5.2, 2.ES, TS.2.8.1] Other policy categories are fiscal incentives such as tax policies and direct government payments such as rebates and grants; and public finance mechanisms such as loans and guarantees. Wider policies aimed at reducing GHG emissions such as carbon pricing mechanisms may also support RE.

Policies can be sector specific, can be implemented at the local, state/provincial, national and in some cases regional level, and can be complemented by bilateral, regional and international cooperation. [11.5]
Policies have promoted an increase in RE capacity installations by helping to overcome various barriers. [1.4, 11.1, 11.4, 11.5, 11.6] Barriers to RE deployment include:

- Institutional and policy barriers related to existing industry, infrastructure and regulation of the energy system;

- Market failures, including non-internalized environmental and health costs, where applicable;

- Lack of general information and access to data relevant to the deployment of RE, and lack of technical and knowledge capacity; and

- Barriers related to societal and personal values and affecting the perception and acceptance of RE technologies. [1.4, 9.5.1, 9.5.2.1]

Public R&D investments in RE technologies are most effective when complemented by other policy instruments, particularly deployment policies that simultaneously enhance demand for new technologies. Together, R&D and deployment policies create a positive feedback cycle, inducing private sector investment. Enacting deployment policies early in the development of a given technology can accelerate learning by inducing private R&D, which in turn further reduces costs and provides additional incentives for using the technology. [11.5.2]

Some policies have been shown to be effective and efficient in rapidly increasing RE deployment. However, there is no one-size-fits-all policy. Experience shows that different policies or combinations of policies can be more effective and efficient depending on factors such as the level of technological maturity, affordable capital, ease of integration into the existing system and the local and national RE resource base. [11.5]

- Several studies have concluded that some feed in tariffs have been effective and efficient at promoting RE electricity, mainly due to the combination of long-term fixed price or premium payments, network connections, and guaranteed purchase of all RE electricity generated. Quota policies can be effective and efficient if designed to reduce risk; for example, with long-term contracts. [11.5.4]

- An increasing number of governments are adopting fiscal incentives for RE heating and cooling. Obligations to use RE heat are gaining attention for their potential to encourage growth independent of public financial support. [11.5.5]

- In the transportation sector, RE fuel mandates or blending requirements are key drivers in the development of most modern biofuel industries. Other policies include direct government payments or tax reductions. Policies have influenced the development of an international biofuel trade. [11.5.6]

The flexibility to adjust as technologies, markets and other factors evolve is important. The details of design and implementation are critical in determining the effectiveness and efficiency of a policy. [11.5]. Policy frameworks that are transparent and sustained can reduce investment risks and facilitate deployment of RE and the evolution of low-cost applications. [11.5, 11.6]

'Enabling' policies support RE development and deployment. A favourable, or enabling, environment for RE can be created by addressing the possible interactions of a given policy with other RE policies as well as with energy and non-energy policies (e.g., those targeting agriculture, transportation, water management and urban planning); by easing the ability of RE developers to obtain finance and to successfully site a project; by removing barriers for access to networks and markets for RE installations and output; by increasing education and awareness through dedicated communication and dialogue initiatives; and by enabling technology transfer. In turn, the existence of an 'enabling' environment can increase the efficiency and effectiveness of policies to promote RE. [9.5.1.1, 11.6]

Two separate market failures create the rationale for the additional support of innovative RE technologies that have high potential for technological development, even if an emission market (or GHG pricing policy in general) exists. The first market failure refers to the external cost of GHG emissions. The second market failure is in the field of innovation: if firms underestimate the future benefits of investments into learning RE technologies or if they cannot appropriate these benefits, they will invest less than is optimal from a macroeconomic perspective. In addition to GHG pricing policies, RE-specific policies may be appropriate from an economic point of view if the related opportunities for technological development are to be addressed (or if other goals beyond climate mitigation are pursued). Potentially adverse consequences such as lock-in, carbon leakage and rebound effects should be taken into account in the design of a portfolio of policies. [11.1.1, 11.5.7.3]

The literature indicates that long-term objectives for RE and flexibility to learn from experience would be critical to achieve cost-effective and high penetrations of RE. This would require systematic development of policy frameworks that reduce risks and enable attractive returns that provide stability over a time frame relevant to the investment. An appropriate and reliable mix of policy instruments, including energy efficiency policies, is even more important where energy infrastructure is still developing and energy demand is expected to increase in the future. [11.5, 11.6, 11.7]

8. Advancing knowledge about renewable energy

Enhanced scientific and engineering knowledge should lead to performance improvements and cost reductions in RE technologies. Additional knowledge related to RE and its role in GHG emissions reductions remains to be gained in a number of broad areas including: [for details, see Table 1.1]

- Future cost and timing of RE deployment;
- Realizable technical potential for RE at all geographical scales;
- Technical and institutional challenges and costs of integrating diverse RE technologies into energy systems and markets;
- Comprehensive assessments of socioeconomic and environmental aspects of RE and other energy technologies;
- Opportunities for meeting the needs of developing countries with sustainable RE services; and
- Policy, institutional and financial mechanisms to enable cost-effective deployment of RE in a wide variety of contexts.

Knowledge about RE and its climate change mitigation potential continues to advance. The existing scientific knowledge is significant and can facilitate the decision-making process. [1.1.8]

TS

Technical Summary

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Table of Contents

1. Overview of Climate Change and Renewable Energy

1.1 Background

All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility, communication) and to serve productive processes. For development to be sustainable, delivery of energy services needs to be secure and have low environmental impacts. Sustainable social and economic development requires assured and affordable access to the energy resources necessary to provide essential and sustainable energy services. This may mean the application of different strategies at different stages of economic development. To be environmentally benign, energy services must be provided with low environmental impacts and low greenhouse gas (GHG) emissions. However, the IPCC Fourth Assessment Report (AR4) reported that fossil fuels provided 85%[1] of the total primary energy in 2004, which is the same value as in 2008. Furthermore, the combustion of fossil fuels accounted for 56.6% of all anthropogenic GHG emissions (CO_2eq)[2] in 2004. [1.1.1, 9.2.1, 9.3.2, 9.6, 11.3]

Renewable energy (RE) sources play a role in providing energy services in a sustainable manner and, in particular, in mitigating climate change. This Special Report on *Renewable Energy Sources and Climate Change Mitigation* explores the current contribution and potential of RE sources to provide energy services for a sustainable social and economic development path. It includes assessments of available RE resources and technologies, costs and co-benefits, barriers to up-scaling and integration requirements, future scenarios and policy options. In particular, it provides information for policymakers, the private sector and civil society on:

- Identification of RE resources and available technologies and impacts of climate change on these resources [Chapters 2–7];
- Technology and market status, future developments and projected rates of deployment [Chapters 2–7,10];
- Options and constraints for integration into the energy supply system and other markets, including energy storage, modes of transmission, integration into existing systems and other options [Chapter 8];
- Linkages among RE growth, opportunities and sustainable development [Chapter 9];
- Impacts on secure energy supply [Chapter 9];
- Economic and environmental costs, benefits, risks and impacts of deployment [Chapters 9, 10];
- Mitigation potential of RE resources [Chapter 10];
- Scenarios that demonstrate how accelerated deployment might be achieved in a sustainable manner [Chapter 10];
- Capacity building, technology transfer and financing [Chapter 11]; and
- Policy options, outcomes and conditions for effectiveness [Chapter 11].

The report consists of 11 chapters. Chapter 1 sets the scene on RE and climate change; Chapters 2 through 7 provide information on six RE technologies while Chapters 8 through 11 deal with integrative issues (see Figure TS.1.1). The report communicates uncertainty where relevant.[3] This Technical Summary (TS) provides an overview of the report, summarizing the essential findings.

While the TS generally follows the structure of the full report, references to the various applicable chapters and sections are indicated with corresponding chapter and section numbers in square brackets. An explanation of terms, acronyms and chemical symbols used in the TS can be found in Annex I. Conventions and methodologies for determining costs, primary energy and other topics of analysis can be found in Annex II. Information on levelized costs of RE can be found in Annex III.

GHG emissions associated with the provision of energy services is a major cause of climate change. The AR4 concluded that "Most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic GHG (greenhouse gas) concentrations." Concentrations have continued to grow since the AR4 to over 390 ppm CO_2 or 39% above pre-industrial levels by the end of 2010. Since approximately 1850, global use of fossil fuels (coal, oil and gas) has increased to dominate energy supply, leading to a rapid growth in carbon dioxide (CO_2) emissions [Figure 1.6]. The amount of carbon in fossil fuel reserves and resources not yet burned [Figure 1.7] has the potential to add quantities of CO_2 to the atmosphere—if burned over coming centuries—that would exceed the range of any scenario considered in the AR4 [Figure 1.5] or in Chapter 10 of this report. [1.1.3, 1.1.4]

Despite substantial associated decarbonization, the overwhelming majority of the non-intervention emission projections exhibit considerably higher emissions in 2100 compared with those in 2000, implying rising GHG concentrations and, in turn, an increase in global mean temperatures. To avoid such adverse impacts of climate change on water resources, ecosystems, food security, human health and coastal settlements with potentially irreversible abrupt changes in the climate system,

1 The number from AR4 is 80% and has been converted from the physical content method for energy accounting to the direct equivalent method as the latter method is used in this report. Please refer to Section 1.1.9 and Annex II (Section A.II.4) for methodological details.

2 The contributions from other sources and/or gases are: CO_2 from deforestation, decay of biomass etc. (17.3%), CO_2 from other (2.8%), CH_4 (14.3%), N_2O (7.9%) and fluorinated gases (1.1%).

3 This report communicates uncertainty, for example, by showing the results of sensitivity analyses and by quantitatively presenting ranges in cost numbers as well as ranges in the scenario results. This report does not apply formal IPCC uncertainty terminology because at the time of the approval of this report, IPCC uncertainty guidance was in the process of being revised.

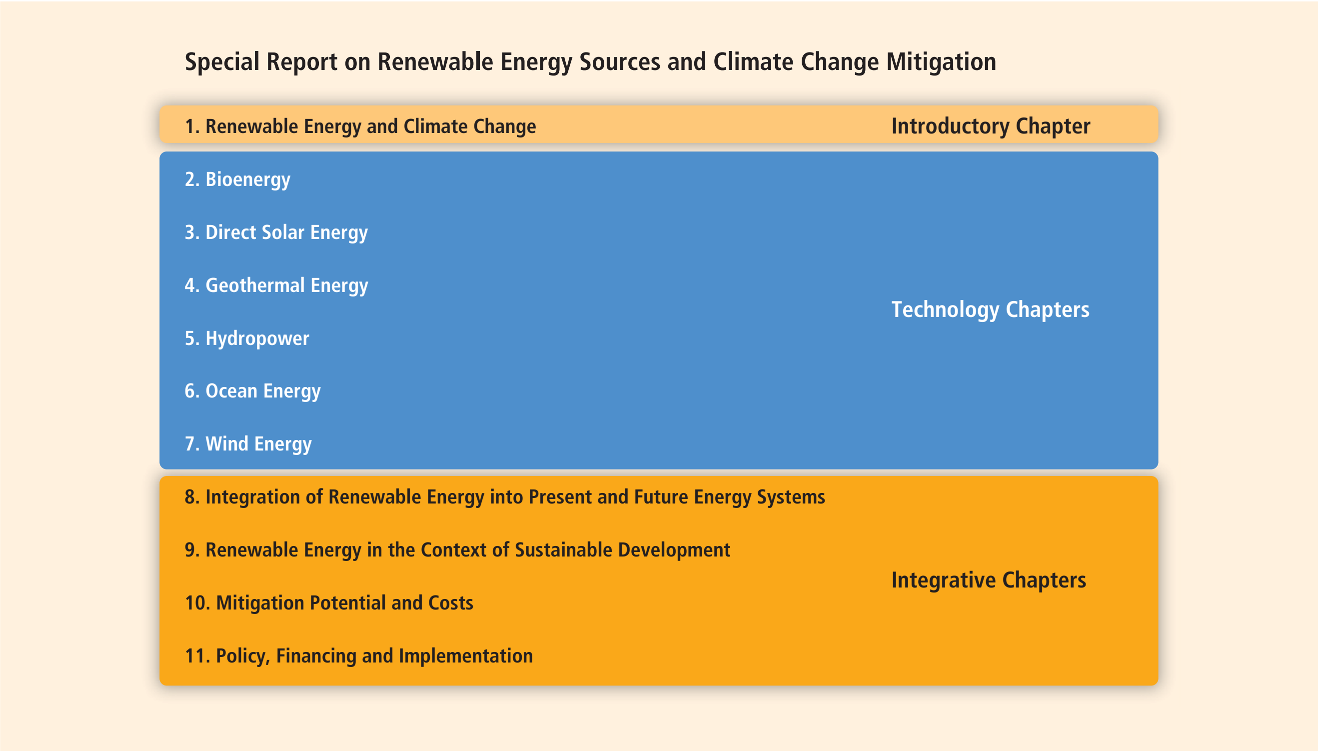


Figure TS.1.1 | Structure of the report. [Figure 1.1]

the Cancun Agreements call for limiting global average temperature rises to no more than 2°C above pre-industrial values, and agreed to consider limiting this rise to 1.5°C. In order to be confident of achieving an equilibrium temperature increase of only 2°C to 2.4°C, atmospheric GHG concentrations would need to be stabilized in the range of 445 to 490 ppm CO_2eq in the atmosphere. This in turn implies that global emissions of CO_2 will need to decrease by 50 to 85% below 2000 levels by 2050 and begin to decrease (instead of continuing their current increase) no later than 2015. [1.1.3]

To develop strategies for reducing CO_2 emissions, the Kaya identity can be used to decompose energy-related CO_2 emissions into four factors: 1) population, 2) gross domestic product (GDP) per capita, 3) energy intensity (i.e., total primary energy supply (TPES) per GDP) and 4) carbon intensity (i.e., CO_2 emissions per TPES). [1.1.4]

CO_2 emissions = Population x (GDP/population) x (TPES/GDP) x (CO_2/TPES)

The annual change in these four components is illustrated in Figure TS.1.2. [1.1.4]

While GDP per capita and population growth had the largest effect on emissions growth in earlier decades, decreasing energy intensity significantly slowed emissions growth in the period from 1971 to 2008. In the past, carbon intensity fell because of improvements in energy efficiency and switching from coal to natural gas and the expansion of nuclear energy in the 1970s and 1980s that was particularly driven by Annex I countries.[4] In recent years (2000 to 2007), increases in carbon intensity have been driven mainly by the expansion of coal use in both developed and developing countries, although coal and petroleum use have fallen slightly since 2007. In 2008 this trend was broken due to the financial crisis. Since the early 2000s, the energy supply has become more carbon intensive, thereby amplifying the increase resulting from growth in GDP per capita. [1.1.4]

On a global basis, it is estimated that RE accounted for 12.9% of the 492 EJ of total primary energy supply in 2008. The largest RE contributor was biomass (10.2%), with the majority (roughly 60%) of the biomass fuel used in traditional cooking and heating applications in developing countries but with rapidly increasing use of modern biomass as well.[5] Hydropower represented 2.3%, whereas other RE sources accounted for 0.4%. (Figure TS.1.3). In 2008, RE contributed approximately 19% of global electricity supply (16% hydropower, 3% other RE). [1.1.5]

Deployment of RE has been increasing rapidly in recent years. Under most conditions, increasing the share of RE in the energy mix will require policies to stimulate changes in the energy system. Government policy, the declining cost of many RE technologies, changes in the prices of fossil

4 See Glossary (Annex I) for a definition of Annex I countries.

5 Not accounted for here or in official databases is the estimated 20 to 40% of additional traditional biomass used in informal sectors. [2.1]

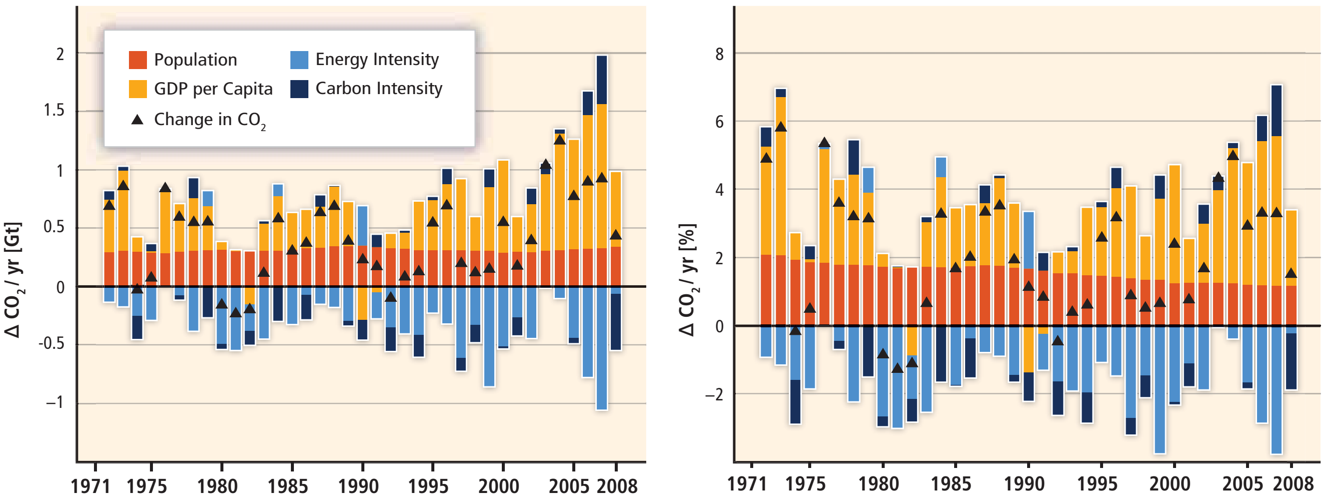


Figure TS.1.2 | Decomposition of (left) annual absolute change and (right) annual growth rate in global energy-related CO_2 emissions by the factors in the Kaya identity; population (red), GDP per capita (orange), energy intensity (light blue) and carbon intensity (dark blue) from 1971 to 2008. The colours show the changes that would occur due to each factor alone, holding the respective other factors constant. Total annual changes are indicated by a black triangle. [Figure 1.8]

fuels and other factors have supported the continuing increase in the use of RE. While the RE share is still relatively small, its growth has accelerated in recent years as shown in Figure TS.1.4. In 2009, despite global financial challenges, RE capacity continued to grow rapidly, including wind power (32%, 38 GW added), hydropower (3%, 31 GW added), grid-connected photovoltaics (53%, 7.5 GW added), geothermal power (4%, 0.4 GW added), and solar hot water/heating (21%, 31 GW_{th} added). Biofuels accounted for 2% of global road transport fuel demand in 2008 and nearly 3% in 2009. The annual production of ethanol increased to 1.6 EJ (76 billion litres) by the end of 2009 and biodiesel production increased to 0.6 EJ (17 billion litres). Of the approximate 300 GW of new electricity generating capacity added globally from 2008 to 2009, about 140 GW came from RE additions. Collectively, developing countries host 53% of global RE electricity generation capacity (including all sizes of hydropower), with China adding more RE power capacity than any other country in 2009. The USA and Brazil accounted for 54 and 35% of global bioethanol production in 2009, respectively, while China led in the use of solar hot water. At the end of 2009, the use of RE in hot water/heating

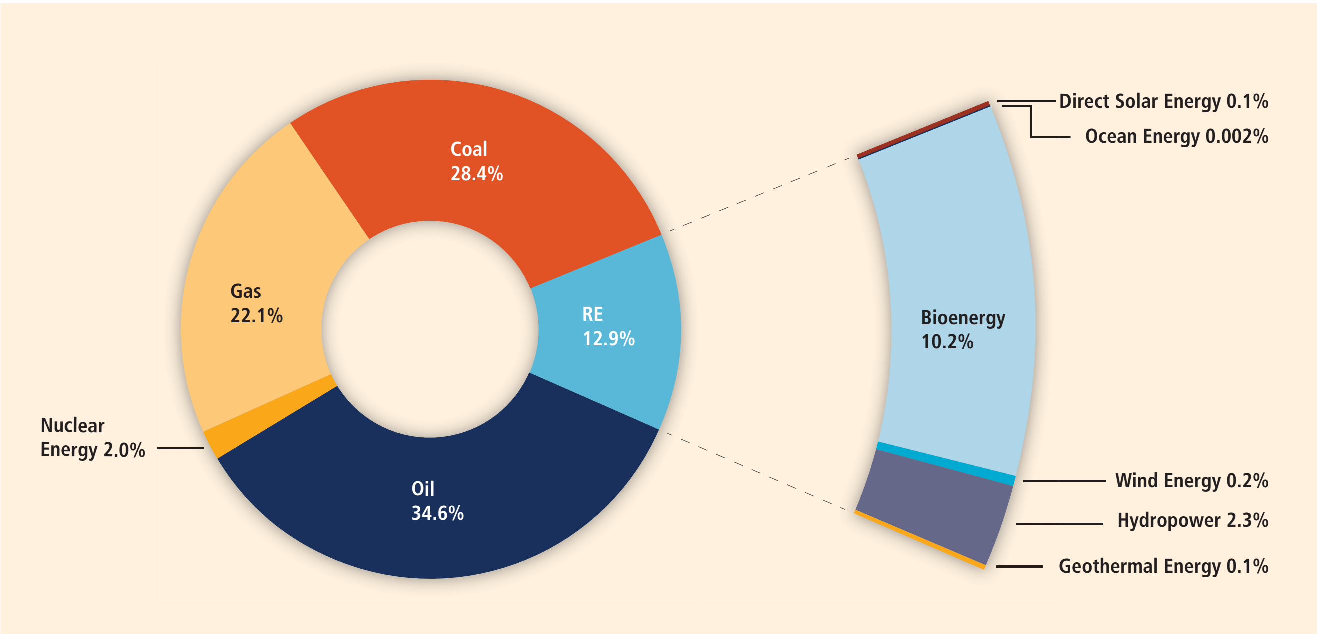


Figure TS.1.3 | Shares of energy sources in total global total primary energy supply in 2008 (492 EJ). Modern biomass contributes 38% of the total biomass share. [Figure 1.10]

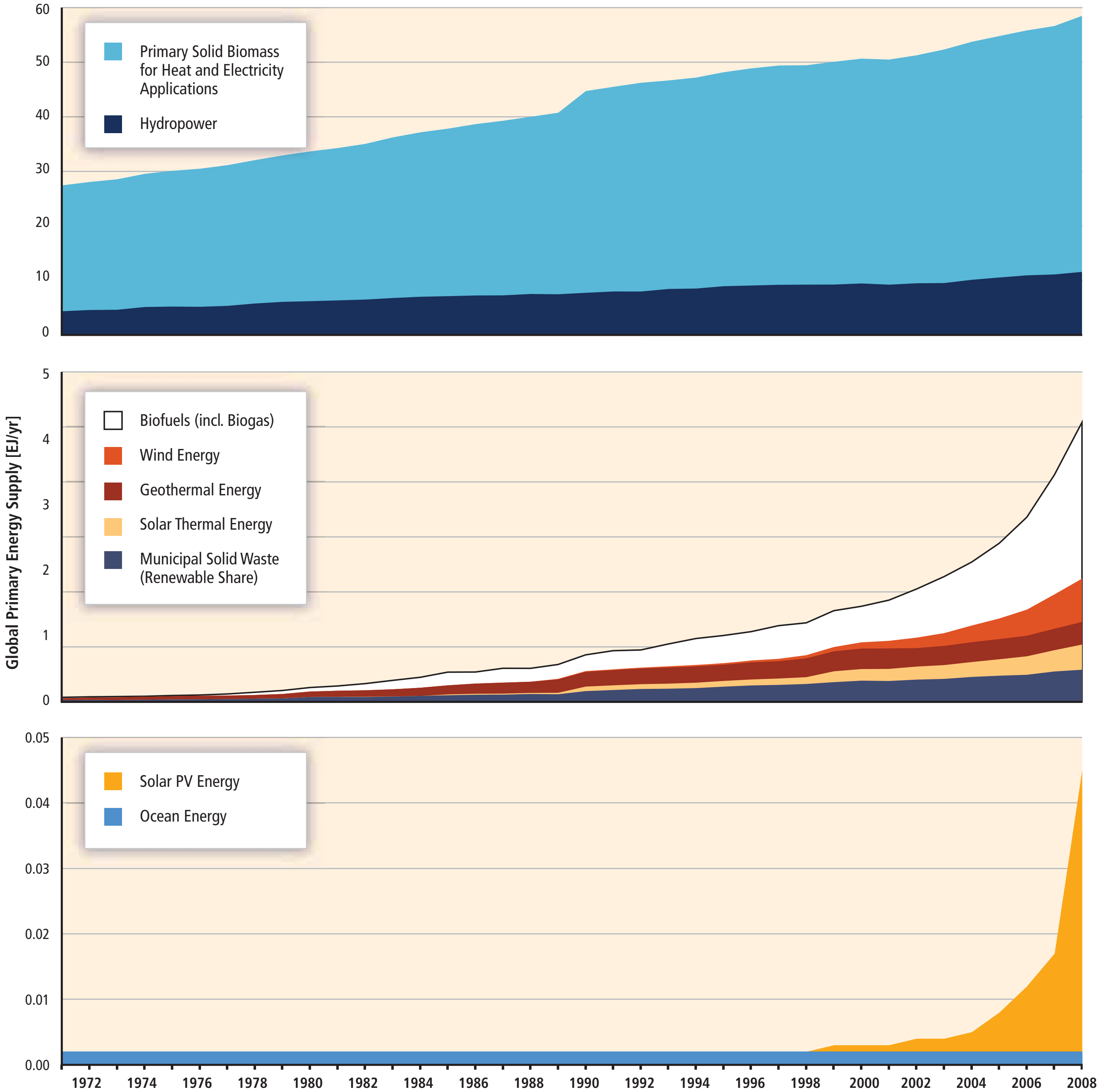


Figure TS.1.4 | Historical development of global primary energy supply from renewable energy from 1971 to 2008. [Figure 1.12]

Note: Technologies are referenced to separate vertical units for display purposes only. Underlying data for the figure has been converted to the 'direct equivalent' method of accounting for primary energy supply [1.1.9, Annex II.4], except that the energy content of biofuels is reported in secondary energy terms (the primary biomass used to produce the biofuel would be higher due to conversion losses [2.3, 2.4]).

markets included modern biomass (270 GW_{th}), solar energy (180 GW_{th}), and geothermal energy (60 GW_{th}). The use of RE (excluding traditional biomass) in meeting rural energy needs has also increased, including small-scale hydropower stations, various modern biomass options, and household or village photovoltaic (PV), wind or hybrid systems that combine multiple technologies. [1.1.5]

There are multiple means for lowering GHG emissions from the energy system while still providing desired energy services. The AR4 identified a number of ways to lower heat-trapping emissions from energy sources while still providing energy services: [1.1.6]

- Improve supply side efficiency of energy conversion, transmission and distribution, including combined heat and power.
- Improve demand side efficiency in the respective sectors and applications (e.g., buildings, industrial and agricultural processes, transportation, heating, cooling and lighting).
- Shift from high-GHG energy carriers such as coal and oil to lower-GHG energy carriers such as natural gas, nuclear fuels and RE sources.
- Utilize CO_2 capture and storage (CCS) to prevent post-combustion or industrial process CO_2 from entering the atmosphere. CCS has the potential for removing CO_2 from the atmosphere when biomass is processed, for example, through combustion or fermentation.
- Change behaviour to better manage energy use or to use fewer carbon- and energy-intensive goods and services.

The future share of RE applications will heavily depend on climate change mitigation goals, the level of requested energy services and resulting energy needs as well as their relative merit within the portfolio of zero- or low-carbon technologies (Figure TS.1.5). A comprehensive evaluation of any portfolio of mitigation options would involve an evaluation of their respective mitigation potential as well as all associated risks, costs and their contribution to sustainable development. [1.1.6]

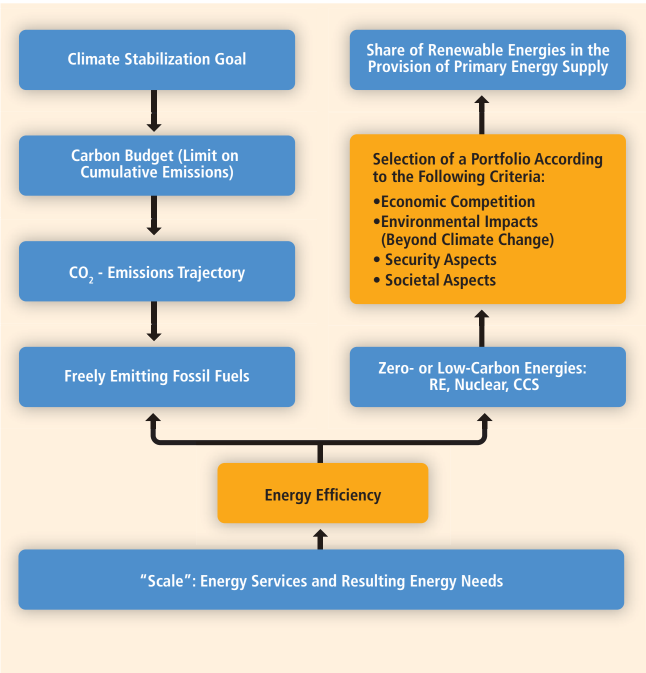


Figure TS.1.5 | The role of renewable energies within the portfolio of zero- or low-carbon mitigation options (qualitative description). [Figure 1.14]

Setting a climate protection goal in terms of the admissible change in global mean temperature broadly defines a corresponding GHG concentration limit with an associated CO_2 budget and subsequent time-dependent emission trajectory, which then defines the admissible amount of freely emitting fossil fuels. The complementary contribution of zero- or low-carbon energies to the primary energy supply is influenced by the 'scale' of the requested energy services. [1.1.6]

As many low-cost options to improve overall energy efficiency are already part of the non-intervention scenarios, the *additional* opportunities to decrease energy intensity in order to mitigate climate change are limited. In order to achieve ambitious climate protection goals, energy efficiency improvements alone do not suffice, requiring additional zero- or low-carbon technologies. The contribution RE will provide within the portfolio of these low-carbon technologies heavily depends on the economic competition between these technologies, a comparison of the relative environmental burden (beyond climate change) associated with them, as well as security and societal aspects (Figure TS.1.5). [1.1.6]

The body of scientific knowledge on RE and on the possible contribution of RE towards meeting GHG mitigation goals, as compiled and assessed in this report, is substantial. Nonetheless, due in part to the site-specific nature of RE, the diversity of RE technologies, the multiple end-use energy service needs that those technologies might serve, the range of markets and regulations governing integration, and the complexity of energy system transitions, knowledge about RE and its climate mitigation potential continues to advance. Additional knowledge remains to be gained in a number of broad areas related to RE and its possible role in GHG emissions reductions: [1.1.8]

- Future cost and timing of RE deployment;
- Realizable technical potential for RE at all geographical scales;
- Technical and institutional challenges and costs of integrating diverse RE technologies into energy systems and markets;
- Comprehensive assessment of socioeconomic and environmental aspects of RE and other energy technologies;
- Opportunities for meeting the needs of developing countries with sustainable RE services; and
- Policy, institutional and financial mechanisms to enable cost-effective deployment of RE in a wide variety of contexts.

Though much is already known in each of these areas, as compiled in this report, additional research and experience would further reduce uncertainties and thus facilitate decision making related to the use of RE in the mitigation of climate change. [1.1.6]

1.2 Summary of renewable energy resources and potential

RE is any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. RE is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes resources such as biomass, solar energy, geothermal heat, hydropower, tide and waves, ocean thermal energy and wind energy. However, it is possible to utilize biomass at a greater rate than it can grow or to draw heat from a geothermal field at a faster rate than heat flows can replenish it. On the other hand, the rate of utilization of direct solar energy has no bearing on the rate at which it reaches the Earth. Fossil fuels (coal, oil, natural gas) do not fall under this definition, as they are not replenished within a time frame that is short relative to their rate of utilization. [1.2.1]

There is a multi-step process whereby primary energy is converted into an energy carrier, and then into an energy service. RE technologies are diverse and can serve the full range of energy service needs. Various types of RE can supply electricity, thermal energy and mechanical energy, as well as produce fuels that are able to satisfy multiple energy service needs. Figure TS.1.6 illustrates the multi-step conversion processes. [1.2.1]

Since it is energy services and not energy that people need, the process should be driven in an efficient manner that requires less primary energy consumption with low-carbon technologies that minimize CO_2 emissions. Thermal conversion processes to produce electricity (including biomass and geothermal) suffer losses of approximately 40 to 90%, and losses of around 80% occur when supplying the mechanical energy needed for transport based on internal combustion engines. These conversion losses raise the share of primary energy from fossil fuels, and the primary energy required from fossil fuels to produce electricity and mechanical energy from heat. Direct energy conversions from solar PV, hydro, ocean and wind energy to electricity do not suffer thermodynamic power cycle (heat to work) losses although they do experience other conversion inefficiencies in extracting energy from natural energy flows that may also be relatively large and irreducible (chapters 2-7). [1.2.1]

Some RE technologies can be deployed at the point of use (decentralized) in rural and urban environments, whereas others are primarily employed within large (centralized) energy networks. Though many

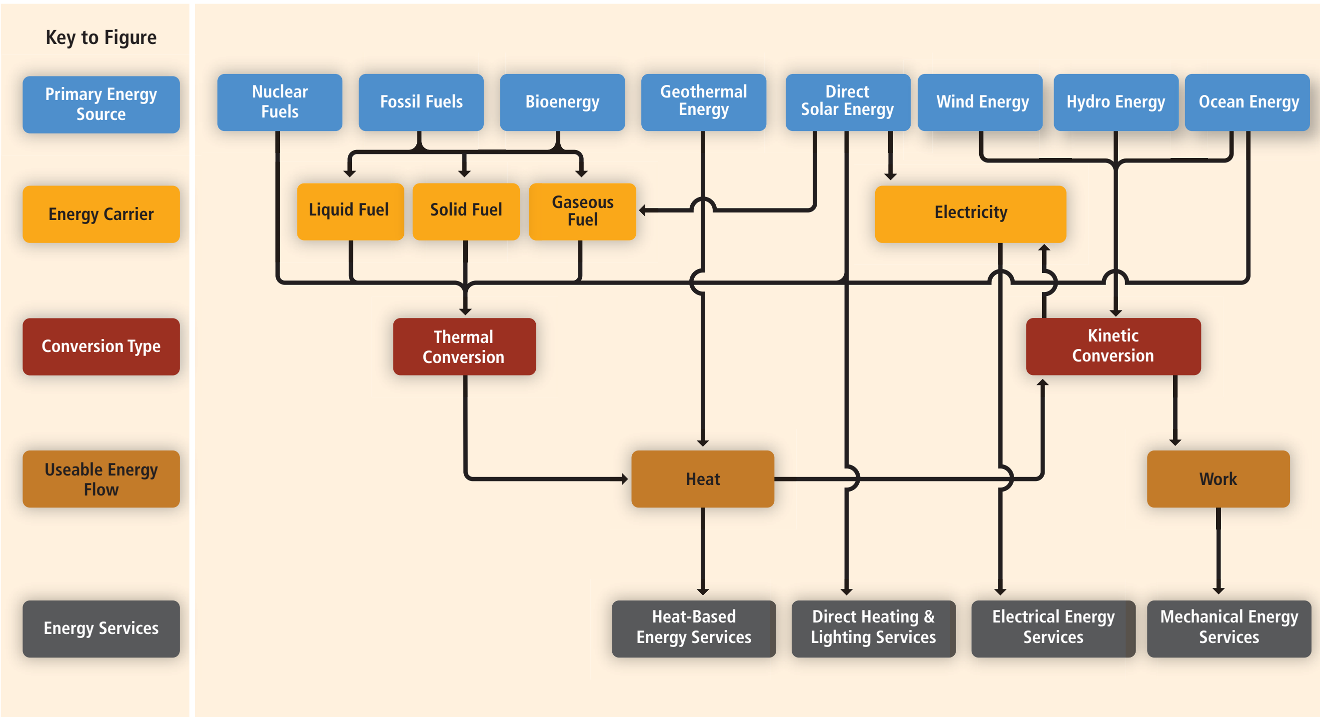


Figure TS.1.6 | Illustrative paths of energy from source to service. All connected lines indicate possible energy pathways. The energy services delivered to the users can be provided with differing amounts of end-use energy. This in turn can be provided with more or less primary energy from different sources, and with differing emissions of CO_2 and other environmental impacts. [Figure 1.16]

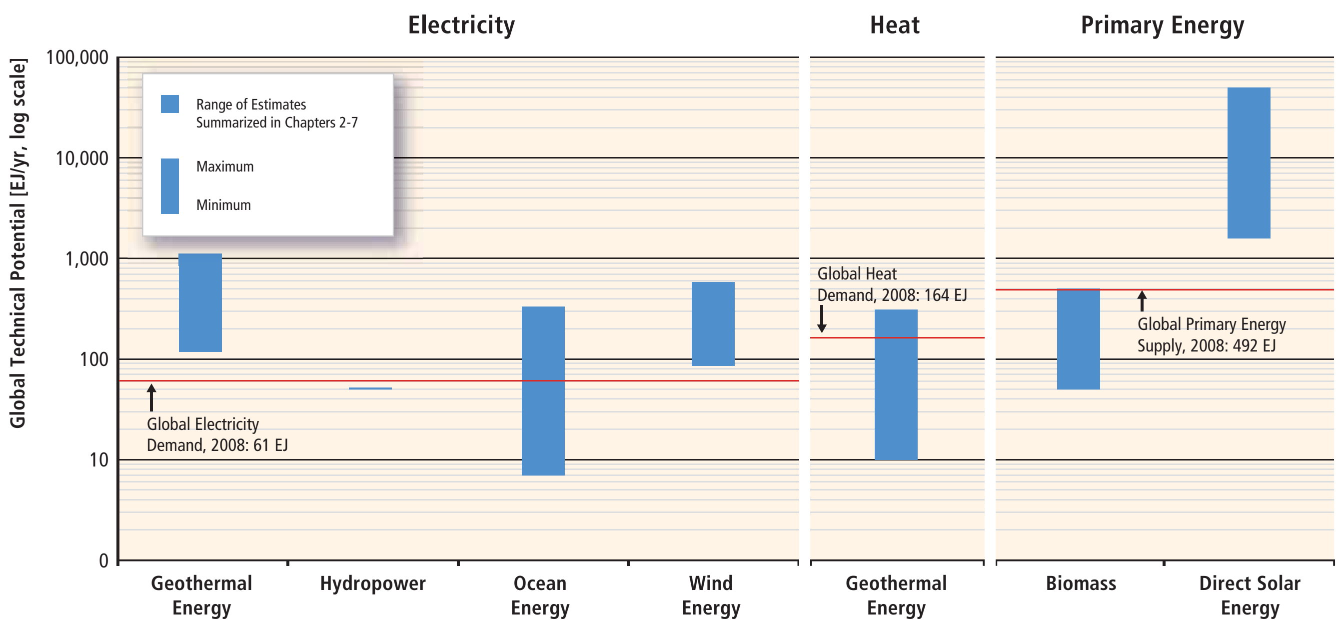
RE technologies are technically mature and are being deployed at significant scale, others are in an earlier phase of technical maturity and commercial deployment. [1.2.1]

The theoretical potential for RE exceeds current and projected global energy demand by far, but the challenge is to capture and utilize a sizable share of that potential to provide the desired energy services in a cost-effective and environmentally sound manner. [1.2.2]

The global technical potential of RE sources will also not limit continued market growth. A wide range of estimates are provided in the literature but studies have consistently found that the total global technical potential for RE is substantially higher than both current and projected future global energy demand. The technical potential for solar energy is the highest among the RE sources, but substantial technical potential exists for all forms of RE. The absolute size of the global technical potential for RE as a whole is unlikely to constrain RE deployment. [1.2.3]

Figure TS.1.7 shows that the technical potential[6] exceeds by a considerable margin the global electricity and heat demand, as well as the global primary energy supply, in 2008. While the figure provides a perspective for the reader to understand the relative sizes of the RE resources in the context of current energy demand and supply, note that the technical potentials are highly uncertain. Table A.1.1 in the Annex to Chapter 1 includes more detailed notes and explanations. [1.2.3]

RE can be integrated into all types of electricity systems from large, interconnected continental-scale grids down to small autonomous buildings. Whether for electricity, heating, cooling, gaseous fuels or liquid fuels, RE integration is contextual, site specific and complex. Partially dispatchable wind and solar energy can be more difficult to integrate than fully dispatchable hydropower, bioenergy and geothermal energy. As the penetration of partially dispatchable RE electricity increases, maintaining system reliability becomes more challenging and costly. A portfolio of solutions to minimize the risks and costs of RE integration can include the development of complementary flexible generation, strengthening and extending network infrastructure and interconnections, electricity demand that can respond in relation to supply availability, energy storage technologies (including reservoir-based hydropower), and modified institutional arrangements



Range of Estimates of Global Technical Potentials

	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Geothermal Energy (Heat)	Biomass	Direct Solar Energy
Max (in EJ/yr)	1109	52	331	580	312	500	49837
Min (in EJ/yr)	118	50	7	85	10	50	1575

Figure TS.1.7 | Ranges of global technical potentials of RE sources derived from studies presented in Chapters 2 through 7. Biomass and solar are shown as primary energy due to their multiple uses. Note that the figure is presented in logarithmic scale due to the wide range of assessed data. [Figure 1.17]

Notes: Technical potentials reported here represent total worldwide potentials for annual RE supply and do not deduct any potential that is already being utilized. Note that RE electricity sources could also be used for heating applications, whereas biomass and solar resources are reported only in primary energy terms but could be used to meet various energy service needs. Ranges are based on various methods and apply to different future years; consequently, the resulting ranges are not strictly comparable across technologies. For the data behind the figure and additional notes that apply, see Table A.1.1 (as well as the underlying chapters).

6 See Annex I for a complete definition of technical potential.

including regulatory and market mechanisms. As the penetration level of RE increases, there is need for a mixture of inexpensive and effective communications systems and technologies, as well as smart meters. [1.2.4]

Energy services are the tasks performed using energy. A specific energy service can be provided in many ways and may therefore be characterized by high or low energy efficiency, implying the release of relatively smaller or larger amounts of CO_2 (under a given energy mix). Reducing energy needs at the energy services delivery stage through energy efficiency is an important means of reducing primary energy demand. This is particularly important for RE sources since they usually have lower power densities than fossil or nuclear fuels. Efficiency measures are often the lowest-cost option to reducing end-use energy demand. This report provides some specific definitions for different dimensions of efficiency. [1.2.5]

Energy savings resulting from efficiency measures are not always fully realized in practice. There may be a rebound effect in which some fraction of the measure is offset because the lower total cost of energy (due to less energy use) to perform a specific energy service may lead to utilization of more energy services. It is estimated that the rebound effect is probably limited by saturation effects to between 10 and 30% for home heating and vehicle use in Organisation for Economic Co-operation and Development (OECD) countries, and is very small for more efficient appliances and water heating. An efficiency measure that is successful in lowering economy-wide energy demand, however, lowers the price of energy as well, leading in turn to a decrease in economy-wide energy costs and additional cost savings (lower energy prices and less energy use). It is expected that the rebound effect may be greater in developing countries and among poor consumers. For climate change, the main concern with any rebound effect is its influence on CO_2 emissions. [1.2.5]

Carbon leakage may also reduce the effectiveness of carbon reduction policies. If carbon reduction policies are not applied uniformly across sectors and political jurisdictions, then it may be possible for carbon emitting activities to move to a sector or country without such policies. Recent research suggests, however, that estimates of carbon leakage are too high. [1.2.5]

1.3 Meeting energy service needs and current status

Global renewable energy flows from primary energy through carriers to end uses and losses in 2008 are shown in Figure TS.1.8. [1.3.1]

Globally in 2008, around 56% of RE was used to supply heat in private households and in the public and services sector. Essentially, this refers to wood and charcoal, widely used in developing countries for cooking. On the other hand, only a small amount of RE is used in the transport sector. Electricity production accounts for 24% of the end-use consumption. Biofuels contributed 2% of global road transport fuel supply in 2008, and traditional biomass (17%), modern biomass (8%), solar thermal and geothermal energy (2%) together fuelled 27% of the total global demand for heat in 2008. [1.3.1]

While the resource is obviously large and could theoretically supply all energy needs long into the future, the levelized cost of energy for many RE technologies is currently higher than existing energy prices, though in various settings RE is already economically competitive. Ranges of recent levelized costs of energy for selected commercially available RE technologies are wide, depending on a number of factors, including, but not limited to, technology characteristics and size, regional variations in cost and performance and differing discount rates (Figure TS.1.9). [1.3.2, 2.3, 2.7, 3.8, 4.8, 5.8, 6.7, 7.8, 10.5, Annex III]

The cost of most RE technologies has declined and additional expected technical advances would result in further cost reductions. Such cost reductions as well as monetizing the external cost of energy supply would improve the relative competitiveness of RE. The same applies if market prices increase due to other reasons. [1.3.2, 2.6, 2.7, 3.7, 3.8, 4.6, 4.7, 5.3, 5.7, 5.8, 6.6, 6.7, 7.7, 7.8, 10.5]

The contribution of RE to primary energy supply varies substantially by country and region. The geographic distribution of RE manufacturing, use and export is now being diversified from the developed world to other developing regions, notably Asia including China. In terms of installed renewable power capacity, China now leads the world followed by the USA, Germany, Spain and India. RE is more evenly distributed than fossil fuels and there are countries or regions rich in specific RE resources. [1.3.3]

1.4 Opportunities, barriers, and issues

The major global energy challenges are securing energy supply to meet growing demand, providing everybody with access to energy services and curbing energy's contribution to climate change. For developing countries, especially the poorest, energy is needed to stimulate production, income generation and social development, and to reduce the serious health problems caused by the use of fuel wood, charcoal, dung and agricultural waste. For industrialized countries, the primary reasons to encourage RE include emission reductions to mitigate climate change, secure energy supply concerns and employment creation. RE can open opportunities for addressing these multiple environmental, social and economic development dimensions, including adaptation to climate change. [1.4, 1.4.1]

Some form of renewable resource is available everywhere in the world, for example, solar radiation, wind, falling water, waves, tides and stored ocean heat or heat from the Earth. Furthermore, technologies exist that can harness these forms of energy. While the opportunities [1.4.1] seem great, there are barriers [1.4.2] and issues [1.4.3] that slow the introduction of RE into modern economies. [1.4]

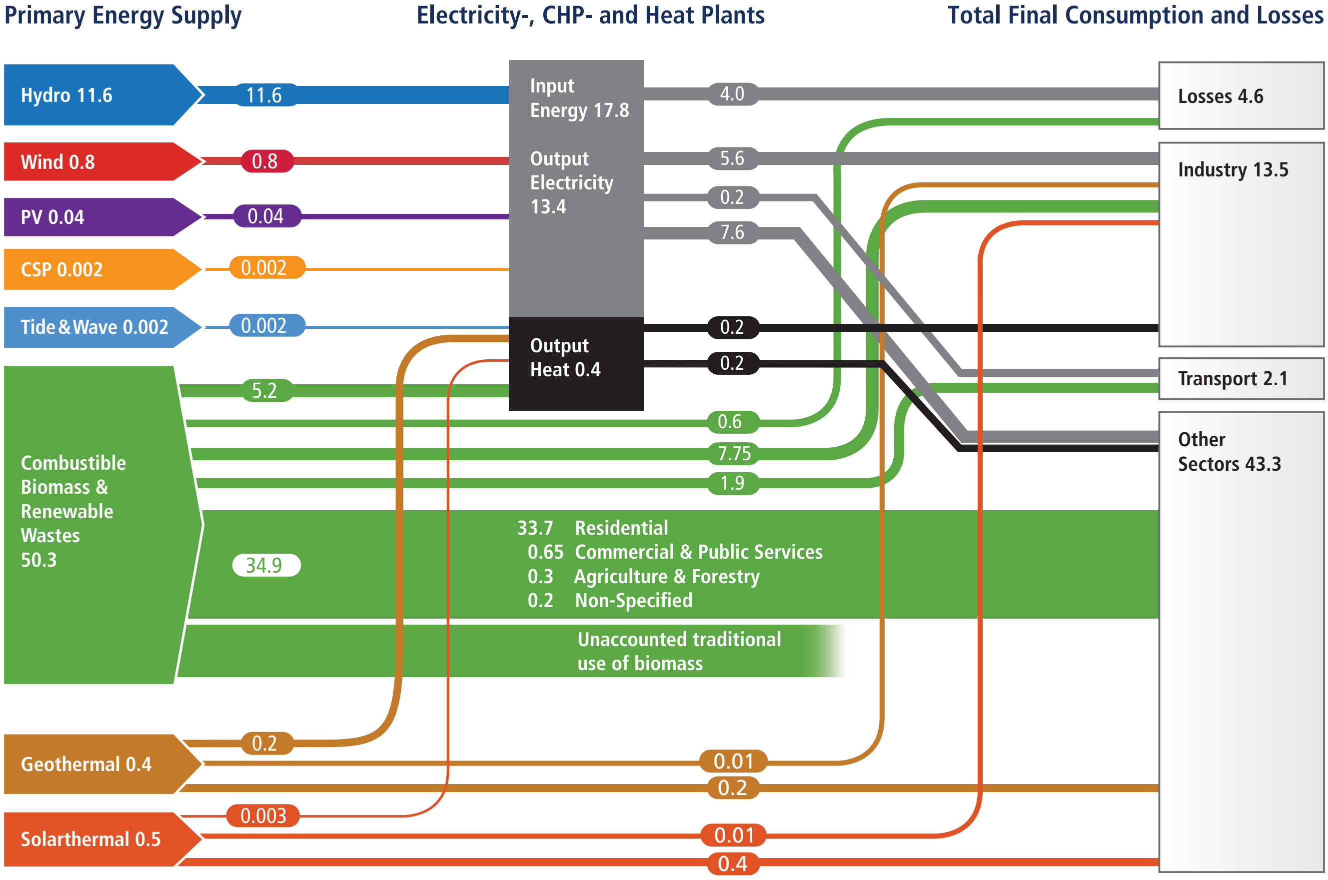


Figure TS.1.8 | Global energy flows (EJ in 2008) from primary RE through carriers to end-uses and losses (based on International Energy Agency (IEA) data). 'Other sectors' include agriculture, commercial and residential buildings, public services and non-specified other sectors. 'Transport sector' includes road transport, international aviation and international marine bunkers. [Figure 1.18]

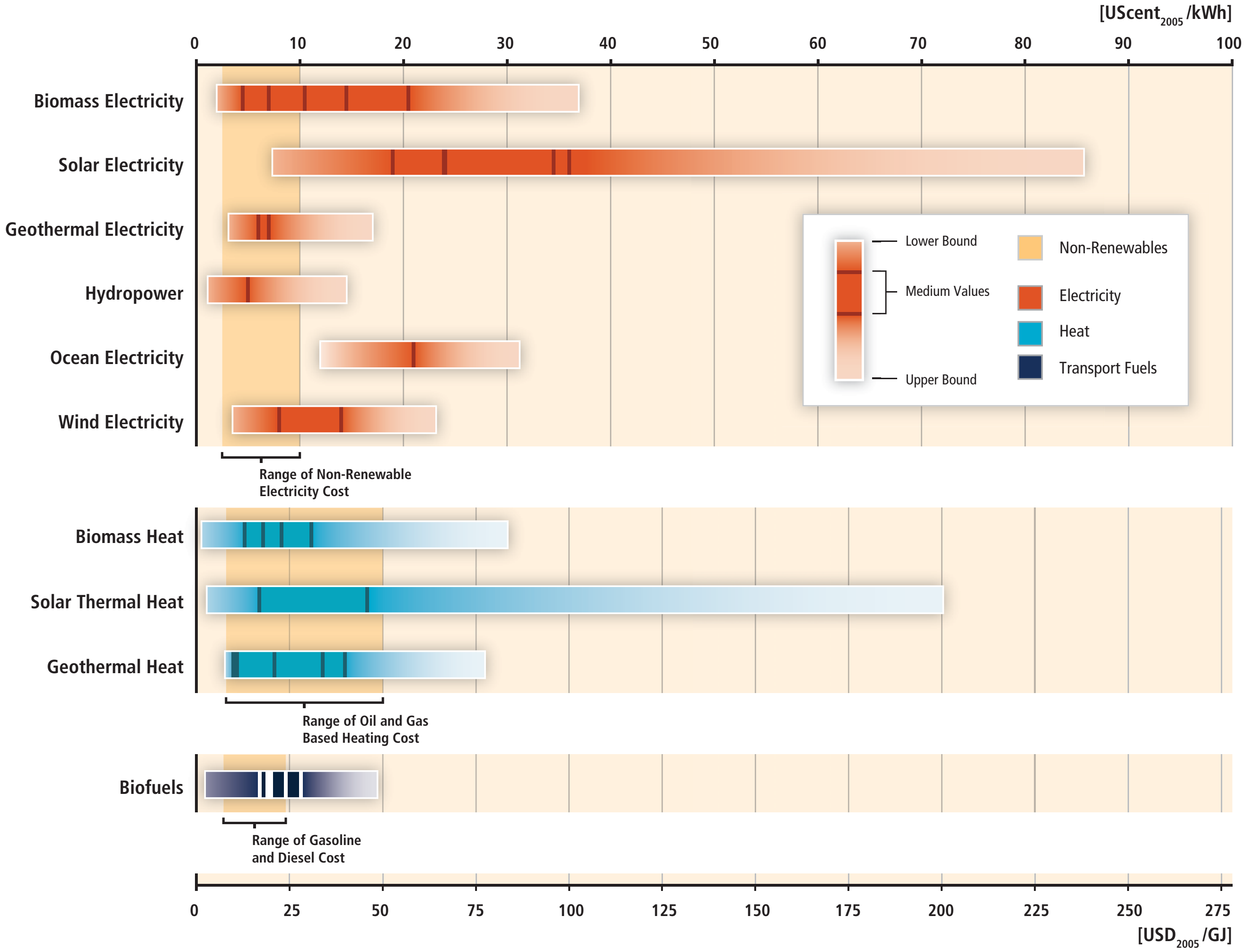
Opportunities can be defined as circumstances for action with the attribute of a chance character. In the policy context that could be the anticipation of additional benefits that may go along with the deployment of RE but that are not intentionally targeted. These include four major opportunity areas: social and economic development; energy access; energy security; and climate change mitigation and the reduction of environmental and health impacts. [1.4.1, 9.2–9.4]

Globally, per capita incomes as well as broader indicators such as the Human Development Index (HDI) are positively correlated with per capita energy use, and economic growth can be identified as the most relevant factor behind increasing energy consumption in the last decades. Economic development has been associated with a shift from direct combustion of fuels to higher quality electricity. [1.4.1, 9.3.1]

Particularly for developing countries, the link between social and economic development and the need for modern energy services is evident. Access to clean and reliable energy constitutes an important prerequisite for fundamental determinants of human development, contributing, inter alia, to economic activity, income generation, poverty alleviation, health, education and gender equality. Due to their decentralized nature, RE technologies can play an important role in fostering rural development. The creation of (new) employment opportunities is seen as a positive long-term effect of RE in both developed and developing countries. [1.4.1, 9.3.1.4, 11.3.4]

Access to modern energy services can be enhanced by RE. In 2008, 1.4 billion people around the world lacked electricity, some 85% of them in rural areas, and the number of people relying on the traditional use of biomass for cooking is estimated to be 2.7 billion. In particular, reliance on RE in rural applications, use of locally produced bioenergy to produce electricity, and access to clean cooking facilities will contribute to attainment of universal access to modern energy services. The transition to modern energy access is referred to as moving up the energy ladder and implies a progression from traditional to more modern devices/fuels that are more environmentally benign and have fewer negative health impacts. This transition is influenced by income level. [1.4.1, 9.3.2]

Energy security concerns that may be characterized as availability and distribution of resources, as well as variability and reliability of energy supply, may also be enhanced by the deployment of RE. As RE technologies help to diversify the portfolio of energy sources and to reduce the economy's



Notes: Medium values are shown for the following subcategories, sorted in the order as they appear in the respective ranges (from left to right):

Electricity	Heat	Transport Fuels
Biomass: 1. Cofiring 2. Small scale combined heat and power, CHP (Gasification internal combustion engine) 3. Direct dedicated stoker & CHP 4. Small scale CHP (steam turbine) 5. Small scale CHP (organic Rankine cycle) **Solar Electricity:** 1. Concentrating solar power 2. Utility-scale PV (1-axis and fixed tilt) 3. Commercial rooftop PV 4. Residential rooftop PV **Geothermal Electricity:** 1. Condensing flash plant 2. Binary cycle plant **Hydropower:** 1. All types **Ocean Electricity:** 1. Tidal barrage **Wind Electricity:** 1. Onshore 2. Offshore	**Biomass Heat:** 1. Municipal solid waste based CHP 2. Anaerobic digestion based CHP 3. Steam turbine CHP 4. Domestic pellet heating system **Solar Thermal Heat:** 1. Domestic hot water systems in China 2. Water and space heating **Geothermal Heat:** 1. Greenhouses 2. Uncovered aquaculture ponds 3. District heating 4. Geothermal heat pumps 5. Geothermal building heating	**Biofuels:** 1. Corn ethanol 2. Soy biodiesel 3. Wheat ethanol 4. Sugarcane ethanol 5. Palm oil biodiesel

The lower range of the levelized cost of energy for each RE technology is based on a combination of the most favourable input-values, whereas the upper range is based on a combination of the least favourable input values. Reference ranges in the figure background for non-renewable electricity options are indicative of the levelized cost of centralized non-renewable electricity generation. Reference ranges for heat are indicative of recent costs for oil and gas based heat supply options. Reference ranges for transport fuels are based on recent crude oil spot prices of USD 40 to 130/barrel and corresponding diesel and gasoline costs, excluding taxes.

Figure TS.1.9 | (Preceding page) Range in recent levelized cost of energy for selected commercially available RE technologies in comparison to recent non-renewable energy costs. Technology subcategories and discount rates were aggregated for this figure. For related figures with less or no such aggregation, see [1.3.2, 10.5, Annex III]. Additional information concerning the cost of non-renewable energy supply options is given in [10.5]. [Figure 10.28]

vulnerability to price volatility and redirect foreign exchange flows away from energy imports, they reduce social inequities in energy supply. Current energy supplies are dominated by fossil fuels (petroleum and natural gas) whose prices have been volatile with significant implications for social, economic and environmental sustainability in the past decades, especially for developing countries and countries with high shares of imported fuels. [1.4.1, 9.2.2, 9.3.3, 9.4.3]

Climate change mitigation is one of the key driving forces behind a growing demand for RE technologies. In addition to reducing GHG emissions, RE technologies can also offer benefits with respect to air pollution and health compared to fossil fuels. However, to evaluate the overall burden from the energy system on the environment and society, and to identify potential trade-offs and synergies, environmental impacts apart from GHG emissions and categories have to be taken into account as well. The resource may also be affected by climate change. Lifecycle assessments facilitate a quantitative comparison of 'cradle to grave' emissions across different energy technologies. Figure TS.1.10 illustrates the lifecycle structure for CO_2 emission analysis, and qualitatively indicates the relative GHG implications for RE, nuclear power and fossil fuels. [1.4.1, 9.2.2, 9.3.4, 11.3.1]

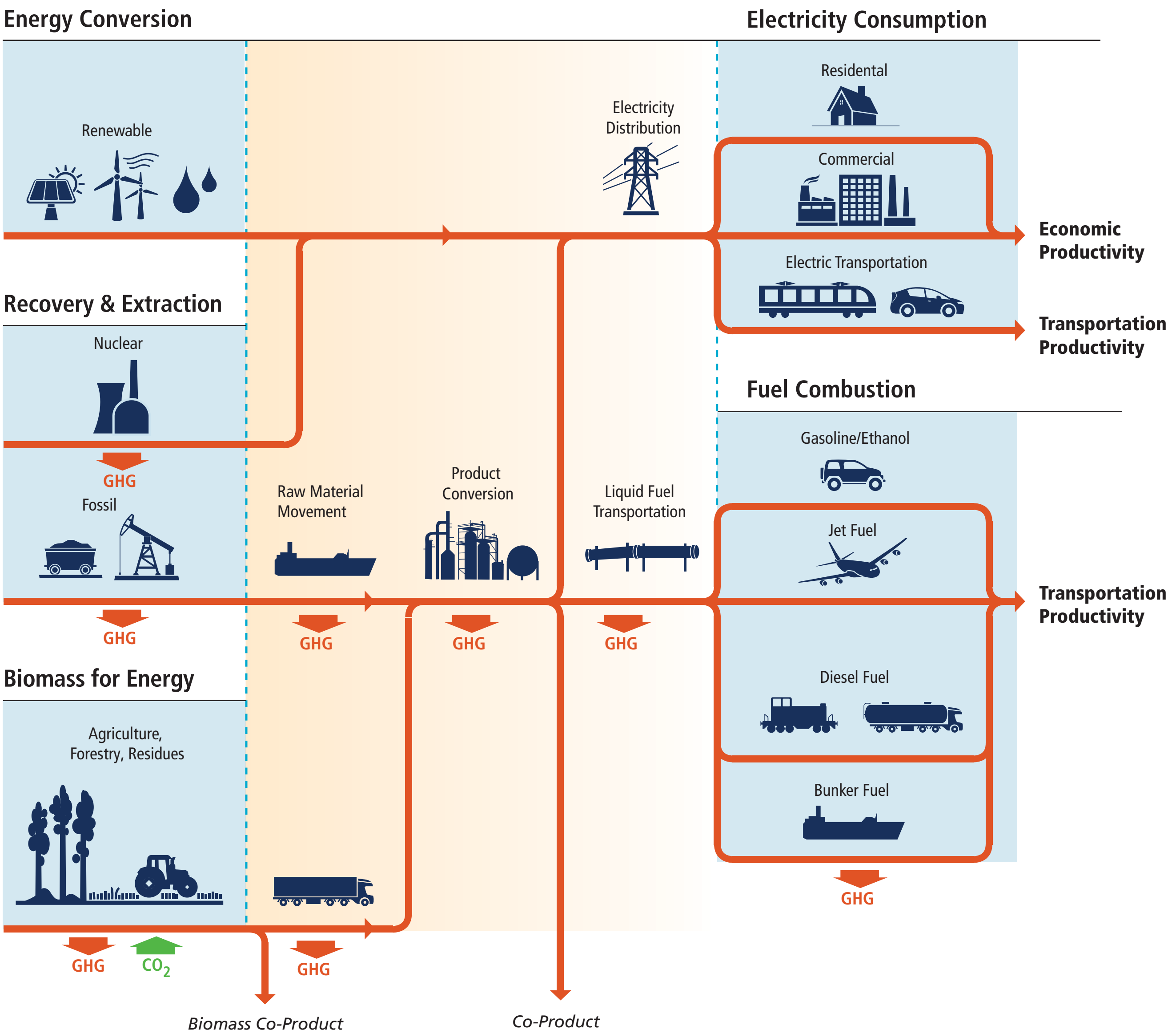


Figure TS.1.10 | Illustrative system for energy production and use illustrating the role of RE along with other production options. A systemic approach is needed to conduct lifecycle assessments. [Figure 1.22]

Traditional biomass use results in health impacts from the high concentrations of particulate matter and carbon monoxide, among other pollutants. In this context, non-combustion-based RE power generation technologies have the potential to significantly reduce local and regional air pollution and lower associated health impacts compared to fossil-based power generation. Improving traditional biomass use can reduce negative sustainable development (SD) impacts, including local and indoor air pollution, GHG emissions, deforestation and forest degradation. [1.4.1, 2.5.4, 9.3.4, 9.3.4, 9.4.2]

Impacts on water resources from energy systems strongly depend on technology choice and local conditions. Electricity production with wind and solar PV, for example, requires very little water compared to thermal conversion technologies, and has no impacts on water or air quality. Limited water availability for cooling thermal power plants decreases their efficiency, which can affect plants operating on coal, biomass, gas, nuclear and concentrating solar power. There have been significant power reductions from nuclear and coal plants during drought conditions in the USA and France in recent years. Surface-mined coal in particular produces major alterations of land; coal mines can create acid mine drainage and the storage of coal ash can contaminate surface and ground waters. Oil production and transportation have led to significant land and water spills. Most renewable technologies produce lower conventional air and water pollutants than fossil fuels, but may require large amounts of land as, for example, reservoir-based hydropower, wind and biofuels. Since a degree of climate change is now inevitable, adaptation to climate change is also an essential component of sustainable development. [1.4.1, 9.3.4]

Barriers are defined in AR4 as "any obstacle to reaching a goal, adaptation or mitigation potential that can be overcome or attenuated by a policy programme or measure". The various barriers to RE use can be categorized as market failures and economic barriers, information and awareness barriers, socio-cultural barriers and institutional and policy barriers. Policies and financing mechanisms to overcome those barriers are extensively assessed in Chapter 11. When a barrier is particularly pertinent to a specific technology, it is examined in the appropriate 'technology' chapters of this report [Chapters 2–7]. A summary of barriers and potential policy instruments to overcome these barriers is shown in Table 1.5 of Chapter 1. Market failures are often due to external effects. These arise from a human activity, when agents responsible for the activity do not take full account of the activity's impact on others. Another market failure is rent appropriation by monopolistic entities. In the case of RE deployment, these market failures may appear as underinvestment in invention and innovation in RE technologies, un-priced environmental impacts and risks of energy use as well as the occurrence of monopoly (one seller) or monopsony (one buyer) powers in energy markets. Other economic barriers include up-front investment cost and financial risks, the latter sometimes due to immaturity of the technology. [1.4.2, 1.5, 11.4]

Informational and awareness barriers include deficient data about natural resources, often due to site-specificity (e.g., local wind regimes), lack of skilled human resources (capacity) especially in rural areas of developing countries as well as the lack of public and institutional awareness. Socio-cultural barriers are intrinsically linked to societal and personal values and norms that affect the perception and acceptance of RE and may be slow to change. Institutional and policy barriers include existing industry, infrastructure and energy market regulation. Despite liberalization of energy markets in several countries in the 1990s, current industry structures are still highly concentrated and regulations governing energy businesses in many countries are still designed around monopoly or near-monopoly providers. Technical regulations and standards have evolved under the assumption that energy systems are large and centralized, and of high power density and/or high voltage. Intellectual property rights, tariffs in international trade and lack of allocation of government financial support may constitute further barriers. [1.4.2]

Issues are not readily amenable to policies and programmes. An issue is that the resource may be too small to be useful at a particular location or for a particular purpose. Some renewable resources such as wind and solar energy are variable and may not always be available for dispatch when needed. Furthermore, the energy density of many renewable sources is relatively low, so that their power levels may be insufficient on their own for some purposes such as very large-scale industrial facilities. [1.4.3]

1.5 Role of policy, research and development, deployment and implementation strategies

An increasing number and variety of RE policies—motivated by a variety of factors—have driven escalated growth in RE technologies in recent years. For policymakers wishing to support the development and deployment of RE technologies for climate change mitigation goals, it is critical to consider the potential of RE to reduce emissions from a lifecycle perspective, as addressed in each technology chapter of this report. Various policies have been designed to address every stage of the development chain involving research and development (R&D), testing, deployment, commercialization, market preparation, market penetration, maintenance and monitoring, as well as integration into the existing system. [1.4.1, 1.4.2, 9.3.4, 11.1.1, 11.2, 11.4, 11.5]

Two key market failures are typically addressed: 1) the external cost of GHG emissions are not priced at an appropriate level; and 2) deployment of low-carbon technologies such as RE create benefits to society beyond those captured by the innovator, leading to under-investment in such efforts. [1.4, 1.5, 11.1, 11.4]

Policy- and decision-makers approach the market in a variety of ways. No globally-agreed list of RE policy options or groupings exists. For the purpose of simplification, R&D and deployment policies have been organized within the following categories in this report: [1.5.1, 11.5]

- **Fiscal incentive:** actors (individuals, households, companies) are granted a reduction of their contribution to the public treasury via income or other taxes;

- **Public finance:** public support for which a financial return is expected (loans, equity) or financial liability is incurred (guarantee); and

- **Regulation:** rule to guide or control conduct of those to whom it applies.

R&D, innovation, diffusion and deployment of new low-carbon technologies create benefits to society beyond those captured by the innovator, resulting in under-investment in such efforts. Thus, government R&D can play an important role in advancing RE technologies. Public R&D investments are most effective when complemented by other policy instruments, particularly RE deployment policies that simultaneously enhance demand for new RE technologies. [1.5.1, 11.5.2]

Some policy elements have been shown to be more effective and efficient in rapidly increasing RE deployment, but there is no one-size-fits-all policy. Experience shows that different policies or combinations of policies can be more effective and efficient depending on factors such as the level of technological maturity, affordable capital, ease of integration into the existing system and the local and national RE resource base:

- Several studies have concluded that some feed-in tariffs have been effective and efficient at promoting RE electricity, mainly due to the combination of long-term fixed price or premium payments, network connections, and guaranteed purchase of all RE electricity generated. Quota policies can be effective and efficient if designed to reduce risk; for example, with long-term contracts.

- An increasing number of governments are adopting fiscal incentives for RE heating and cooling. Obligations to use RE heat are gaining attention for their potential to encourage growth independent of public financial support.

- In the transportation sector, RE fuel mandates or blending requirements are key drivers in the development of most modern biofuel industries. Other policies include direct government payments or tax reductions. Policies have influenced the development of an international biofuel and pellet trade.

One important challenge will be finding a way for RE and carbon-pricing policies to interact such that they take advantage of synergies rather than tradeoffs. In the long-term, support for technological learning in RE can help reduce costs of mitigation, and putting a price on carbon can increase the competitiveness of RE. [1.5.1, 11.1, 11.4, 11.5.7]

RE technologies can play a greater role if they are implemented in conjunction with 'enabling' policies. A favourable, or 'enabling', environment for RE can be created by addressing the possible interactions of a given policy with other RE policies as well as with other non-RE policies and the existence of an 'enabling' environment can increase the efficiency and effectiveness of policies to promote RE. Since all forms of RE capture and production involve spatial considerations, policies need to consider land use, employment, transportation, agricultural, water, food security and trade concerns, existing infrastructure and other sectoral specifics. Government policies that complement each other are more likely to be successful. [1.5.2, 11.6]

Advancing RE technologies in the electric power sector, for example, will require policies to address their integration into transmission and distribution systems both technically [Chapter 8] and institutionally [Chapter 11]. The grid must be able to handle both traditional, often more central, supply as well as modern RE supply, which is often variable and distributed. [1.5.2, 11.6.5]

In the transport sector, infrastructure needs for biofuels, recharging hydrogen, battery or hybrid electric vehicles that are 'fuelled' by the electric grid or from off-grid renewable electrical production need to be addressed.

If decision makers intend to increase the share of RE and, at the same time, to meet ambitious climate mitigation targets, then long-standing commitments and flexibility to learn from experience will be critical. To achieve international GHG concentration stabilization levels that incorporate high shares of RE, a structural shift in today's energy systems will be required over the next few decades. The available time span is restricted to a few decades and RE must develop and integrate into a system constructed in the context of an existing energy structure that is very different from what might be required under higher-penetration RE futures. [1.5.3, 11.7]

A structural shift towards a world energy system that is mainly based on RE might begin with a prominent role for energy efficiency in combination with RE. Additional policies are required that extend beyond R&D to support technology deployment; the creation of an enabling environment that includes education and awareness raising; and the systematic development of integrative policies with broader sectors, including agriculture, transportation, water management and urban planning. The appropriate and reliable mix of instruments is even more important where energy infrastructure is not yet developed and energy demand is expected to increase significantly in the future. [1.2.5, 1.5.3, 11.7, 11.6, 11.7]

2. Bioenergy

2.1 Introduction to biomass and bioenergy

Bioenergy is embedded in complex ways in global biomass systems for food, fodder and fibre production and for forest products as well as in wastes and residue management. Perhaps most importantly, bioenergy plays an intimate and critical role in the daily livelihoods of billions of people in developing countries. Figure TS.2.1 shows the types of biomass used for bioenergy in developing and developed countries. Expanding bioenergy production significantly will require sophisticated land and water use management; global feedstock productivity increases for food, fodder, fibre, forest products and energy; substantial conversion technology improvements; and a refined understanding of the complex social, energy and environmental interactions associated with bioenergy production and use.

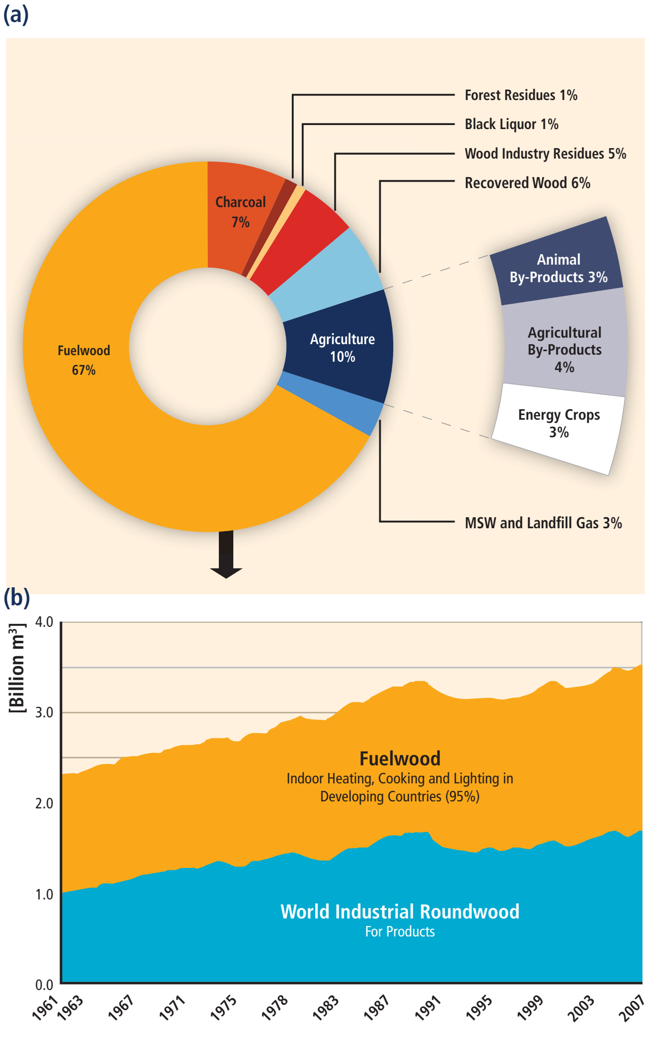


Figure TS.2.1 | (a) Shares of global primary biomass sources for energy; and (b) fuelwood used in developing countries parallels world industrial roundwood[1] production levels. [Figure 2.1]

Note: 1. Roundwood products are saw logs and veneer logs for the forest products industry and wood chips that are used for making pulpwood used in paper, newsprint and Kraft paper. In 2009, reflecting the downturn in the economy, there was a decline to 3.25 (total) and 1.25 (industrial) billion m^3.

In 2008, biomass provided about 10% (50.3 EJ/yr) of the global primary energy supply (see Table TS.2.1). Major biomass uses fall into two broad categories:

- Low-efficiency traditional biomass[7] such as wood, straws, dung and other manures are used for cooking, lighting and space heating, generally by the poorer populations in developing countries. This biomass is mostly combusted, creating serious negative impacts on health and living conditions. Increasingly, charcoal is becoming secondary energy carrier in rural areas with opportunities to create productive chains. As an indicator of the magnitude of traditional biomass use, Figure TS.2.1(b) illustrates that the global primary energy supply from traditional biomass parallels the world's industrial wood production. [2.5.4, 2.3, 2.3.2.2, 2.4.2, 2.5.7]

- High-efficiency modern bioenergy uses more convenient solids, liquids and gases as secondary energy carriers to generate heat, electricity, combined heat and power (CHP), and transport fuels for various sectors. Liquid biofuels include ethanol and biodiesel for global road transport and some industrial uses. Biomass derived gases, primarily methane, from anaerobic digestion of agricultural residues and municipal solid waste (MSW) treatment are used to generate electricity, heat or both. The most important contribution to these energy services is based on solids, such as chips, pellets, recovered wood previously used and others. Heating includes space and hot water heating such as in district heating systems. The estimated total primary biomass supply for modern bioenergy is 11.3 EJ/yr and the secondary energy delivered to end-use consumers is roughly 6.6 EJ/yr. [2.3.2, 2.4, 2.4.6, 2.6.2]

Additionally, the industry sector, such as the pulp and paper, forestry, and food industries, consumes approximately 7.7 EJ of biomass annually, primarily as a source for industrial process steam. [2.7.2, 8.3.4]

2.2 Bioenergy resource potential

The inherent complexity of biomass resources makes the assessment of their combined technical potential controversial and difficult to characterize. Estimates in the literature range from zero technical potential (no biomass available for energy production) to a maximum theoretical potential of

7 Traditional biomass is defined as biomass consumption in the residential sector in developing countries and refers to the often unsustainable use of wood, charcoal, agricultural residues and animal dung for cooking and heating. All other biomass use is defined as modern biomass; this report further differentiates between highly efficient modern bioenergy and industrial bioenergy applications with varying degrees of efficiency. [Annex I] The renewability and sustainability of biomass use is primarily discussed in Sections 2.5.4 and 2.5.5, respectively (see also Section 1.2.1 and Annex I).

Table TS.2.1 | Examples of traditional and select modern biomass energy flows in 2008; see Table 2.1 for notes on specific flows and accounting challenges. [Table 2.1]

Type	Approximate Primary Energy (EJ/yr)	Approximate Average Efficiency (%)	Approximate Secondary Energy (EJ/yr)
Traditional Biomass			
Accounted for in IEA energy balance statistics	30.7	10–20	3–6
Estimated for informal sectors (e.g., charcoal) [2.1]	6–12		0.6–2.4
Total Traditional Biomass	37–43		3.6–8.4
Modern Bioenergy			
Electricity and CHP from biomass, MSW, and biogas	4.0	32	1.3
Heat in residential, public/commercial buildings from solid biomass and biogas	4.2	80	3.4
Road Transport Fuels (ethanol and biodiesel)	3.1	60	1.9
Total Modern Bioenergy	11.3	58	6.6

about 1,500 EJ from global modelling efforts. Figure TS.2.2 presents a summary of technical potentials found in major studies, including data from the scenario analysis of Chapter 10. To put biomass technical potential for energy in perspective, global biomass used for energy currently amounts to approximately 50 EJ/yr and all harvested biomass used for food, fodder and fibre, when expressed in a caloric equivalent, contains about 219 EJ/yr (2000 data); nearly the entire current global biomass harvest would be required to achieve a 150 EJ/yr deployment level of bioenergy by 2050. [2.2.1]

An assessment of technical potential based on an analysis of the literature available in 2007 and additional modelling studies arrived at the conclusion that the upper bound of the technical potential in 2050 could amount to about 500 EJ, shown in the stacked bar of Figure TS.2.2. The study assumes policy frameworks that secure good governance of land use and major improvements in agricultural management and takes into account water limitations, biodiversity protection, soil degradation and competition with food. Residues originating from forestry, agriculture and organic wastes (including the organic fraction of MSW, dung, process residues, etc.) are estimated to amount to 40 to 170 EJ/yr, with a mean estimate of around 100 EJ/yr. This part of the technical potential is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range. Surplus forestry products other than from forestry residues have an additional technical potential

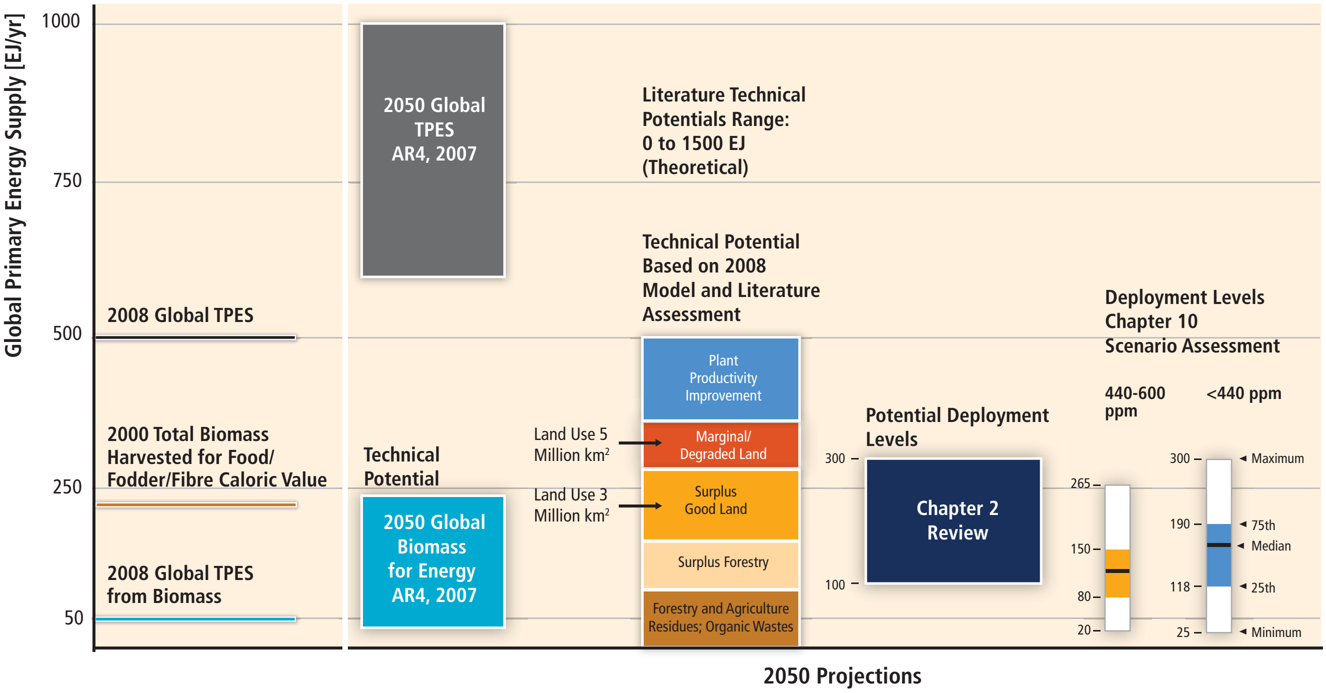


Figure TS.2.2 | A summary of major 2050 projections of global terrestrial biomass technical potential for energy and possible deployment levels compared to 2008 global total primary energy and biomass supply as well as the equivalent energy of world total biomass harvest. [Figure 2.25] of about 60 to 100 EJ/yr. A lower estimate for energy crop production on possible surplus, good quality agricultural and pasture lands is 120 EJ/yr. The potential contribution of water-scarce, marginal and degraded lands could amount to up to an additional 70 EJ/yr. This would comprise a large area where water scarcity imposes limitations and soil degradation is more severe. Assuming strong learning in agricultural technology for improvements in agricultural and livestock management would add 140 EJ/yr. The three categories added together lead to a technical potential from this analysis of up to about 500 EJ/yr (Figure TS 2.2).

Developing this technical potential would require major policy efforts, therefore, actual deployment would likely be lower and the biomass resource base will be largely constrained to a share of the biomass residues and organic wastes, some cultivation of bioenergy crops on marginal and degraded lands, and some regions where biomass is a cheaper energy supply option compared to the main reference options (e.g., sugarcane-based ethanol production). [2.2.2, 2.2.5, 2.8.3]

The expert review conclusions based on available scientific literature are: [2.2.2–2.2.4]

- Important factors include (1) population and economic/technology development, food, fodder and fibre demand (including diets), and developments in agriculture and forestry; (2) climate change impacts on future land use including its adaptation capability; and (3) the extent of land degradation, water scarcity and biodiversity and nature conservation requirements.

- Residue flows in agriculture and forestry and unused (or extensively used thus becoming marginal/degraded) agricultural land are important sources for expansion of biomass production for energy, both in the near- and longer term. Biodiversity-induced limitations and the need to ensure maintenance of healthy ecosystems and avoidance of soil degradation set limits on residue extraction in agriculture and forestry.

- The cultivation of suitable plants (e.g., perennial crops or woody species) can allow for higher technical potentials by making it possible to produce bioenergy on lands less suited for conventional food crops—also when considering that the cultivation of conventional crops on such lands can lead to soil carbon emissions.

- Multi-functional land use systems with bioenergy production integrated into agriculture and forestry systems could contribute to biodiversity conservation and help restore/maintain soil productivity and healthy ecosystems.

- Regions experiencing water scarcity may have limited production. The possibility that conversion of lands to biomass plantations reduces downstream water availability needs to be considered. The use of suitable drought-tolerant energy crops can help adaptation in water-scarce situations. Assessments of biomass resource potentials need to more carefully consider constraints and opportunities in relation to water availability and competing uses.

Following the restrictions outlined above, the expert review concludes that potential deployment levels of biomass for energy by 2050 could be in the range of 100 to 300 EJ. However, there are large uncertainties in this potential, such as market and policy conditions, and there is strong dependence on the rate of improvements in the agricultural sector for food, fodder and fibre production and forest products. One example from the literature suggests that bioenergy can expand from around 100 EJ/yr in 2020 to 130 EJ/yr in 2030, and could reach 184 EJ/yr in 2050. [2.2.1, 2.2.2, 2.2.5]

To reach the upper range of the expert review deployment level of 300 EJ/yr (shown in Figure TS.2.2) would require major policy efforts, especially targeting improvements and efficiency increases in the agricultural sector and good governance, such as zoning, of land use.

2.3 Bioenergy technology and applications

Commercial bioenergy technology applications include heat production—with scales ranging from home cooking with stoves to large district heating systems; power generation from biomass via combustion, CHP, or co-firing of biomass and fossil fuels; and first-generation liquid biofuels from oil crops (biodiesel) and sugar and starch crops (ethanol) as shown in the solid lines of Figure TS.2.3. The figure also illustrates developing feedstocks (e.g., aquatic biomass), conversion routes and products.[8] [2.3, 2.6, 2.7, 2.8]

Section 2.3 addresses key issues related to biomass production and the logistics of supplying feedstocks to the users (individuals for traditional and modern biomass, firms that use and produce secondary energy products or, increasingly, an informal sector of production and distribution of charcoal). The conversion technologies that transform biomass to convenient secondary energy carriers use thermochemical, chemical or biochemical processes, and are summarized in Sections 2.3.1–2.3.3 and 2.6.1–2.6.3. Chapter 8 addresses energy product integration with the existing and evolving energy systems. [2.3.1–2.3.3, 2.6.1–2.6.3]

2.4 Global and regional status of markets and industry deployment

A review of biomass markets and policy shows that bioenergy has seen rapid developments in recent years such as the use of modern biomass for liquid and gaseous energy carriers (an increase of 37% from 2006 to 2009). Projections from the IEA, among others, count on biomass delivering a substantial increase in the share of RE, driven in some cases by national targets. International trade in biomass and biofuels has

8 Biofuels produced via new processes are also called advanced or next-generation biofuels, e.g. lignocellulosic.

also become much more important over recent years, with roughly 6% (reaching levels of up to 9% in 2008) of biofuels (ethanol and biodiesel only) traded internationally and one-third of all pellet production for energy use in 2009. The latter facilitated both increased utilization of biomass in regions where supplies were constrained as well as mobilized resources from areas lacking demand. Nevertheless, many barriers remain in developing effective commodity trading of biomass and biofuels that, at the same time, meets sustainability criteria. [2.4.1, 2.4.4]

In many countries, the policy context for bioenergy and, in particular, biofuels, has changed rapidly and dramatically in recent years. The debate surrounding biomass in the food versus fuel competition, and growing concerns about other conflicts, have resulted in a strong push for the development and implementation of sustainability criteria and frameworks as well as changes in target levels and schedules for bioenergy and biofuels. Furthermore, support for advanced biorefinery and next-generation biofuel[9] options is driving bioenergy to be more sustainable. [2.4.5]

Persistent and stable policy support has been a key factor in building biomass production capacity and markets, requiring infrastructure and conversion capacity that gets more competitive over time. These conditions have led to the success of the Brazilian programme to the point that ethanol production costs are now lower than those for gasoline. Sugarcane fibre bagasse generates heat and electricity, with an energy portfolio mix that is substantially based on RE and that minimizes foreign oil imports. Sweden and Finland also have shown significant growth in renewable electricity and in management of integrated resources, which steadily resulted in innovations such as industrial symbiosis of collocated industries. The USA has been able to quickly ramp up production with alignment of national and sub-national policies for power in the 1980s to 1990s and for biofuels in the 1990s to the present, as

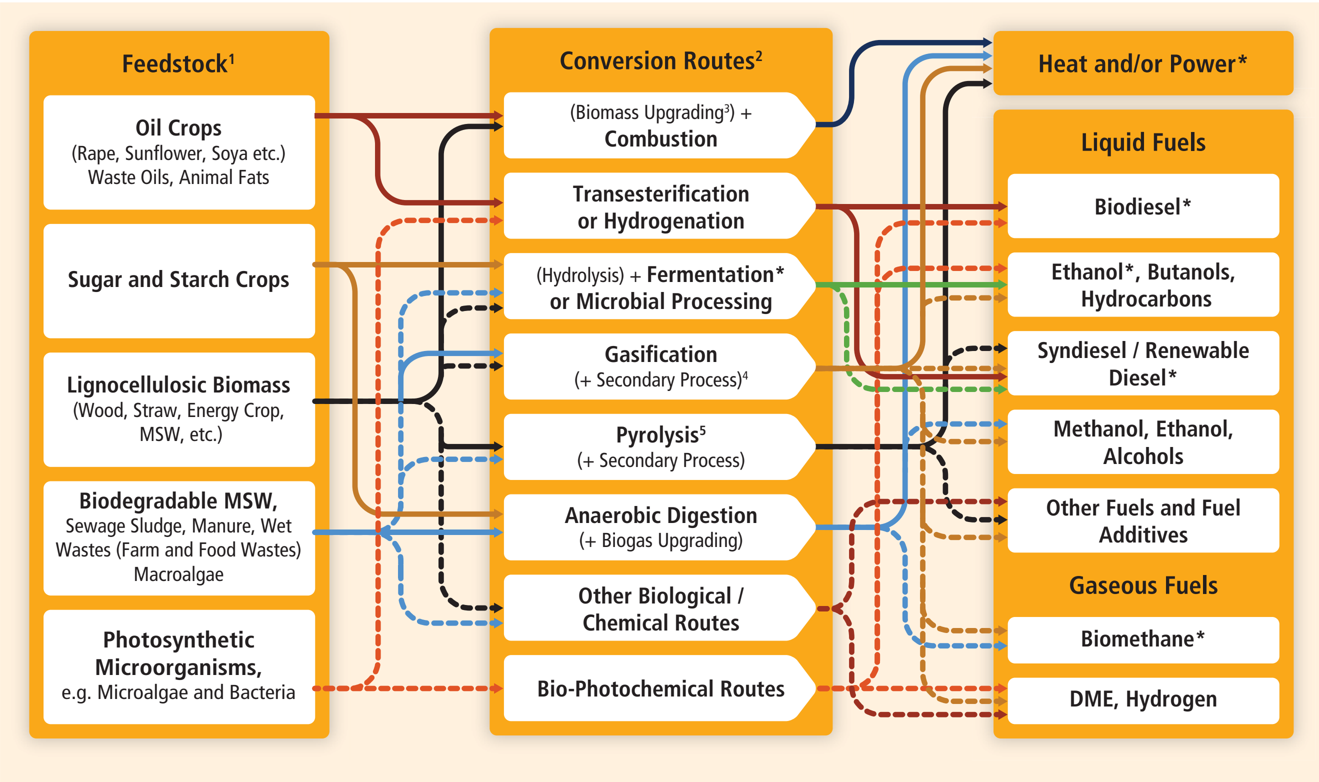


Figure TS.2.3 | Schematic view of the variety of commercial (solid lines) and developing bioenergy routes (dotted lines) from biomass feedstocks through thermochemical, chemical, biochemical and biological conversion routes to heat, power, CHP and liquid or gaseous fuels. Commercial products are marked with an asterisk. [Figure 2.2, 2.1.1]

Notes: 1. Parts of each feedstock could be used in other routes. 2. Each route can also make coproducts. 3. Biomass upgrading includes densification processes (such as pelletization, pyrolysis, torrefaction, etc.). 4. Anaerobic digestion processes to various gases which can be upgraded to biomethane, essentially methane, the major component of natural gas. 5. Could be other thermal processing routes such as hydrothermal, liquefaction, etc. Other chemical routes include aqueous phase reforming. DME=dimethyl ether.

9 Biofuels produced by new processes (e.g. from lignocellulosic biomass) are also called advanced biofuels.

petroleum prices and instability in key producing countries increased and to foster rural development and a secure energy supply. [2.4.5]

Countries differ in their priorities, approaches, technology choices and support schemes for further developing bioenergy. Market and policy complexities emerge when countries seek to balance specific priorities in agriculture and land use, energy policy and security, rural development and environmental protection while considering their unique stage of development, geographic access to resources, and availability and costs of resources. [2.4.5, 2.4.7]

One overall trend is that as policies surrounding bioenergy and biofuels become more holistic, sustainability becomes a stronger criterion at the starting point. This is true for the EU, the USA and China, but also for many developing countries such as Mozambique and Tanzania. This is a positive development, but by no means settled. The registered 70 initiatives worldwide by 2009 to develop and implement sustainability frameworks and certification systems for bioenergy and biofuels, as well as agriculture and forestry, can lead to a fragmentation of efforts. The need for harmonization and international and multilateral collaboration and dialogue are widely stressed. [2.4.6, 2.4.7]

2.5 Environmental and social impacts

Bioenergy production has complex interactions with other social and environmental systems. Concerns—ranging from health and poverty to biodiversity and water scarcity and quality—vary depending upon many factors including local conditions, technology and feedstock choices, sustainability criteria design, and the design and implementation of specific projects. Perhaps most important is the overall management and governance of land use when biomass is produced for energy purposes on top of meeting food and other demands from agricultural, livestock and fibre production. [2.5]

Direct land use change (dLUC) occurs when bioenergy feedstock production modifies an existing land use, resulting in a change in above- and below-ground carbon stocks. Indirect LUC (iLUC) occurs when a change in production level of an agricultural product (i.e., a reduction in food or feed production induced by agricultural land conversion to produce a bioenergy feedstock) leads to a market-mediated shift in land management activities (i.e., dLUC) outside the region of primary production expansion. iLUC is not directly observable and is complex to model and difficult to attribute to a single cause as multiple actors, industry, countries, policies and markets dynamically interact. [2.5.3, 9.3.4.1]

In cases where increases in land use due to biomass production for bioenergy are accompanied by improvements in agricultural management (e.g., intensification of perennial crop and livestock production in degraded lands), undesirable (i)LUC effects can be avoided. If left unmanaged, conflicts can emerge. The overall performance of bioenergy production systems is therefore interlinked with management of land and water resources use. Trade-offs between those dimensions exist and need to be managed through appropriate strategies and decision making (Figure TS.2.4). [2.5.8]

Most bioenergy systems can contribute to climate change mitigation if they replace traditional fossil fuel use and if the bioenergy production emissions are kept low. High nitrous oxide emissions from feedstock production and use of fossil fuels (especially coal) in the biomass conversion process can strongly impact the GHG savings. Options to lower GHG emissions include best practices in fertilizer management, process integration to minimize losses, utilization of surplus heat, and use of biomass or other low-carbon energy sources as process fuel. However, the displacement efficiency (GHG emissions relative to carbon in biomass) can be low when additional biomass feedstock is used for process energy in the conversion process - unless the displaced energy is generated from coal. If the biomass feedstock can produce both liquid fuel and electricity, the displacement efficiency can be high. [2.5.1–2.5.3]

There are different methods to evaluate the GHG emissions of key first- and second-generation biofuel options. Well-managed bioenergy projects can reduce GHG emissions significantly compared to fossil alternatives, especially for lignocellulosic biomass used in power generation and heat, and when that feedstock is commercially available. Advantages can be achieved by making appropriate use of agricultural residues and organic wastes, principally animal residues. Most current biofuel production systems have significant reductions in GHG emissions relative to the fossil fuels displaced, if no iLUC effects are considered. Figure TS.2.5 shows a snapshot of the ranges of lifecycle GHG emissions associated with various energy generation technologies from modern biomass compared to the respective fossil reference systems commonly used in these sectors. Commercial chains such as biomass direct power, anaerobic digestion biogas to power, and very efficient modern heating technologies are shown on the right side and provide significant GHG savings compared to the fossil fuels. More details of the GHG meta-analysis study comparing multiple biomass electricity generating technologies are available in Figure 2.11, which shows that the majority of lifecycle GHG emission estimates cluster between about 16 and 74 g CO_2eq/kWh.

The transport sector is addressed for today's and tomorrow's technologies. For light-duty vehicle applications, sugarcane today and lignocellulosic feedstocks in the medium term can provide significant emissions savings relative to gasoline. In the case of diesel, the range of GHG emissions depends on the feedstock carbon footprint. Biogas-derived biomethane also offers emission reductions (compared to natural gas) in the transport sector. [2.5.2, 9.3.4.1]

When land high in carbon (notably forests and especially drained peat soil forests) is converted to bioenergy production, upfront emissions may cause a time lag of decades to centuries before net emission savings are achieved. In contrast, the establishment of bioenergy plantations on marginal and degraded soils can lead to assimilation of CO_2 into soils

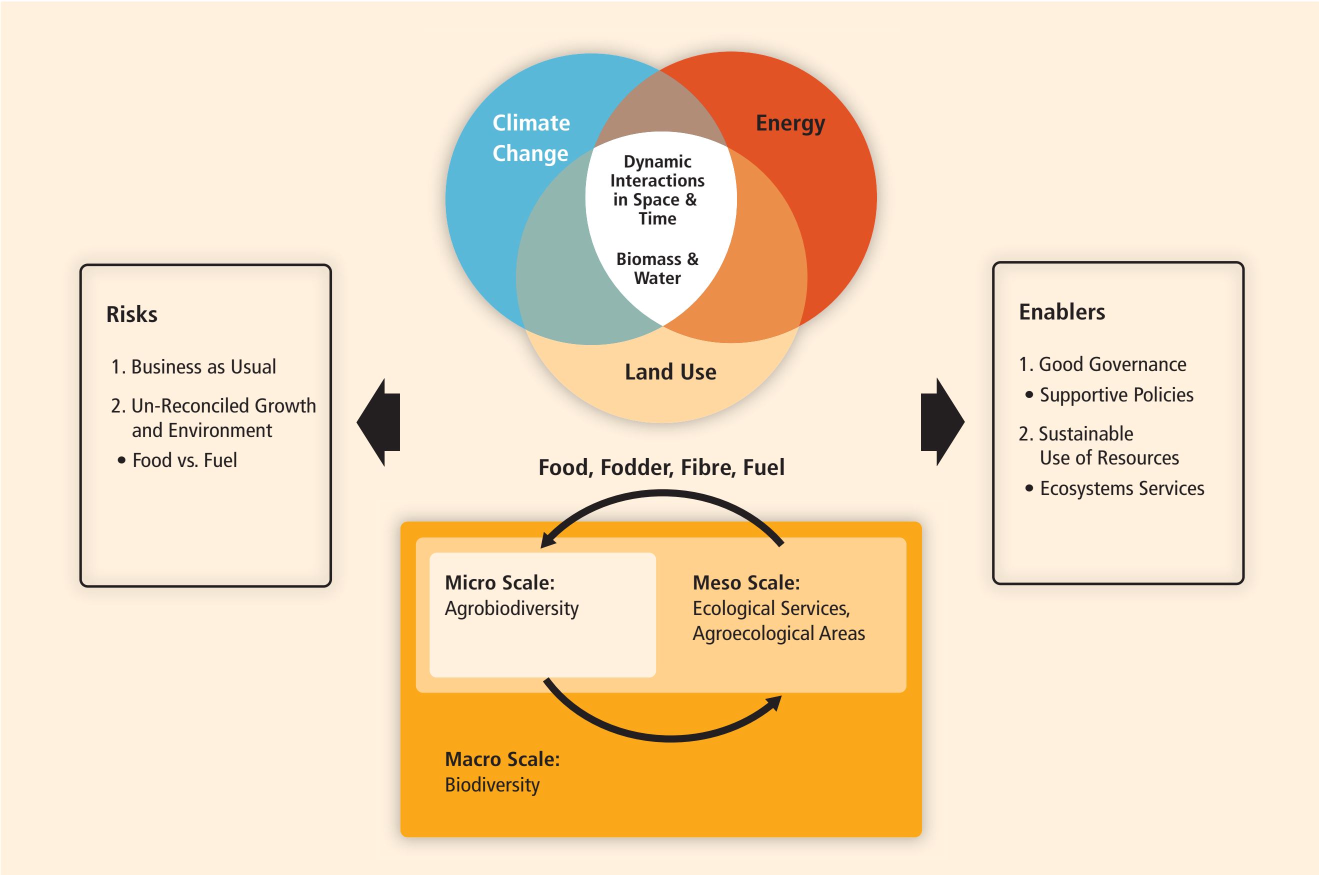


Figure TS.2.4 | The complex dynamic interactions among society, energy and the environment associated with bioenergy. Approaches of uncoordinated production of food and fuel that emerge in poor governance of land use are examples of business as usual practices. [Figure 2.15]

and aboveground biomass and when harvested for energy production it will replace fossil fuel use. Appropriate governance of land use (e.g., proper zoning) and choice of biomass production systems are crucial to achieve good performance. The use of post-consumer organic waste and by-products from the agricultural and forest industries does not cause LUC if these biomass sources were not utilized for alternative purposes. [2.5.3]

Lignocellulosic feedstocks for bioenergy can decrease the pressure on prime cropland. Stimulating increased productivity in all forms of land use reduces the LUC pressure. [2.2.4.2, 2.5.2]

The assessment of available iLUC literature indicates that initial models were lacking in geographic resolution leading to higher proportions of assignments of land use to deforestation. While a 2008 study claimed an iLUC factor of 0.8 (losing 0.8 ha of forest land for each hectare of land used for bioenergy) later (2010) studies that coupled macro-economic to biophysical models reported a reduction to 0.15 to 0.3. Major factors are the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. The results from increased model sophistication and improved data on the actual dynamics of land distribution in the major biofuel producing countries are leading to lower overall LUC impacts, but still with wide uncertainties. All studies acknowledge that land use management at large is a key. Research to improve LUC assessment methods and increase the availability and quality of information on current land use, bioenergy-derived products and other potential LUC drivers can facilitate evaluation and provide tools to mitigate the risk of bioenergy-induced LUC. [2.5.3, 9.3.4.1]

Air pollution effects of bioenergy depend on both the bioenergy technology (including pollution control technologies) and the displaced energy technology. Improved biomass cookstoves for traditional biomass use can provide large and cost-effective mitigation of GHG emissions with substantial co-benefits for the 2.7 billion people that rely on traditional biomass for cooking and heating in terms of health and quality of life. [2.5.4, 2.5.5]

Without proper management, increased biomass production could come with increased competition for water in critical areas, which is highly undesirable. Water is a critical issue that needs to be better analyzed at a regional level to understand the full impact of changes in vegetation and land use management. Recent studies indicate that considerable improvements can be made in water use efficiency in conventional

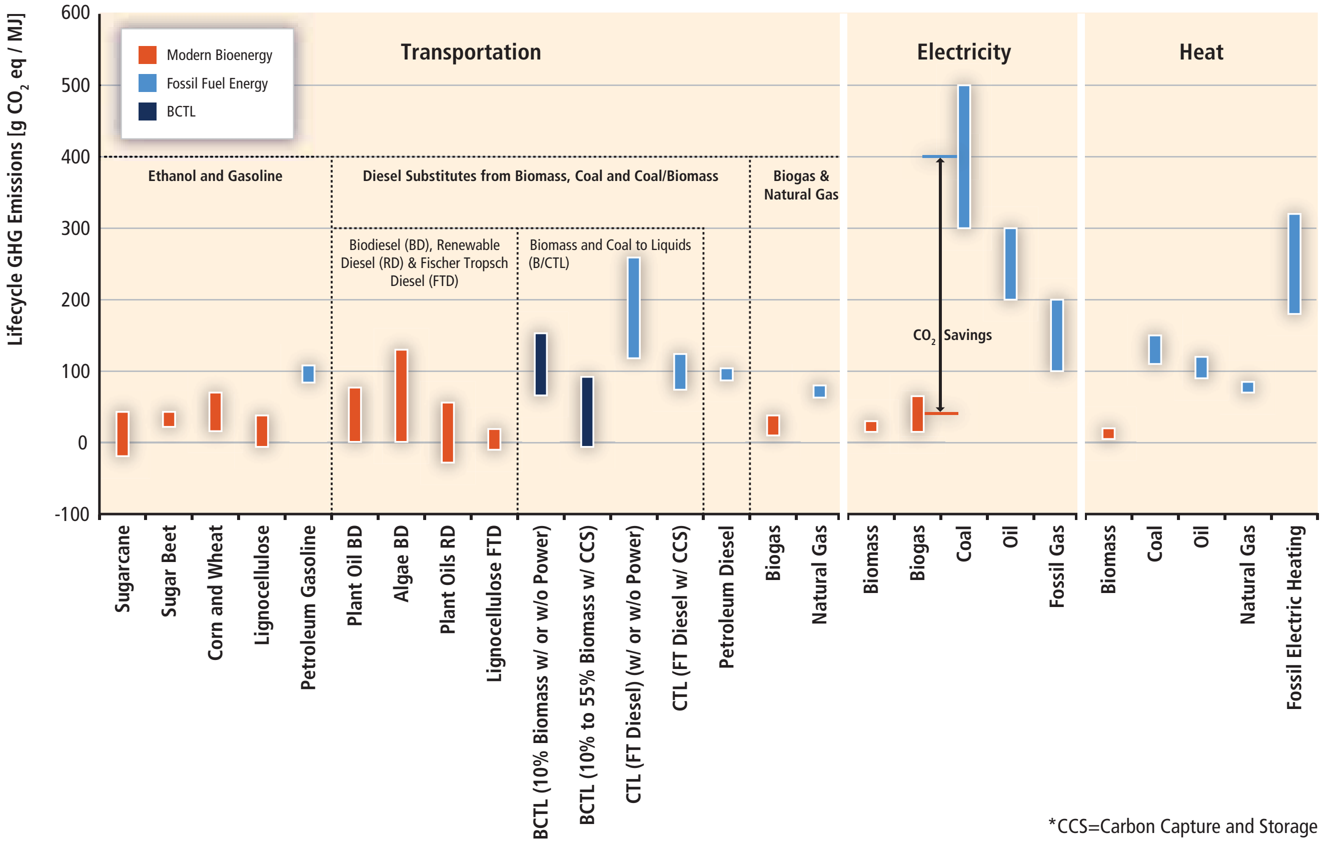


Figure TS.2.5 | Ranges of GHG emissions per unit energy output (MJ) from major modern bioenergy chains compared to current and selected advanced fossil fuel energy systems (land use-related net changes in carbon stocks and land management impacts are excluded). Commercial and developing (e.g., algae biofuels, Fischer-Tropsch) systems for biomass and fossil technologies are illustrated. When CCS technologies are developed, capture and sequestration of biomass carbon emissions can compensate fossil fuel-based energy production emissions. [Figure 2.10]

agriculture, bioenergy crops and, depending on location and climate, perennial cropping systems by improving water retention and lowering direct evaporation from soils. [2.5.5, 2.5.5.1]

Similar remarks can be made with respect to biodiversity, although more scientific uncertainty exists due to ongoing debates on methods of biodiversity impact assessment. Clearly, development of large-scale monocultures at the expense of natural areas is detrimental for biodiversity, as highlighted in the 2007 Convention on Biological Diversity. However, integrating different perennial grasses and woody crops into agricultural landscapes can also increase soil carbon and productivity, reduce shallow landslides and local 'flash floods', provide ecological corridors, reduce wind and water erosion and reduce sediment and nutrients transported into river systems. Forest biomass harvesting can improve conditions for replanting, improve productivity and growth of the remaining stand and reduce wildfire risk. [2.5.5.3]

Social impacts associated with large expansions in bioenergy production are very complex and difficult to quantify. The demand for biofuels represents one driver of demand growth in the agricultural and forestry sectors and therefore contributes to global food price increases. Even considering the benefit of increased prices to poor farmers, higher food prices adversely affect poverty levels, food security, and malnourishment of children. On the other hand, biofuels can also provide opportunities for developing countries to make progress in rural development and agricultural growth, especially when this growth is economically sustainable. In addition, expenditures on imported fossil fuels can be reduced. However, whether such benefits end up with rural farmers depends largely on the way production chains are organized and how land use is governed. [2.5.7.4–2.5.7.6, 9.3.4]

The development of sustainability frameworks and standards can reduce potential negative impacts associated with bioenergy production and lead to higher efficiency than today's systems. Bioenergy can contribute to climate change mitigation, a secure and diverse energy supply, and economic development in developed and developing countries alike, but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, and how projects are designed and implemented, among many other factors. [2.4.5.2, 2.8.3, 2.5.8, 2.2.5, 9.3.4]

2.6 Prospects for technology improvement and integration

Further improvements in biomass feedstock production and conversion technologies are quite possible and necessary if bioenergy is to contribute to global energy supply to the degree reflected in the high end of deployment levels shown in Figure TS.2.2. Increasing land productivity, whether for food or energy purposes, is a crucial prerequisite for realizing large-scale future deployment of biomass for energy since it would make more land available for growing biomass and reduce the associated demand for land. In addition, multi-functional land and water use systems could develop with bioenergy and biorefineries integrated into agricultural and forestry systems, contributing to biodiversity conservation and helping to restore/maintain soil productivity and healthy ecosystems. [2.6.1]

Lignocellulosic feedstocks offer significant promise because they 1) do not compete directly with food production, 2) can be bred specifically for energy purposes, enabling higher production per unit land area and a large market for energy products, 3) can be harvested as residues from crop production and other systems that increase land use efficiency, and 4) allow the integration of waste management operations with a variety of other industries offering prospects for industrial symbiosis at the local level. Literature on and investment trends in conversion technologies indicate that the industry is poised to increase product diversification, as did the petroleum industry, with increased interest in the high energy density fuels for air transport, an application for which other non-carbon fuels have not been identified. [2.6.4]

A new generation of aquatic feedstocks that produce algal lipids for diesel, jet fuels, or higher value products from CO_2 and water with sunlight can provide strategies for lower land use impacts, as algae can grow in brackish waters, lands inappropriate for cultivation, and industrial waste water. Algal organisms can operate in the dark and metabolize sugars for fuels and chemicals. Many microbes could become microscopic factories to produce specific products, fuels and materials that decrease society's dependence on fossil energy sources. [2.6.1.2, 2.7.3]

Although significant technical progress has been made, the more complex processing required by solid lignocellulosic biomass and the integration of a number of new steps takes time and support to bring development through the 'Valley of Death' in demonstration plants, first-of-a-kind plants and early commercialization. Projected costs of biofuels from a wide range of sources and process variables are very sensitive to feedstock cost and range from USD_{2005} 10 to 30/GJ. The US National Academies project a 40% reduction in operating costs for biochemical routes by 2035 to USD_{2005} 12 to 15/GJ. [2.6.3, 2.6.4]

Biomass gasification currently provides about 1.4 GW_{th} in industrial applications, thermal applications and co-firing. Small-scale systems ranging from cooking stoves and anaerobic digestion systems to small gasifiers have been improving in efficiency over time. Many stakeholders have had a special interest in integrated gasification combined-cycle (IGCC) power plants that use bioenergy as a feedstock. These plants are projected to be more efficient than traditional steam turbine systems but have not yet reached full commercialization. However, they also have the potential to be integrated into CCS systems more effectively. In addition to providing power, syngas from gasification plants can be used to produce a wide range of fuels (methanol, ethanol, butanols and syndiesel) or can be used in a combined power and fuels approach. Technical and engineering challenges have so far prevented more rapid deployment of this technology option. Biomass to liquids conversion uses commercial technology developed for fossil fuels. Figure TS.2.5 illustrates projected emissions from coal to liquid fuels and the offsetting emissions that biomass could offer all the way to removal of GHG from the atmosphere when coupled with CCS technologies. Gaseous products (hydrogen, methane, synthetic natural gas) have lower estimated production costs and are in an early commercialization phase. [2.6.3, 2.6.4]

Pyrolysis and hydrothermal oils are low-cost transportable oils, used in heat or CHP applications and could become a feedstock for upgrading either in stand-alone facilities or coupled to a petrochemical refinery. [2.3.4, 2.6.3, 2.6.4, 2.7.1]

The production of biogas from a variety of waste streams and its upgrading to biomethane is already penetrating small markets for multiple applications, including transport in small networks in Sweden and for heat and power in Nordic and European countries. A key factor is the combination of waste streams, including agriculture residues. Improved upgrading and reducing costs is also needed. [2.6.3, 2.6.4]

Many bioenergy/biofuels routes enable CCS with significant opportunities for emissions reductions and sequestration. As CCS technologies are further developed and verified, coupling fermentation with concentrated CO_2 streams or IGCC offers opportunities to achieve carbon-neutral fuels, and in some cases negative net emissions. Achieving this goal will be facilitated by well-designed systems that span biomass selection, feedstock supply system, conversion to a secondary energy carrier and integration of this carrier into the existing and future energy systems. [2.6.3, 2.6.4, 9.3.4]

2.7 Current costs and trends

Biomass production, supply logistics, and conversion processes contribute to the cost of final products. [2.3, 2.6, 2.7]

The economics and yields of feedstocks vary widely across world regions and feedstock types with costs ranging from USD_{2005} 0.9 to 16/GJ (data from 2005 to 2007). Feedstock production for bioenergy competes with the forestry and food sectors, but integrated production systems such as agro-forestry or mixed cropping may provide synergies along with additional environmental services. Handling and transport of biomass from production sites to conversion plants may contribute 20 to up to 50% of the total costs of bioenergy production. Factors such as scale increase and technological innovations increase competition and contribute to a decrease in economic and energy costs of supply chains by more than 50%. Densification via pelletization or briquetting is required for transportation distances over 50 km. [2.3.2, 2.6.2]

Several important bioenergy systems today, most notably sugarcane-based ethanol and heat and power generation from residues and waste biomass, can be deployed competitively. [Tables 2.6, 2.7]

Based on a standardized methodology outlined in Annex II, and the cost and performance data summarized in Annex III, the estimated production costs for commercial bioenergy systems at various scales and with some consideration of geographical regions are summarized in Figure TS.2.6. Values include production, supply logistics and conversion costs. [1.3.2, 2.7.2, 10.5.1, Annex II, Annex III]

Costs vary by world regions, feedstock types, feedstock supply costs, the scale of bioenergy production, and production time during the year, which is often seasonal. Examples of estimated commercial bioenergy levelized[10] cost ranges are roughly USD_{2005} 2 to 48/GJ for liquid and gaseous biofuels; roughly 3.5 to 25 US $cents_{2005}$/kWh (USD_{2005} 10 to 50/GJ) for electricity or CHP systems larger than about 2 MW (with feed stock costs of USD_{2005} 3/GJ feed and a heat value of USD_{2005} 5/GJ for steam or USD_{2005} 12/GJ for hot water); and roughly USD_{2005} 2 to 77/GJ for domestic or district heating systems with feedstock costs in the range of USD_{2005} 0 to 20/GJ (solid waste to wood pellets). These calculations refer to 2005 to 2008 data and are in expressed USD_{2005} at a 7% discount rate. The cost ranges for biofuels in Figure TS.2.6 cover the Americas, India, China and European countries. For heating systems, the costs are primarily European and the electricity and CHP costs come from primarily large user countries. [2.3.1–2.3.3, 2.7.2, Annex III]

In the medium term, the performance of existing bioenergy technologies can still be improved considerably, while new technologies offer the prospect of more efficient and competitive deployment of biomass for energy (and materials). Bioenergy systems, namely for ethanol and biopower production, show technological learning and related cost reductions with learning rates comparable to those of other RE technologies. This applies to cropping systems (following progress in agricultural management for sugarcane and maize), supply systems and logistics (as observed in Nordic countries and international logistics) and in conversion (ethanol production, power generation and biogas) as shown in Table TS.2.2.

Although not all bioenergy options discussed in Chapter 2 have been investigated in detail with respect to technological learning, several important bioenergy systems have reduced their cost and improved environmental performance. However, they usually still require government subsidies provided for economic development (e.g., poverty reduction and a secure energy supply) and other country-specific reasons. For traditional biomass, charcoal made from biomass is a major fuel in developing countries, and should benefit from the adoption of higher-efficiency kilns. [2.3, 2.6.1, 2.6.2, 2.6.3, 2.7.2, 10.4, 10.5]

The competitive production of bio-electricity (through methane or biofuels) depends on the integration with the end-use systems, performance of alternatives such as wind and solar energy, developing CCS technologies coupled with coal conversion, and nuclear energy. The implications of successful deployment of CCS in combination with biomass conversion could result in removal of GHGs from the atmosphere and attractive mitigation cost levels but have so far received limited attention. [2.6.3.3, 8.2.1, 8.2.3, 8.2.4, 8.3, 9.3.4]

Table TS.2.3 illustrates that costs for some key bioenergy technology are expected to decline over the near- to mid-term. With respect to lignocellulosic biofuels, recent analyses have indicated that the improvement potential is large enough for competition with oil at prices of USD_{2005} 60 to 80/barrel (USD_{2005} 0.38 to 0.44/litre). Currently available scenario analyses indicate that if shorter-term R&D and market support is strong, technological progress could allow for their commercialization around 2020 (depending on oil and carbon prices). Some scenarios also indicate that this would mean a major shift in the deployment of biomass for energy, since competitive production would decouple deployment from policy targets (mandates) and demand for biomass would move away from food crops to biomass residues, forest biomass and perennial cropping systems. The implications of such a (rapid) shift are so far poorly studied. [2.8.4, 2.4.3, 2.4.5]

Lignocellulosic ethanol development and demonstration continues in several countries. A key development step is the pretreatment to overcome the recalcitrance of the cell wall of woody, herbaceous or agricultural residues to make carbohydrate polymers accessible to hydrolysis (e.g., by enzymes) and fermentation of sugars to ethanol (or butanol) and lignin for process heat or electricity. Alternatively, multiple steps can be combined and bio-processed with multiple organisms simultaneously. A review of progress in the enzymatic area suggests that a 40% reduction in cost could be expected by 2030 from process improvements, which would bring down the estimated cost of production from USD_{2005} 18 to 22/GJ (pilot data) to USD 12 to 15/GJ, a competitive range. [2.6.3]

Biomass pyrolysis routes and hydrothermal concepts are also developing in conjunction with the oil industry and have demonstrated technically that upgrading of oils to blendstocks of gasoline or diesel and even jet fuel quality products is possible. [2.6.3]

Photosynthetic organisms such as algae biologically produce (using CO_2, water and sunlight) a variety of carbohydrates and lipids that can be used directly or for biofuels. These developments have significant long-term potential because algae photosynthetic efficiency is much higher

10 As in the electricity production in CHP systems in which calculations assumed a value for the co-produced heat, for biofuels systems, there are cases in which two co-products are obtained; for instance, sugarcane to sugar, ethanol, and electricity. Sugar co-product revenue could be about $US\$_{2005}$ 2.6/GJ and displace the ethanol cost by that amount.

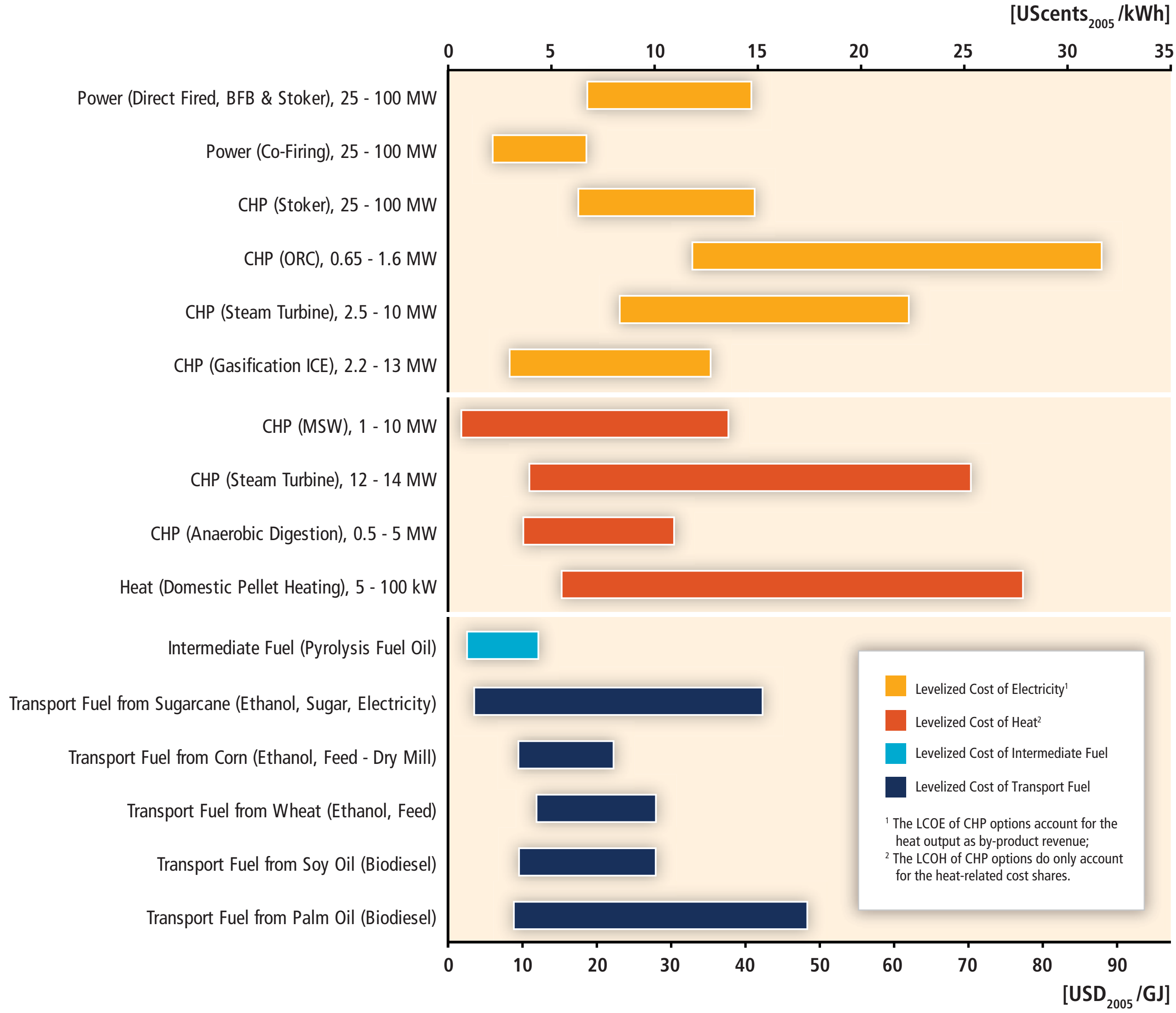


Figure TS.2.6 | Typical recent levelized cost of energy services from commercially available bioenergy systems at a 7% discount rate, calculated over a year of feedstock costs, which differ between technologies. These costs do not include interest, taxes, depreciation and amortization. [Figure 2.18] Levelized costs of electricity (LCOE), heat (LCOH), fuels (LCOF), intermediate fuel (LCOIF), BFB: Bubbling Fluidized Bed, ORC: Organic Rankine Cycle and ICE: Internal Combustion Engine. For biofuels, the range of LCOF represents production in a wide range of countries whereas LCOE and LCOH are given only for major user markets of the technologies for which data were available. Calculations are based on High Heating Value.

than that of oil crops. Potential bioenergy supplies from plants are very uncertain, but because their development can utilize brackish waters and heavily saline soils, their use is a strategy for low LUC impacts. [2.6.2, 3.3.5, 3.7.6]

Data availability is limited with respect to production of biomaterials, while cost estimates for chemicals from biomass are rare in peer-reviewed literature and future projections and learning rates even more so. This condition is linked, in part, to the fact that successful bio-based products are entering the market place either as partial components of otherwise fossil-derived products or as fully new synthetic polymers such as polylactides based on lactic acid derived from sugar fermentation. In addition to producing biomaterials to replace fossil fuels, analyses indicate that cascaded use of biomaterials and subsequent use of waste material for energy can offer more effective and larger mitigation impacts per hectare or tonne of biomass used. [2.6.3.5]

2.8 Potential deployment levels

Between 1990 and 2008, bioenergy use increased at an average annual growth rate of 1.5% for solid biomass, while the more modern biomass use for secondary carriers such as liquid and gaseous forms increased at 12.1 and 15.4% respectively. As a result, the share of biofuels in global road transport was 2% in 2008. The production of ethanol and biodiesel increased by 10 and 9%, respectively, in 2009, to 90 billion litres, such that biofuels contributed nearly 3% of global road transport in 2009, as oil demand decreased for the first time since 1980. Government

Table TS.2.2 | Experience curves for major components of bioenergy systems and final energy carriers expressed as reduction (%) in cost (or price) per doubling of cumulative production, the Learning Rate (LR); N: number of doublings of cumulative production; R2 is the correlation coefficient of the statistical data; O&M: Operations and Maintenance. [Table 2.17]

Learning system	LR (%)	Time frame	Region	N	R^2
Feedstock production					
Sugarcane (tonnes sugarcane)	32±1	1975–2005	Brazil	2.9	0.81
Corn (tonnes corn)	45±1.6	1975–2005	USA	1.6	0.87
Logistic chains					
Forest wood chips (Sweden)	15–12	1975–2003	Sweden/Finland	9	0.87–0.93
Investment and O&M costs					
CHP plants	19-25	1983–2002	Sweden	2.3	0.17–0.18
Biogas plants	12	1984–1998		6	0.69
Ethanol production from sugarcane	19±0.5	1975–2003	Brazil	4.6	0.80
Ethanol production from corn (only O&M costs)	13±0.15	1983–2005	USA	6.4	0.88
Final energy carriers					
Ethanol from sugarcane	7	1970–1985	Brazil		
	29	1985–2002		~6.1	N/A
Ethanol from sugarcane	20±0.5	1975–2003	Brazil	4.6	0.84
Ethanol from corn	18±0.2	1983–2005	USA	6.4	0.96
Electricity from biomass CHP	9-8	1990–2002	Sweden	~9	0.85–0.88
Electricity from biomass	15	Unknown	OECD	N/A	N/A
Biogas	0–15	1984–2001	Denmark	~10	0.97

Table TS.2.3 | Projected production cost ranges for developing technologies. [Table 2.18]

Selected Bioenergy Technologies	Energy Sector (Electricity, Thermal, Transport)[6]	2020-2030 Projected Production Costs (USD_{2005}/GJ)
Integrated gasification combined cycle [1]	Electricity and/or transport	12.8–19.1 (4.6–6.9 cents/kWh)
Oil plant-based renewable diesel and jet fuel	Transport and electricity	15–30
Lignocellulose sugar-based biofuels[2]	Transport	6–30
Lignocellulose syngas-based biofuels[3]	Transport	12–25
Lignocellulose pyrolysis-based biofuels[4]	Transport	14–24 (fuel blend components)
Gaseous biofuels[5]	Thermal and transport	6–12
Aquatic plant-derived fuels, chemicals	Transport	30–140

Notes: 1. Feed cost USD_{2005} 3.1/GJ, IGCC (future) 30 to 300 MW, 20-yr life, 10% discount rate. 2. Ethanol, butanols, microbial hydrocarbons and microbial hydrocarbons from sugar or starch crops or lignocellulose sugars. 3. Syndiesel, methanol and gasoline, etc.; syngas fermentation routes to ethanol. 4. Biomass pyrolysis and catalytic upgrading to gasoline and diesel blend components or to jet fuels. 5. Synfuel to synthetic natural gas, methane, dimethyl ether, hydrogen from biomass thermochemical and anaerobic digestion (larger scale). 6. Several applications can be coupled with CCS when these technologies, including CCS, are mature and thus could remove GHG from the atmosphere.

policies in various countries led to a five-fold increase in global biofuels production from 2000 to 2008. Biomass and renewable waste power generation was 259 TWh (0.93 EJ) in 2007 and 267 TWh (0.96 EJ) in 2008 representing 1% of the world's electricity and a doubling since 1990 (from 131 TWh (0.47 EJ)). [2.4]

The expected continued deployment of biomass for energy in the 2020 to 2050 time frame varies considerably between studies. A key message from the review of available insights is that large-scale biomass deployment strongly depends on sustainable development of the resource base, governance of land use, development of infrastructure and cost reduction of key technologies, for example, efficient and complete use of primary biomass for energy from the most promising first-generation feedstocks and new-generation lignocellulosic biomass. [2.4.3, 2.8]

The scenario results summarized in Figure TS.2.7 derive from a diversity of modelling teams and a wide range of assumptions including energy demand growth, cost and availability of competing low-carbon technologies, and cost and availability of RE technologies. Traditional biomass use is projected to decline in most scenarios while the use of liquid biofuels, biogas and electricity and hydrogen produced from biomass tends to increase. Results for biomass deployment for energy under these scenarios for 2020, 2030 and 2050 are presented for three GHG stabilization ranges based on the AR4: Categories III and IV (440-600 ppm CO_2), Categories I and II (<440 ppm CO_2) and Baselines (>600 ppm CO_2) all by 2100. [10.1–10.3]

Global biomass deployment for energy is projected to increase with more ambitious GHG concentration stabilization levels indicating its long-term role in reducing global GHG emissions. Median levels are 75

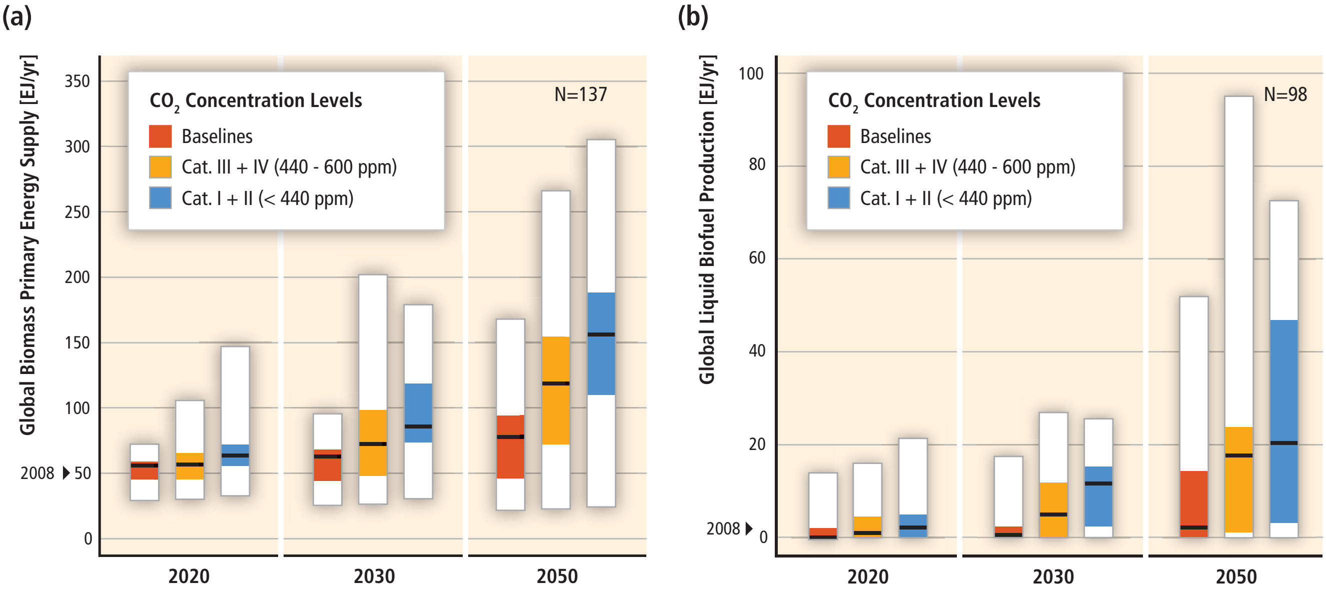


Figure TS.2.7 | (a) The global primary energy supply from biomass in long-term scenarios for electricity, heat and biofuels, all accounted for as primary energy; and (b) global biofuels production in long-term scenarios reported in secondary energy terms. For comparison, the historical levels in 2008 are indicated in the small black arrows on the left axis. [Figure 2.23]

to 85 EJ and 120 to 155 EJ for the two mitigation scenarios in 2030 and 2050, respectively, almost two and three times the 2008 deployment level of 50 EJ. These deployment levels are similar to the expert review mid-range levels for 2050. Global biofuels production shown in Figure TS.2.7(b) for 2020 and 2030 are at fairly low levels, but most models lack a detailed description of different conversion pathways and related learning potential. [2.7.3] For the <440 ppm mitigation scenario, biofuels production reaches six (2030) and ten (2050) times the 2008 actual value of 2 EJ. [2.2.5, 2.8.2, 2.5.8, 2.8.3]

The sector-level penetration of bioenergy is best explained using a single model with detailed transport sector representation such as the 2010 IEA World Energy Outlook (WEO) that also models both traditional and modern biomass applications and takes into account anticipated industrial and government investments and goals. This model projects very significant increases in modern bioenergy and a decrease in traditional biomass use. These projections are in qualitative agreement with the results from Chapter 10. In 2030, for the WEO 450-ppm mitigation scenario, the IEA projects that 11% of global transport fuels will be provided by biofuels with second-generation biofuels contributing 60% of the projected 12 EJ and half of this amount is projected to be supplied owing to continuation of current policies. Biomass and renewable wastes would supply 5% of the world's electricity generation or 1,380 TWh/yr (5 EJ/yr) of which 555 TWh/yr (2 EJ/yr) are a result of the stringent climate mitigation strategy. Biomass industrial heating applications for process steam and space and hot water heating for buildings (3.3 EJ in 2008) would each double in absolute terms from 2008 levels. However, the total heating demand is projected to decrease because of assumed traditional biomass decline. Heating is seen as a key area for continued modern bioenergy growth. Biofuels are projected to mitigate 17% of road and 3% of air transport emissions by 2030. [2.8.3]

2.8.1 Conclusions regarding deployment: Key messages about bioenergy

The long-term scenarios reviewed in Chapter 10 show increases in bioenergy supply with increasingly ambitious GHG concentration stabilization levels, indicating that bioenergy could play a significant long-term role in reducing global GHG emissions. [2.8.3]

Bioenergy is currently the largest RE source and is likely to remain one of the largest RE sources for the first half of this century. There is considerable growth potential, but it requires active development. [2.8.3]

- Assessments in the recent literature show that the technical potential of biomass for energy may be as large as 500 EJ/yr by 2050. However, large uncertainty exists about important factors such as market and policy conditions that affect this potential. [2.8.3]

- The expert assessment in Chapter 2 suggests potential deployment levels by 2050 in the range of 100 to 300 EJ/yr. Realizing this potential represents a major challenge but would make a substantial contribution to the world's primary energy demand in 2050—roughly equal to the equivalent heat content of today's worldwide biomass extraction in agriculture and forestry. [2.8.3]

- Bioenergy has significant potential to mitigate GHGs if resources are sustainably developed and efficient technologies are applied.

Certain current systems and key future options, including perennial crops, forest products and biomass residues and wastes, and advanced conversion technologies, can deliver significant GHG mitigation performance—an 80 to 90% reduction compared to the fossil energy baseline. However, land conversion and forest management that lead to a large loss of carbon stocks and iLUC effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts. [2.8.3]

- In order to achieve the high potential deployment levels of biomas for energy, increases in competing food and fibre demand must be moderate, land must be properly managed and agricultural and forestry yields must increase substantially. Expansion of bioenergy in the absence of monitoring and good governance of land use carries the risk of significant conflicts with respect to food supplies, water resources and biodiversity, as well as a risk of low GHG benefits. Conversely, implementation that follows effective sustainability frameworks could mitigate such conflicts and allow realization of positive outcomes, for example, in rural development, land amelioration and climate change mitigation, including opportunities to combine adaptation measures. [2.8.3]

- The impacts and performance of biomass production and use are region- and site-specific. Therefore, as part of good governance of land use and rural development, bioenergy policies need to consider regional conditions and priorities along with the agricultural (crops and livestock) and forestry sectors. Biomass resource potentials are influenced by and interact with climate change impacts but the specific impacts are still poorly understood; there will be strong regional differences in this respect. Bioenergy and new (perennial) cropping systems also offer opportunities to combine adaptation measures (e.g., soil protection, water retention and modernization of agriculture) with production of biomass resources. [2.8.3]

- Several important bioenergy options (i.e., sugarcane ethanol production in Brazil, select waste-to-energy systems, efficient biomass cookstoves, biomass-based CHP) are competitive today and can provide important synergies with longer-term options. Lignocellulosic biofuels to replace gasoline, diesel and jet fuels, advanced bioelectricity options, and biorefinery concepts can offer competitive deployment of bioenergy for the 2020 to 2030 timeframe. Combining biomass conversion with CCS raises the possibility of achieving GHG removal from the atmosphere in the long term—a necessity for substantial GHG emission reductions. Advanced biomaterials are promising as well for economics of bioenergy production and mitigation, though the potential is less well understood as is the potential role of aquatic biomass (algae), which is highly uncertain. [2.8.3]

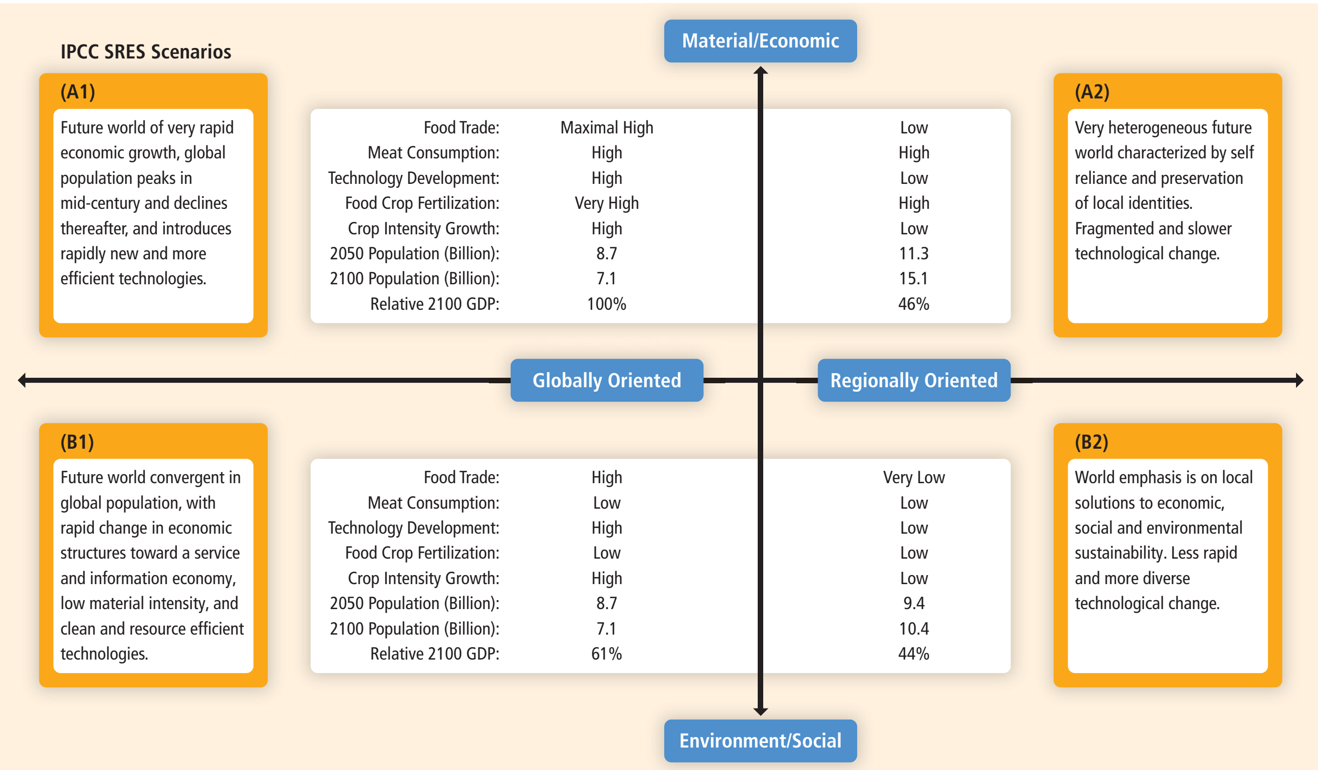


Figure TS.2.8 | Storylines for the key SRES scenario variables used to model biomass and bioenergy, the basis for the 2050 sketches adapted to this report and used to derive the stacked bar showing the biomass technical potential in Figure TS.2.2. [Figure 2.26]

- Rapidly changing policy contexts, recent market-based activities, the increasing support for advanced biorefineries and lignocellulosic biofuel options, and in particular the development of sustainability criteria and frameworks, all have the potential to drive bioenergy systems and their deployment in sustainable directions. Achieving this goal will require sustained investments that reduce costs of key technologies, improved biomass production and supply infrastructure, and implementation strategies that can gain public and political acceptance. [2.8.3]

In conclusion and for illustrating the interrelations between scenario variables (see Figure TS.2.8), key preconditions under which bioenergy production capacity is developed and what the resulting impacts may be, Figure TS.2.8 presents four different sketches for biomass deployment for energy at a global scale by 2050. The 100 to 300 EJ range that follows from the resource potential review delineates the lower and upper limit for deployment. The assumed storylines roughly follow the IPCC Special Report on Emissions Scenarios (SRES) definitions, applied to bioenergy and summarized in Figure TS.2.9 and which were also used

Figure TS.2.9 | Possible futures for 2050 biomass deployment for energy: Four illustrative contrasting sketches describing key preconditions and impacts following world conditions typical of the IPCC SRES storylines summarized in Figure TS.2.8. [Figure 2.27] to derive the technical potential shown on the stacked bar of Figure TS.2.2. [2.8.3]

Biomass and its multiple energy products can be developed alongside food, fodder, fibre and forest products in both sustainable and unsustainable ways. As viewed through IPCC scenario storylines and sketches, high and low penetration levels can be reached with and without taking into account sustainable development and climate change mitigation pathways. Insights into bioenergy technology developments and integrated systems can be gleaned from these storylines. [2.8.3]

3. Direct Solar

3.1 Introduction

Direct solar energy technologies are diverse in nature. Responding to the various ways that humans use energy—such as heating, electricity, and fuels—they constitute a family of technologies. This summary focuses on four major types: 1) solar thermal, which includes both active and passive heating of buildings, domestic and commercial solar water heating, swimming pool heating and process heat for industry; 2) photovoltaic (PV) electricity generation via direct conversion of sunlight to electricity by photovoltaic cells; 3) concentrating solar power (CSP) electricity generation by optical concentration of solar energy to obtain high-temperature fluids or materials to drive heat engines and electrical generators; and 4) solar fuels production methods, which use solar energy to produce useful fuels. [3.1]

The term 'direct' solar energy refers to the energy base for those RE technologies that draw on the Sun's energy directly. Certain renewable technologies, such as wind and ocean thermal, use solar energy after it has been absorbed on the Earth and converted to other forms. (In the remainder of this section, the adjective 'direct' applied to solar energy will often be deleted as being understood.) [3.1]

3.2 Resource potential

Solar energy constitutes the thermal radiation emitted by the Sun's outer layer. Just outside Earth's atmosphere, this radiation, called solar irradiance, has a magnitude that averages 1,367 W/m^2 for a surface perpendicular to the Sun's rays. At ground level (generally specified as sea level with the sun directly overhead), this irradiance is attenuated by the atmosphere to about 1,000 W/m^2 in clear sky conditions within a few hours of noon—a condition called 'full sun'. Outside the atmosphere, the Sun's energy is carried in electromagnetic waves with wavelengths ranging from about 0.25 to 3 µm. Part of the solar irradiance is contributed by rays arriving directly from the sun without being scattered in the atmosphere. This 'beam' irradiance, which is capable of being concentrated by mirrors and lenses, is most available in low cloud-cover areas. The remaining irradiance is called the diffuse irradiance. The sum of the beam and diffuse irradiance is called global solar irradiation. [3.2]

The theoretical solar energy potential, which indicates the amount of irradiance at the Earth's surface (land and ocean) that is theoretically available for energy purposes, has been estimated at 3.9×10^6 EJ/yr. This number, clearly intended for illustrative purposes only, would require the full use of all available land and sea area at 100% conversion efficiency. A more useful metric is the technical potential; this requires assessing the fraction of land that is of practical use for conversion devices using a more realistic conversion efficiency. Estimates for solar energy's technical potential range from 1,575 to 49,837 EJ/yr, that is, roughly 3 to 100 times the world's primary energy consumption in 2008. [3.2, 3.2.2]

3.3 Technology and applications

Figure TS.3.1 illustrates the types of passive and active solar technologies currently in use to capture the Sun's energy to provide both residential energy services and direct electricity. In this summary, only technologies for active heating and electricity are treated in depth. [3.3.1–3.3.4]

Solar thermal: The key component in active solar thermal systems is the solar collector. A flat-plate solar collector consists of a blackened plate with attached conduits, through which passes a fluid to be heated. Flat-plate collectors may be classified as follows: unglazed, which are suitable for delivering heat at temperatures a few degrees above ambient temperature; glazed, which have a sheet of glass or other transparent material placed parallel to the plate and spaced a few centimetres above it, making it suitable for delivering heat at temperatures of about 30°C to 60°C; or evacuated, which are similar to glazed, but the space between the plate and the glass cover is evacuated, making this type of collector suitable for delivering heat at temperatures of about 50°C to 120°C. To withstand the vacuum, the plates of an evacuated collector are usually put inside glass tubes, which constitute both the collector's glazing and its container. In the evacuated type, a special black coating called a 'selective surface' is put on the plate to help prevent re-emission of the absorbed heat; such coatings are often used on the non-evacuated glazed type as well. Typical efficiencies of solar collectors used in their proper temperature range extend from about 40 to 70% at full sun. [3.3.2.1]

Flat-plate collectors are commonly used to heat water for domestic and commercial use, but they can also be used in active solar heating to provide comfort heat for buildings. Solar cooling can be obtained by using solar collectors to provide heat to drive an absorption refrigeration cycle. Other applications for solar-derived heat are industrial process heat, agricultural applications such as drying of crops, and for cooking. Water tanks are the most commonly used items to store heat during

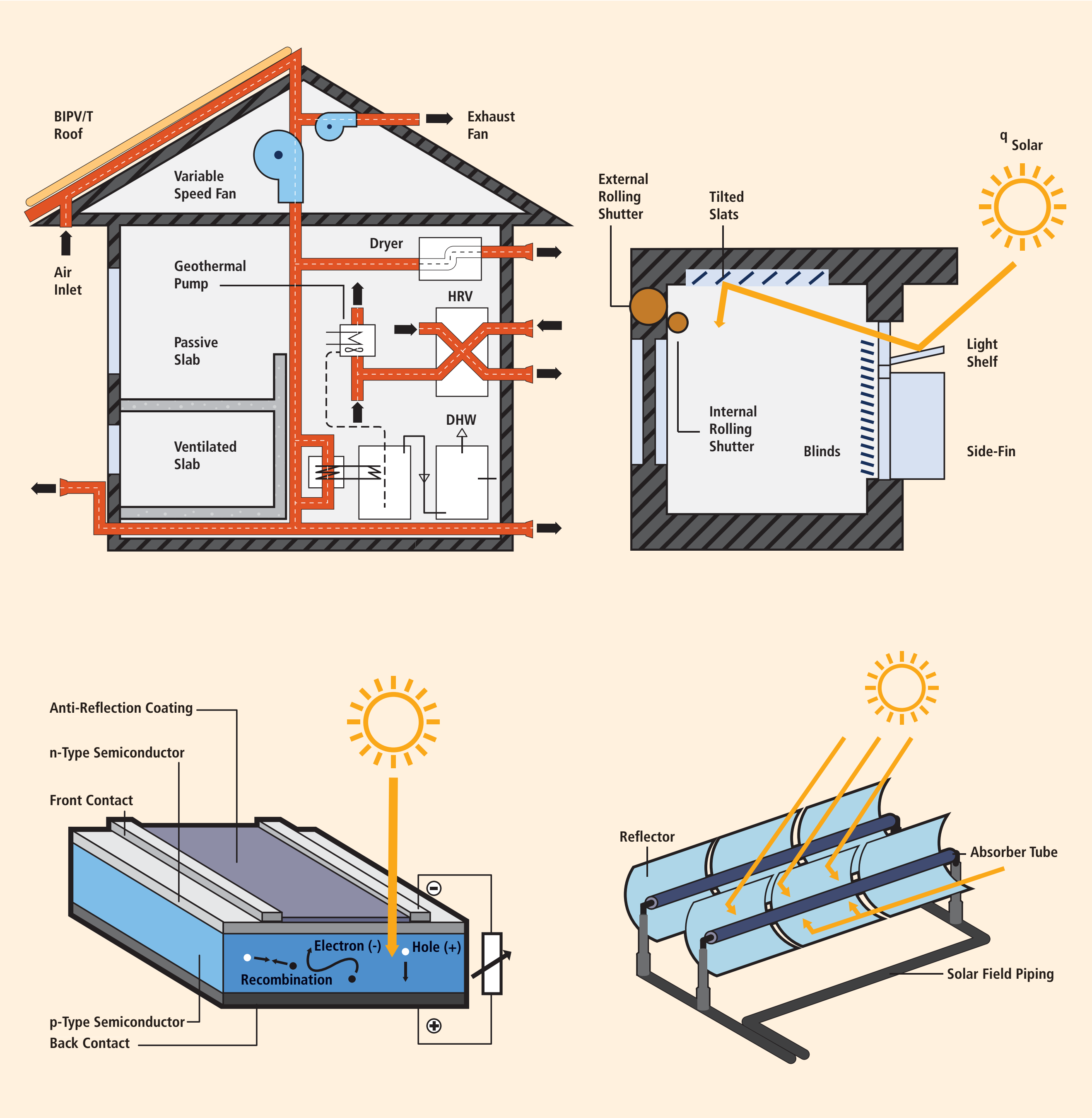


Figure TS.3.1 | Selected examples of (top) solar thermal, both passive and active integrated into a building; (bottom left) a photovoltaic device schematic for direct solar to electricity conversion; and (bottom right) one common type of concentrating solar power technology, a trough collector. [Derived from Figures 3.2, 3.5, 3.7]

the day/night period or short periods of cloudy weather. Supplemented by other energy sources, these systems typically provide 40 to 80% of the demand for heat energy of the target application. [3.3.2.2–3.3.2.4]

For passive solar heating, the building itself—particularly its windows—acts as the solar collector, and natural methods are used to distribute and store the heat. The basic elements of passive heating architecture are high-efficiency equatorial-facing windows and large internal thermal mass. The building must also be well insulated and incorporate methods such as shading devices to prevent it from overheating. Another feature of passive solar is 'daylighting', which incorporates special strategies to maximize the use of natural (solar) lighting in the building. Studies have shown that with current technology, using these strategies in new buildings in northern Europe or North America can reduce the building heating demands by as much as 40%. For existing, rather than new, buildings retrofitted with passive heating concepts, reductions of as much as 20% are achievable. [3.3.1]

Photovoltaic electricity generation: A detailed description of how PV conversion works is available in many textbooks. In the simplest terms, a thin sheet of semiconductor material such as silicon is placed in the Sun. The sheet, known as a cell, consists of two distinct layers formed by introducing impurities into the silicon resulting in an n-type layer and a p-type layer that form a junction at the interface. Solar photons striking the cell generate electron-hole pairs that are separated spatially by an internal electric field at the junction. This creates negative charges on one side of the interface and positive charges are on the other side. This resulting charge separation creates a voltage. When the two sides of the illuminated cell are connected to a load, current flows from one side of the device via the load to the other side of the cell generating electricity. [3.3.3]

Various PV technologies have been developed in parallel. Commercially available PV technologies include wafer-based crystalline silicon PV, as well as the thin-film technologies of copper indium/gallium disulfide/(di) selenide (CIGS), cadmium telluride (CdTe), thin-film silicon (amorphous and microcrystalline silicon), and dye-sensitized solar cells. In addition, there are commercially available concentrating PV concepts, in which very high efficiency cells (such as gallium arsenide (GaAs)-based materials) are placed at the focus of concentrating mirrors or other collectors such as Fresnel lenses. Mono- and multi- crystalline (sometimes called "polycrystalline") silicon wafer PV (including ribbon technologies) are the dominant technologies on the PV market, with a 2009 market share of about 80%. Peak efficiencies achieved by various cell types include more than 40% for GaAs-based concentrator cells, about 25% for monocrystalline, 20% for multicrystalline and CIGS, 17% for CdTe, and about 10% for amorphous silicon. Typically, groups of cells are mounted side by side under a transparent sheet (usually glass) and connected in series to form a 'module' with dimensions of up to 1 m by 1 m. In considering efficiencies, it is important to distinguish between cell efficiencies (quoted above) and module efficiencies; the latter are typically 50 to 80% of the former. Manufacturers continue to improve performance and reduce costs with automation, faster cell processing, and low-cost, high-throughput manufacturing. The performance of modules is typically guaranteed by manufacturers for 20 to 30 years. [3.3.3.1, 3.3.3.2]

The application of PV for useful power involves more than just the cells and modules; the PV system, for example, will often include an inverter to convert the DC power from the cells to AC power to be compatible with common networks and devices. For off-grid applications, the system may include storage devices such as batteries. Work is ongoing to make these devices more reliable, reduce their cost, and extend their lifetime to be comparable with that of the modules. [3.3.3.4]

PV power systems are classified as two major types: off-grid and grid-connected. Grid-connected systems are themselves classified into two types: distributed and centralized. The distributed system is made up of a large number of small local power plants, some of which supply the electricity mainly to an on-site customer, and the remaining electricity feeds the grid. The centralized system, on the other hand, works as one large power plant. Off-grid systems are typically dedicated to a single or small group of customers and generally require an electrical storage element or back-up power. These systems have significant potential in non-electrified areas. [3.3.3.5]

Concentrating solar power electricity generation: CSP technologies produce electricity by concentrating the Sun's rays to heat a medium that is then used (either directly or indirectly) in a heat engine process (e.g., a steam turbine) to drive an electrical generator. CSP uses only the beam component of solar irradiation, and so its maximum benefit tends to be restricted to a limited geographical range. The concentrator brings the solar rays to a point (point focus) when used in central-receiver or dish systems and to a line (line focus) when used in trough or linear Fresnel systems. (These same systems can also be used to drive thermochemical processes for fuel production, as described below.) In trough concentrators, long rows of parabolic reflectors that track the movement of the Sun concentrate the solar irradiation on the order of 70 to 100 times onto a heat-collection element (HCE) mounted along the reflector's focal line. The HCE comprises a blackened inner pipe (with a selective surface) and a glass outer tube, with an evacuated space between the two. In current commercial designs, a heat transfer oil is circulated through the steel pipe where it is heated (to nearly 400°C), but systems using other heat transfer materials such as circulating molten salt or direct steam are currently being demonstrated. [3.3.4]

The second kind of line-focus system, the linear Fresnel system, uses long parallel mirror strips as the concentrator, again with a fixed linear receiver. One of the two point-focus systems, the central-receiver (also called the 'power tower'), uses an array of mirrors (heliostats) on the ground, each tracking the Sun on two axes so as to focus the Sun's rays at a point on top of a tall tower. The focal point is directed onto a receiver, which comprises either a fixed inverted cavity and/or tubes in which the heat transfer fluid circulates. It can reach higher temperatures (up to 1,000°C) than the line-focus types, which allows the heat engine to convert (at least theoretically) more of the collected heat to power. In the second type of point-focus system, the dish concentrator, a single paraboloidal reflector (as opposed to an array of reflectors) tracking the sun on two axes is used for concentration. The dish focuses the solar rays onto a receiver that is not fixed, but moves with the dish, being only about one dish diameter away. Temperatures on the receiver engine can reach as high as 900°C. In one popular realization of this concept, a Stirling engine driving an electrical generator is mounted at the focus. Stirling dish units are relatively small, typically producing 10 to 25 kW, but they can be aggregated in field configuration to realize a larger central station-like power output. [3.3.4]

The four different types of CSP plants have relative advantages and disadvantages. [3.3.4] All four have been built and demonstrated. An important advantage of CSP technologies (except for dishes) is the ability to store thermal energy after it has been collected at the receiver and before going to the heat engine. Storage media considered include molten salt, pressurized air or steam accumulators (for short-term storage only), solid ceramic particles, high-temperature, phase-change materials, graphite, and high-temperature concrete. Commercial CSP plants are being built with thermal storage capacities reaching 15 hours, allowing CSP to offer dispatchable power. [3.3.4]

Solar fuel production: Solar fuel technologies convert solar energy into chemical fuels such as hydrogen, synthetic gas and liquids such as methanol and diesel. The three basic routes to solar fuels, which can work alone or in combination, are: (1) electrochemical; (2) photochemical/photo-biological; and (3) thermo-chemical. In the first route, hydrogen is produced by an electrolysis process driven by solar-derived electrical power that has been generated by a PV or CSP system. Electrolysis of water is an old and well-understood technology, typically achieving 70% conversion efficiency from electricity to hydrogen. In the second route, solar photons are used to drive photochemical or photobiological reactions, the products of which are fuels: that is, they mimic what plants and organisms do. Alternatively, semiconductor material can be used as a solar light-absorbing anode in photoelectrochemical cells, which also generate hydrogen by water decomposition. In the third route, high-temperature solar-derived heat (such as that obtained at the receiver of a central-receiver CSP plant) is used to drive an endothermic chemical reaction that produces fuel. Here, the reactants can include combinations of water, CO_2, coal, biomass and natural gas. The products, which constitute the solar fuels, can be any (or combinations) of the following: hydrogen, syngas, methanol, dimethyl ether and synthesis oil. When a fossil fuel is used as the reactant, overall calorific values of the products will exceed those of the reactants, so that less fossil fuel needs to be burned for the same energy release. Solar fuel can also be synthesized from solar hydrogen and CO_2 to produce hydrocarbons compatible with existing energy infrastructures. [3.3.5]

3.4 Global and regional status of market and industry deployment

3.4.1 Installed capacity and generated energy

Solar thermal: Active solar heating and cooling technologies for residential and commercial buildings represent a mature market. This market, which is distributed to various degrees in most countries of the world, grew by 34.9% from 2007 to 2009 and continues to grow at a rate of about 16% per year. At the end of 2009, the global installed capacity of thermal power from these devices was estimated to be 180 GW_{th}. The global market for sales of active solar thermal systems reached an estimated 29.1 GW_{th} in 2008 and 31 GW_{th} in 2009. Glazed collectors comprise the majority of the world market. China accounted for 79% of the installation of glazed collectors in 2008, and the EU accounted for about 14.5%. In the USA and Canada, swimming pool heating is still the dominant application, with an installed capacity of 12.9 GW_{th} of unglazed plastic collectors. Notably in 2008, China led the world in installed capacity of flat-plate and evacuated-tube collectors with 88.7 GW_{th}. Europe had 20.9 GW_{th} and Japan 4.4 GW_{th}. In Europe, the market size more than tripled between 2002 and 2008. Despite these gains, solar thermal still accounts for only a relatively small portion of the demand for hot water in Europe. For example, in Germany, with the largest market, about 5% of one- and two-family homes are using solar thermal energy. One measure of the market penetration is the per capita annual usage of solar energy. The lead country in this regard is Cyprus, where the figure is 527 kW_{th} per 1,000 people. Note that there is no available information on passive solar regarding the status of its market and its deployment by industry. Consequently, the preceding numbers refer only to active solar. [3.4.1]

Photovoltaic electricity generation: In 2009, about 7.5 GW of PV systems were installed. That brought the cumulative installed PV capacity worldwide in 2009 to about 22 GW—a capacity able to generate up to 26 TWh (93,600 TJ) per year. More than 90% of this capacity is installed in three leading markets: the EU with 73% of the total, Japan with 12% and the USA with 8%. Roughly 95% of the PV installed capacity in the OECD countries is grid connected, the remainder being off-grid. Growth in the top eight PV markets through 2009 is illustrated in Figure TS.3.2. Spain and Germany have seen, by far, the largest amounts of solar installed in recent years. [3.4.1]

Concentrating solar power: CSP has reached a cumulative installed capacity of about 0.7 GW, with another 1.5 GW under construction. The capacity factors for a number of these CSP plants are expected to range from 25 to 75%; these can be higher than for PV because CSP plants contain the opportunity to add thermal storage where there is a commensurate need to overbuild the collector field to charge the thermal storage. The lower end of the capacity factor range is for no thermal storage and the upper end is for up to 15 hours of thermal storage. [3.8.4] The earliest commercial CSP plants were the Solar Electric Generating Systems in California

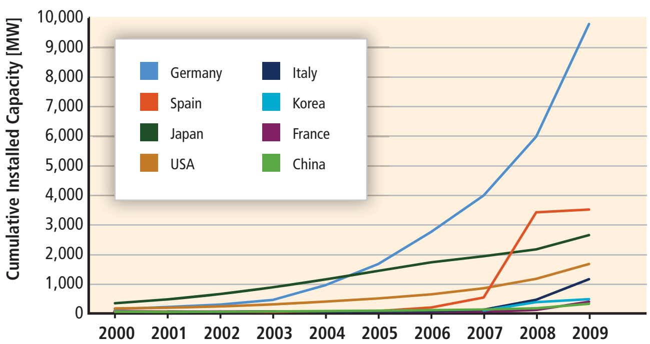


Figure TS.3.2 | Installed PV capacity for the years 2000 to 2009 in eight markets. [Figure 3.9] capable of producing 354 MW of power; installed between 1985 and 1991, they are still operating today. The period from 1991 to the early 2000s was slow for CSP, but since about 2004, there has been strong growth in planned generation. The bulk of the current operating CSP generation consists of trough technology, but central-receiver technology comprises a growing share, and there is strong proposed commercial activity in dish-Stirling. In early 2010, most of the planned global capacity was in the USA and Spain, but recently other countries announced commercial plans. Figure TS.3.3 shows the current and planned deployment of CSP capacity through the year 2015. [3.3.4, 3.4.1]

Solar fuel production: Currently, solar fuel production is in the pilot-plant phase. Pilot plants in the power range of 300 to 500 kW have been built for the carbo-thermic reduction of zinc oxide, steam methane reforming, and steam gasification of petcoke. A 250-kW steam-reforming reactor is operating in Australia. [3.3.4, 3.4.1]

3.4.2 Industry capacity and supply chain

Solar thermal: In 2008, manufacturers produced approximately 41.5 million m² of solar collectors, a scale large enough to adapt to mass production, even though production is spread among a large number of companies around the world. Indeed, large-scale industrial production levels have been attained in most parts of the industry. In the manufacturing process, a number of readily available materials—including copper, aluminium, stainless steel, and thermal insulation—are being applied and combined through different joining technologies to produce the absorber plate. This box is topped by the cover glass, which is almost always low-iron glass, now readily available. Most production is in China, where it is aimed at internal consumption. Evacuated collectors, suitable for mass production techniques, are starting to dominate that market. Other important production sites are in Europe, Turkey, Brazil and India. Much of the export market comprises total solar water heating systems rather than solar collectors per se. The largest exporters of solar water heating systems are Australia, Greece, the USA and France. Australian exports constitute about 50% of its production. [3.4.2]

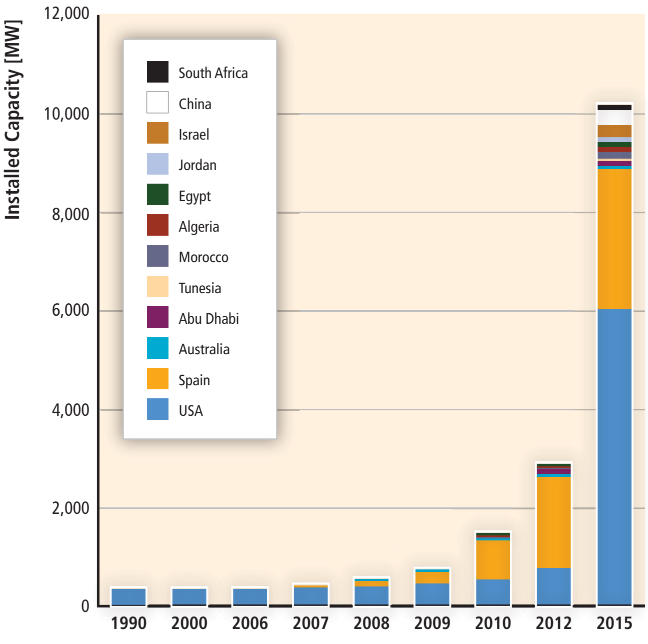


Figure TS.3.3 | Installed and planned concentrated solar power plants by country. [Figure 3.10]

For passive solar heating, part of the industry capacity and supply chain lies in people: namely, the engineers and architects who must systematically collaborate to produce a passively heated building. Close collaboration between the two disciplines has often been lacking in the past, but the dissemination of systematic design methodologies issued by different countries has improved the design capabilities. Windows and glazing are an important part of passively heated buildings, and the availability of a new generation of high-efficiency (low-emissivity, argon-filled) windows is having a major impact on solar energy's contribution to heating requirements in the buildings sector. These windows now constitute the bulk of new windows being installed in most northern-latitude countries. There do not appear to be any issues of industrial capacity or supply chains hindering the adoption of better windows. Another feature of passive design is adding internal mass to the building's structure. Concrete and bricks, the most commonly used storage materials, are readily available; phase-change materials (e.g., paraffin), considered to be the storage materials of the future, are not expected to have supply-chain issues. [3.4.2]

Photovoltaic electricity generation: The compound annual growth rate in PV manufacturing production from 2003 to 2009 exceeded 50%. In 2009, solar cell production reached about 11.5 GW per year (rated at peak capacity) split among several economies: China had about 51% of world production (including 14% from the Chinese province of Taiwan); Europe about 18%; Japan about 14%; and the USA about 5%. Worldwide, more than 300 factories produce solar cells and modules. In 2009, silicon-based solar cells and modules represented about 80% of the worldwide market. The remaining 20% mostly comprised cadmium telluride, amorphous silicon, and copper indium gallium diselenide. The total market is expected to increase significantly during the next few years, with thin-film module production gaining market share. Manufacturers are moving towards original design of manufacturing units and are also moving components of module production closer to the final market. Between 2004 and early 2008, the demand for crystalline silicon (or polysilicon) outstripped supply, which led to a price hike. With the new price, ample supplies have become available; the PV market is now driving its own supply of polysilicon. [3.4.2]

Concentrating solar power: In the past several years, the CSP industry has experienced a resurgence from a stagnant period to more than 2 GW being either commissioned or under construction. More than 10 different companies are now active in building or preparing for commercial-scale plants. They range from start-up companies to large organizations, including utilities, with international construction management expertise. None of the supply chains for construction of plants are limited by the availability of raw material. Expanded capacity can be introduced with a lead time of about 18 months. [3.4.2]

Solar fuel production: Solar fuel technology is still at an emerging stage, and there is no supply chain in place at present for commercial applications. Solar fuels will comprise much of the same solar-field technology as is being deployed for other high-temperature CSP systems, in addition to downstream technologies similar to those in the petrochemical industry. [3.4.2]

3.4.3 Impact of policies

Direct solar energy technologies face a range of potential barriers to achieving wide-scale deployment. Solar technologies differ in levels of maturity, and although some applications are already competitive in localized markets, they generally face one common barrier: the need to reduce costs. Utility-scale CSP and PV systems face different barriers than distributed PV and solar heating and cooling technologies. Important barriers include: siting, permitting, and financing challenges to develop land with favourable solar resources for utility-scale projects; lack of access to transmission lines for large projects far from electric load centres; complex access laws, permitting procedures, and fees for smaller-scale projects; lack of consistent interconnection standards and time-varying utility rate structures that capture the value of distributed generated electricity; inconsistent standards and certifications and enforcement of these issues; and lack of regulatory structures that capture environmental and risk-mitigation benefits across technologies. Through appropriate policy designs, governments have shown that they can support solar technologies by funding R&D and by providing incentives to overcome economic barriers. Price-driven incentive frameworks, for example, were popularized after FIT policies boosted levels of PV deployment in Germany and Spain. Quota-driven frameworks such as renewable portfolio standards and government bidding are common in the USA and China, respectively. In addition to these regulatory frameworks, fiscal policies and financing mechanisms (e.g., tax credits, soft loans and grants) are often employed to support the manufacturing of solar goods and to increase consumer demand. Most successful solar policies are tailored to the barriers imposed by specific applications, and the most successful policies are those that send clear, long-term and consistent signals to the market. [3.4.3]

3.5 Integration into the broader energy system

Solar technologies have a number of attributes that allow their advantageous integration into a broader energy system. In this section, only the integration features unique to solar technologies are summarized. These include low-capacity energy demand, district heating and other thermal loads, PV generation characteristics and smoothing effects, and CSP generation characteristics and grid stabilization. [3.5.1–3.5.4]

For applications that have low power consumption, such as lighting or solar-derived hot water, solar technologies sometimes have a comparative advantage relative to non-renewable fuel technologies. In addition, solar technologies allow small decentralized applications as well as larger centralized ones. In some regions of the world, integration of solar energy into district heating and other thermal loads has proven to be an effective strategy, especially because highly insulated buildings can be heated effectively with relatively low-temperature energy carriers. In some locations, a district cooling and heating system can provide additional advantages compared to decentralized cooling, including cost advantages for economies of scale, diversity of cooling demand of different buildings, reducing noise and structural load, and equipment space savings. Also, by combining biomass and low-temperature solar thermal energy, system capacity factor and emissions profiles can be improved. [3.5.1, 3.5.2]

For PV power generation at a specific location, electricity varies systematically during a day and a year, but also randomly according to weather conditions. This variation can, in some instances, have a large impact on voltage and power flow in the local transmission and distribution system from the early penetration stage, and the supply-demand balance in total power system operation in the high-penetration stage. This effect can potentially constrain PV system integration. However, modelling and system simulations suggest that numerous PV systems in a broad area should have less-random and slower variations, which are sometimes referred to as the 'smoothing effect'. Studies are underway to evaluate and quantify actual smoothing effects at a large scale (1,000 sites at distances from 2 to 200 km) and at time scales of 1 minute or less. [3.5.3]

In a CSP plant, even without storage, the inherent thermal mass in the collector system and spinning mass in the turbine tend to significantly reduce the impact of rapid solar transients on electrical output, and thus, lead to a reduced impact on the grid. By including integrated thermal storage systems, capacity factors typical of base-load operation could be achieved in the future. In addition, integrating CSP plants with fossil fuel generators, especially with gas-fired integrated solar combined-cycle systems (with storage), can offer better fuel efficiency and extended operating hours and ultimately be more cost effective than operating separate CSP and/or combined-cycle plants. [3.5.4]

3.6 Environmental and social impacts

3.6.1 Environmental impacts

Apart from its benefits in GHG reduction, the use of solar energy can reduce the release of pollutants—such as particulates and noxious gases—from the older fossil fuel plants that it replaces. Solar thermal and PV technologies do not generate any type of solid, liquid or gaseous by-products when producing electricity. The family of solar energy technologies may create other types of air, water, land and ecosystem impacts, depending on how they are managed. The PV industry uses some toxic, explosive gases as well as corrosive liquids in its production lines. The presence and amount of those materials depend strongly on the cell type. However, the intrinsic needs of the productive process of the PV industry force the use of quite rigorous control methods that minimize the emission of potentially hazardous elements during module production. For other solar energy technologies, air and water pollution impacts are generally expected to be relatively minor. Furthermore, some solar technologies in certain regions may require water usage for cleaning to maintain performance. [3.6.1]

Lifecycle assessment estimates of the GHGs associated with various types of PV modules and CSP technologies are provided in Figure TS.3.4. The majority of estimates for PV modules cluster between 30 and 80 g of CO_2eq/kWh. Lifecycle GHG emissions for CSP-generated electricity have recently been estimated to range from about 14 to 32 g of CO_2eq/kWh. These emission levels are about an order of magnitude lower than those of natural gas-fired power plants. [3.6.1, 9.3.4]

Land use is another form of environmental impact. For roof-mounted solar thermal and PV systems, this is not an issue, but it can be an issue for central-station PV as well as for CSP. Environmentally sensitive lands may pose a special challenge for CSP permitting. One difference for CSP vis-à-vis PV is that it needs a method to cool the working fluid, and such cooling often involves the use of scarce water. Using local air as the coolant (dry cooling) is a viable option, but this can decrease plant efficiency by 2 to 10%. [3.6.1]

3.6.2 Social impacts

The positive benefits of solar energy in the developing world provide arguments for its expanded use. About 1.4 billion people do not have access to electricity. Solar home systems and local PV-powered community grids can provide electricity to many areas for which connection to a main grid is cost prohibitive. The impact of electricity and solar energy technologies on the local population is shown through a long list of important benefits: the replacement of indoor-polluting kerosene lamps and inefficient cook stoves; increased indoor reading; reduced time gathering firewood for cooking (allowing the women and children who normally gather it to focus on other priorities); street lighting for security; improved health by providing refrigeration for vaccines and food products; and, finally, communications devices (e.g., televisions, radios). All of these provide a myriad of benefits that improve the lives of people. [3.6.2]

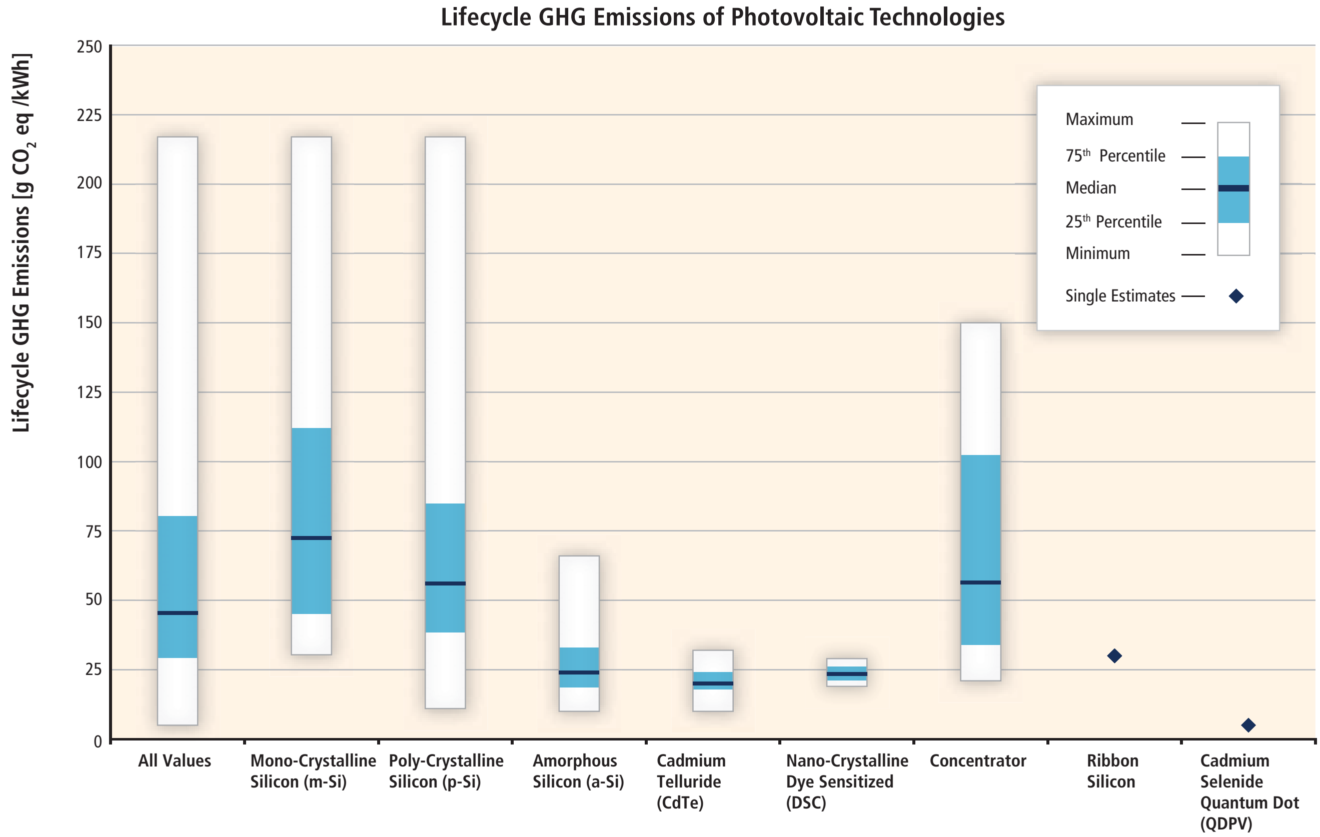
Job creation is an important social consideration associated with solar energy technology. Analysis indicates that solar PV has the highest job-generating potential among the family of solar technologies. Approximately 0.87 job-years per GWh are created through solar PV, followed by CSP with 0.23 job-years per GWh. When properly put forward, these job-related arguments can help accelerate social acceptance and increase public willingness to tolerate the perceived disadvantages of solar energy, such as visual impacts. [3.6.2]

3.7 Prospects for technology improvements and innovation

Solar thermal: If integrated at the earliest stages of planning, buildings of the future could have solar panels – including PV, thermal collector, and combined PV-thermal (hybrids) – making up almost all viewed components of the roof and façades. Such buildings could be established not just through the personal desires of individual builders/owners, but also as a result of public policy mandates, at least in some areas. For example, the vision of the European Solar Thermal Technology Platform is to establish the 'Active Solar Building' as a standard for new buildings by 2030, where an Active Solar Building, on average, covers all of its energy demand for water heating and space conditioning. [3.7.2]

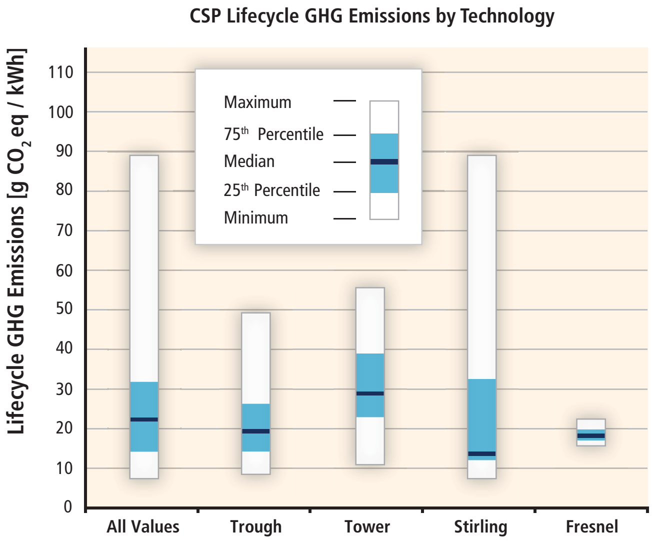
In highlighting the advances in passive solar, two climates can be distinguished between: those that are dominated by the demand for heating and those dominated by the demand for cooling. For the former, a wider-scale adoption of the following items can be foreseen: evacuated (as opposed to sealed) glazing, dynamic exterior night-time insulation, and translucent glazing systems that can automatically change solar/visible transmittance and that also offer improved insulation values. For the latter, there is the expectation for an increased use of cool roofs (i.e., light-coloured roofs that reflect solar energy); heat-dissipation techniques such as use of the ground and water as heat sinks; methods that improve the microclimate around the buildings; and solar control devices that allow penetration of the lighting, but not the thermal, component of solar energy. For both climates, improved thermal storage is expected to be embedded in building materials. Also anticipated are improved methods for distributing the absorbed solar heat around the building and/or to the outside air, perhaps using active methods such as fans. Finally, improved design tools are expected to facilitate these various improved methods. [3.7.1]

Photovoltaic electricity generation: Although now a relatively mature technology, PV is still experiencing rapid improvements in performance and cost, and a continuation of this steady progress is expected. The efforts required are being taken up in a framework of intergovernmental cooperation, complete with roadmaps. For the different PV technologies, four broad technological categories, each requiring specific R&D approaches, have been identified: 1) cell efficiency, stability, and lifetime; 2) module productivity and manufacturing; 3) environmental sustainability; and 4) applicability, all of which include standardization and harmonization. Looking to the future, PV technologies can by categorized in three major classes: current; emerging, which represent medium risk with a mid-term (10 to 20 year) time line; and the high-risk technologies aimed at 2030 and beyond, which have extraordinary potential but require technical breakthroughs. Examples of emerging cells are multiple-junction, polycrystalline thin films and crystalline silicon in the sub-100-µm thickness range. Examples of high-risk cells are organic solar cells, biomimetic devices and quantum dot designs that have the potential to substantially increase the maximum efficiency. Finally, there is important work to be done on the balance of systems (BOS), which comprises inverters, storage, charge controllers, system structures and the energy network. [3.7.3]



	All Values	Mono-Crystalline Silicon (m-Si)	Poly-Crystalline Silicon (p-Si)	Amorphous Silicon (a-Si)	Cadmium Telluride (CdTe)	Nano-Crystalline Dye Sensitized (DSC)	Concentrator	Ribbon Silicon	Cadmium Selenide Quantum Dot (QDPV)
Estimates:	124	30	56	12	13	4	6	2*	1
References:	26	9	15	3	3	1	2	2	1

*same value



	All Values	Trough	Tower	Stirling	Fresnel
Estimates:	42	20	14	4	4
References:	13	7	5	3	1

Figure TS.3.4 | GHG emissions from the life cycles of (top) PV modules and (bottom) CSP technologies. See Annex II for details of literature search and citations of literature contributing to the estimates displayed. [Figures 3.14, 3.15]

CSP electricity generation: Although CSP is now a proven technology at the utility scale, technology advances are still taking place. As plants are built, both mass production and economies of scale are leading to cost reductions. There is scope for continuing improvement in solar-to-electricity efficiency, partly through higher collector temperatures. To increase temperature and efficiency, alternatives to the use of oil as the heat-transfer fluid—such as water (boiling in the receiver) or molten salts—are being developed, permitting higher operating temperatures. For central-receiver systems, the overall efficiencies can be higher because the operating temperatures are higher, and further improvements are expected to achieve peak efficiencies (solar to electricity) almost twice those of existing systems, up to 35%. Trough technology will benefit from continuing advances in solar-selective surfaces, and central receivers and dishes will benefit from improved receiver/absorber designs that afford high levels of solar irradiance at the focus. Capital cost reduction is expected to come from the benefits of mass production, economies of scale and learning from previous experience. [3.7.4]

Solar fuel production: Solar electrolysis using PV or CSP is available for niche applications, but it remains costly. Many paths are being pursued to develop a technology that will reduce the cost of solar fuels. These include solid-oxide electrolysis cells, the photoelectrochemical cell (which combines all the steps in solar electrolysis into a single unit), advanced thermo-chemical processes, and photochemical and photobiological processes—sometimes in combinations that integrate artificial photosynthesis in man-made biomimetic systems and photobiological hydrogen production in living organisms. [3.7.5]

Other potential future applications: Other methods under investigation for producing electricity using solar thermal technologies without an intermediate thermodynamic cycle include thermoelectric, thermionic, magnetohydrodynamic and alkali-metal methods. Space solar power, in which solar power collected in space is beamed via microwaves to receiving antennae on the ground, has also been proposed. [3.7.6]

3.8 Cost trends

Although the cost of solar energy varies widely by technology, application, location and other factors, costs have been reduced significantly during the past 30 years, and technical advances and supportive public policies continue to offer the potential for additional cost reductions. The degree of continued innovation will have a significant bearing on the level of solar deployment. [3.7.2–3.7.5, 3.8.2–3.8.5]

Solar thermal: The economics of solar heating applications depend on appropriate design of the system with regard to energy service needs, which often involves the use of auxiliary energy sources. In some regions, for example, in southern parts of China, solar water heating (SWH) systems are cost competitive with traditional options. SWH systems are generally more competitive in sunny regions, but this picture changes for space heating based on its usually higher overall heating load. In colder regions capital costs can be spread over a longer heating season, and solar thermal can then become more competitive. [3.8.2]

The investment costs for solar thermal heating systems vary widely depending on the complexity of the technology used as well as the market conditions in the country of operation. The costs for an installed system vary from as low as USD_{2005} 83/m² for SWH systems in China to more than USD_{2005} 1,200/m² for certain space-heating systems. The levelized cost of heat (LCOH) mirrors the wide variation in investment cost, and depends on an even larger number of variables, including the particular type of system, investment cost of the system, available solar irradiance in a particular location, conversion efficiency of the system, operating costs, utilization strategy of the system and the applied discount rate. Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOH for solar thermal systems over a large set and range of input parameters has been calculated to vary widely from USD_{2005} 9 to 200/GJ, but can be estimated for more specific settings with parametric analysis. Figure TS.3.5 shows the LCOH over a somewhat narrower set and range of input parameters. More specifically, the figure shows that for SWH systems with costs in the range of USD_{2005} 1,100 to 1,200/kW_{th} and conversion efficiencies of roughly 40%, LCOH is expected to range from slightly more than USD_{2005} 30/GJ to slightly less than USD_{2005} 50/GJ in regions comparable to Central and Southern European locations and up to almost USD_{2005} 90/GJ for regions with less solar irradiation. Not surprisingly, LCOH estimates are highly sensitive to all of the parameters shown in Figure TS.3.5, including investment costs and capacity factors. [3.8.2, Annex II, Annex III]

Over the last decade, for each 50% increase in installed capacity of solar water heaters, investment costs have fallen 20% in Europe. According to the IEA, further cost reductions in OECD countries will come from the use of cheaper materials, improved manufacturing processes, mass production, and the direct integration into buildings of collectors as multi-functional building components and modular, easy-to-install systems. Delivered energy costs in OECD countries are anticipated by the IEA to eventually decline by around 70 to 75%. [3.8.2]

PV electricity generation: PV prices have decreased by more than a factor of 10 during the last 30 years; however, the current levelized cost of electricity (LCOE) from solar PV is generally still higher than wholesale market prices for electricity. In some applications, PV systems are already competitive with other local alternatives (e.g., for electricity supply in certain rural areas in developing countries). [3.8.3, 8.2.5, 9.3.2]

The LCOE of PV highly depends on the cost of individual system components, with the highest cost share stemming from the PV module. The LCOE also includes BOS components, cost of labour for installation, operation and maintenance (O&M) cost, location and capacity factor, and the applied discount rate. [3.8.3]

The price for PV modules dropped from USD_{2005} 22/W in 1980 to less than USD_{2005} 1.50/W in 2010. The corresponding historical learning rate ranges from 11 to 26%, with a median learning rate of 20%. The price in USD/W for an entire system, including the module, BOS, and installation costs, has also decreased steadily, reaching numbers as low as USD_{2005} 2.72/W for some thin-film technologies by 2009. [3.8.3]

The LCOE for PV depends not only on the initial investment; it also takes into account operation costs and the lifetime of the system components, local solar irradiation levels and system performance. Based on the standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the recent LCOE for different types of PV systems has been calculated. It shows a wide variation from as low as USD_{2005} 0.074/kWh to as high as USD_{2005} 0.92/kWh, depending on a large set and range of input parameters. Narrowing the range of parameter variations, the LCOE in 2009 for utility-scale PV electricity generation in regions of high solar irradiance in Europe and the USA were in the range of about USD_{2005} 0.15/kWh to USD_{2005} 0.4/kWh at a

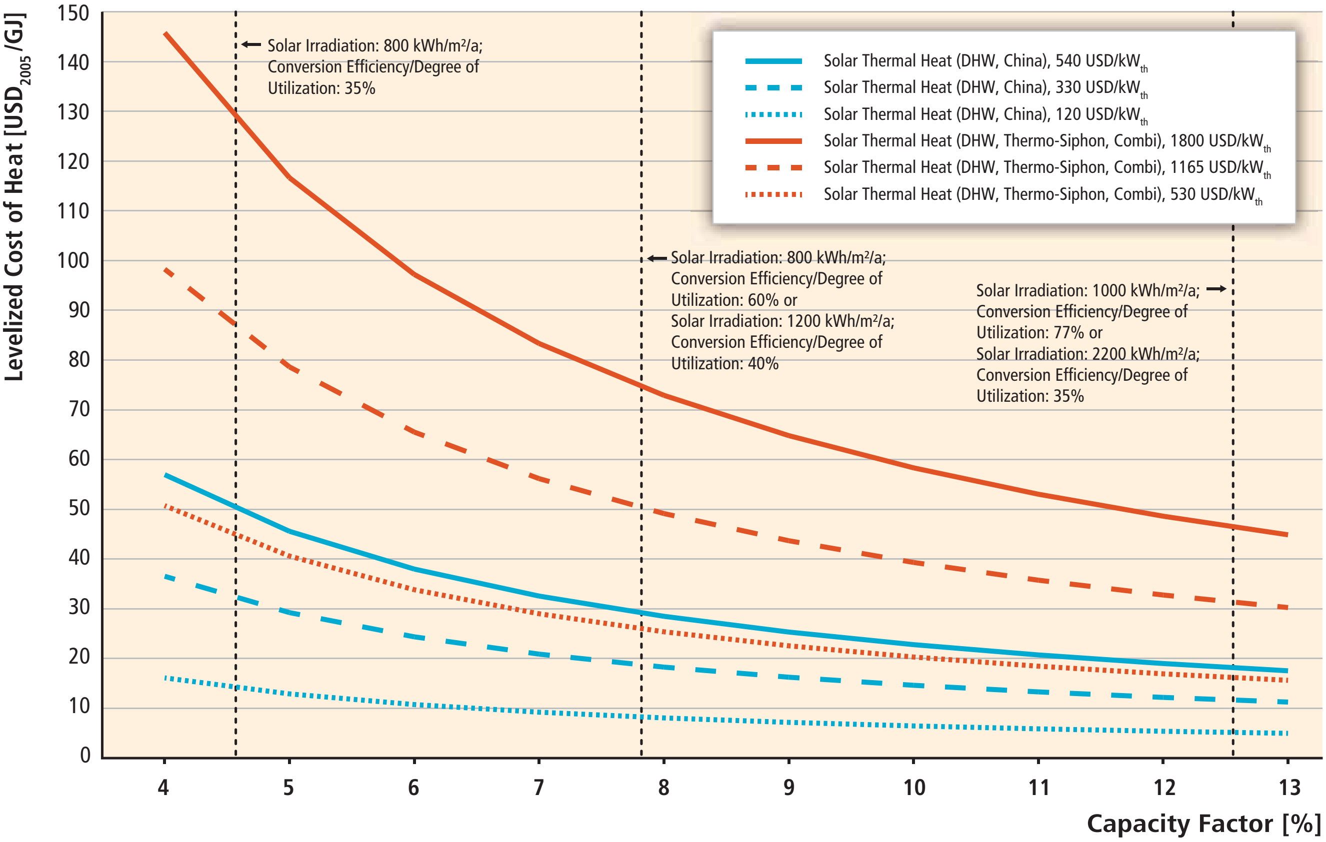


Figure TS.3.5 | Sensitivity of levelized cost of heat with respect to investment cost as a function of capacity factor. (Discount rate assumed to be 7%, annual operation and maintenance cost USD_{2005} 5.6 and14/kW, and lifetimes set at 12.5 and 20 years for domestic hot water (DHW) systems in China and various types of systems in OECD countries, respectively.) [Figure 3.16]

7% discount rate, but may be lower or higher depending on the available resource and on other framework conditions. Figure TS.3.6 shows a wide variation of LCOE for PV depending on the type of system, investment cost, discount rates and capacity factors. [1.3.2, 3.8.3, 10.5.1, Annex II, Annex III]

Costs of electricity generation or LCOE are projected by the IEA to reach the following in 2020: US $cent_{2005}$ 14.5/kWh to US $cent_{2005}$ 28.6/kWh for the residential sector and US $cent_{2005}$ 9.5/kWh to US $cent_{2005}$ 19/kWh for the utility sector under favourable conditions of 2,000 kWh/kW (equivalent to a 22.8% capacity factor) and less favourable conditions of 1,000 kWh/kW (equivalent to a 11.4% capacity factor), respectively. The goal of the US Department of Energy is even more ambitious, with an LCOE goal of US $cent_{2005}$ 5/kWh to US $cent_{2005}$ 10/kWh, depending on the end user, by 2015. [3.8.3]

CSP electricity generation: CSP electricity systems are a complex technology operating in a complex resource and financial environment; so many factors affect the LCOE. The publicized investment costs of CSP plants are often confused when compared to other renewable sources, because varying levels of integrated thermal storage increase the investment, but also improve the annual output and capacity factor of the plant. For large, state-of-the-art trough plants, current investment costs are estimated to be USD_{2005} 3.82/W (without storage) to USD_{2005} 7.65/W (with storage) depending on labour and land costs, technologies, the amount and distribution of beam irradiance and, above all, the amount of storage and the size of the solar field. Performance data for modern CSP plants are limited, particularly for plants equipped with thermal storage, because new plants only became operational from 2007 onward. Capacity factors for early plants without storage were up to 28%. For modern plants without storage, capacity factors of roughly 20 to 30% are envisioned; for plants with thermal storage, capacity factors of 30 to 75% may be achieved. Based on the standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for a solar trough plant with six hours of thermal storage in 2009 over a large set and range of input parameters has been calculated to range from slightly more than US $cent_{2005}$ 10/kWh to about US $cent_{2005}$ 30/kWh. Restricting the range of discount rates to 10% results in a somewhat narrower range of about US $cent_{2005}$ 20/kWh to US $cent_{2005}$ 30/kWh, which is roughly in line with the range of US $cent_{2005}$ 18 to US $cent_{2005}$ 27/kWh available in the literature. Particular cost

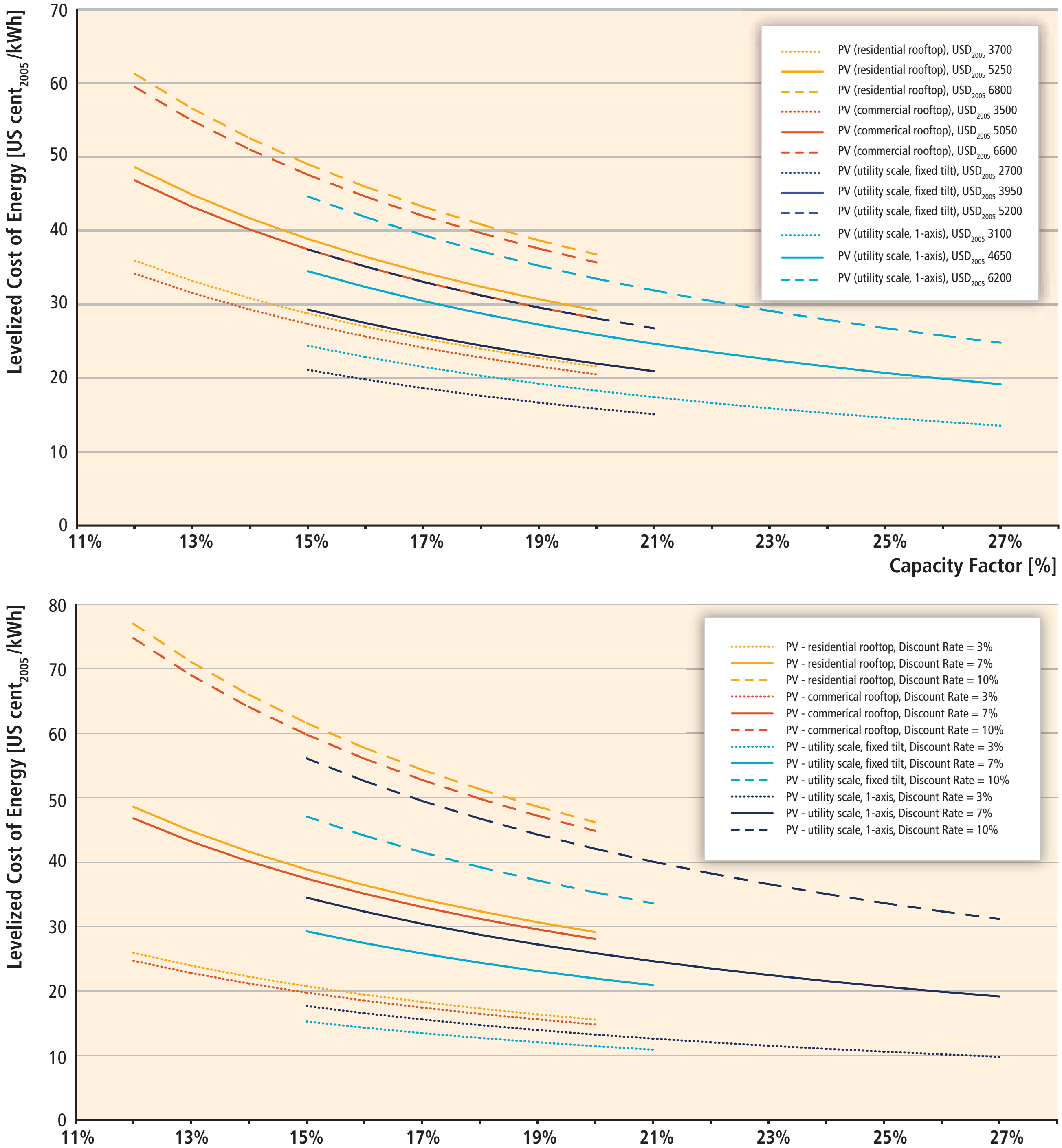


Figure TS.3.6 | Levelized cost of PV electricity generation, 2008–2009: (top) as a function of capacity factor and investment cost*,***; and (bottom) as a function of capacity factor and discount rate**,***. [Figure 3.19]

Notes: * Discount rate assumed to equal 7%. ** Investment cost for residential rooftop systems assumed at USD 5,500 US/kW, for commercial rooftop systems at USD 5,150, for utility-scale fixed tilt projects at USD 3,650/kW and for utility-scale one-axis projects at USD 4,050/kW. ***Annual O&M cost assumed at USD 41 to 64/kW, lifetime at 25 years.

and performance parameters, including the applied discount rate and capacity factor, affect the specific LCOE estimate, although the LCOE of different system configurations for otherwise identical conditions are expected to differ only marginally. [3.8.4]

The learning ratio for CSP, excluding the power block, has been estimated at 10 ± 5%. Specific LCOE goals for the USA are US $cent_{2005}$ 6/kWh to US $cent_{2005}$ 8/kWh with 6 hours storage by 2015 and US $cent_{2005}$ 50/kWh to US $cent_{2005}$ 60/kWh with 12 to 17 hours of storage by 2020. The EU is pursuing similar goals. [3.8.4]

3.9 Potential deployment

3.9.1 Near-term (2020) forecasts

Table TS.3.1 summarizes findings from the available studies on potential deployment up to 2020, as taken from the literature. Sources for the tabulated data are the following: European Renewable Energy Council (EREC) – Greenpeace (Energy [r]evolution, reference and advanced scenarios); and IEA (CSP and PV Technology Roadmaps). With regard to the solar thermal entries, note that passive solar contributions are not included in these data; although this technology reduces the demand for energy, it is not part of the supply chain considered in energy statistics. [3.9]

3.9.2 Long-term deployment in the context of carbon mitigation

Figure TS.3.7 presents the results of more than 150 long-term modelling scenarios described in Chapter 10. The potential deployment scenarios vary widely—from direct solar energy playing a marginal role in 2050 to it becoming one of the major sources of energy supply. Although direct solar energy today provides only a very small fraction of the world energy supply, it remains undisputed that this energy source has one of the largest potential futures.

Reducing cost is a key issue in making direct solar energy more commercially relevant and in position to claim a larger share of the worldwide energy market. This can only be achieved if solar technologies' costs are reduced as they move along their learning curves, which depend primarily on market volumes. In addition, continuous R&D efforts are required to ensure that the slopes of the learning curves do not flatten too early. The true costs of deploying solar energy are still unknown because the main deployment scenarios that exist today consider only a single technology. These scenarios do not take into account the co-benefits of a renewable/sustainable energy supply via a range of different RE sources and energy efficiency measures.

Potential deployment depends on the actual resources and availability of the respective technology. However, to a large extent, the regulatory and legal framework in place can foster or hinder the uptake of direct solar energy applications. Minimum building standards with respect to building orientation and insulation can reduce the energy demand of buildings significantly and can increase the share of RE supply without increasing the overall demand. Transparent, streamlined administrative procedures to install and connect solar power sources to existing grid infrastructures can further lower the cost related to direct solar energy.

4. Geothermal Energy

4.1 Introduction

Geothermal resources consist of thermal energy from the Earth's interior stored in both rock and trapped steam or liquid water, and are used to generate electric energy in a thermal power plant or in other domestic and agro-industrial applications requiring heat as well as in CHP applications. Climate change has no significant impacts on the effectiveness of geothermal energy. [4.1]

Geothermal energy is a renewable resource as the tapped heat from an active reservoir is continuously restored by natural heat production, conduction and convection from surrounding hotter regions, and the extracted geothermal fluids are replenished by natural recharge and by reinjection of the cooled fluids. [4.1]

Table TS.3.1 | Evolution of cumulative solar capacities. [Table 3.7]

		Low-Temperature Solar Heat (GW_{th})			Solar PV Electricity (GW)			CSP Electricity (GW)		
	Year	2009	2015	2020	2009	2015	2020	2009	2015	2020
Name of Scenario	**Current cumulative installed capacity**	**180**			**22**			**0.7**		
	EREC – Greenpeace (reference scenario)		180	230		44	80		5	12
	EREC – Greenpeace ([r]evolution scenario)		715	1,875		98	335		25	105
	EREC – Greenpeace (advanced scenario)		780	2,210		108	439		30	225
	IEA Roadmaps		N/A			95[1]	210		N/A	148

Note: 1. Extrapolated from average 2010 to 2020 growth rate.

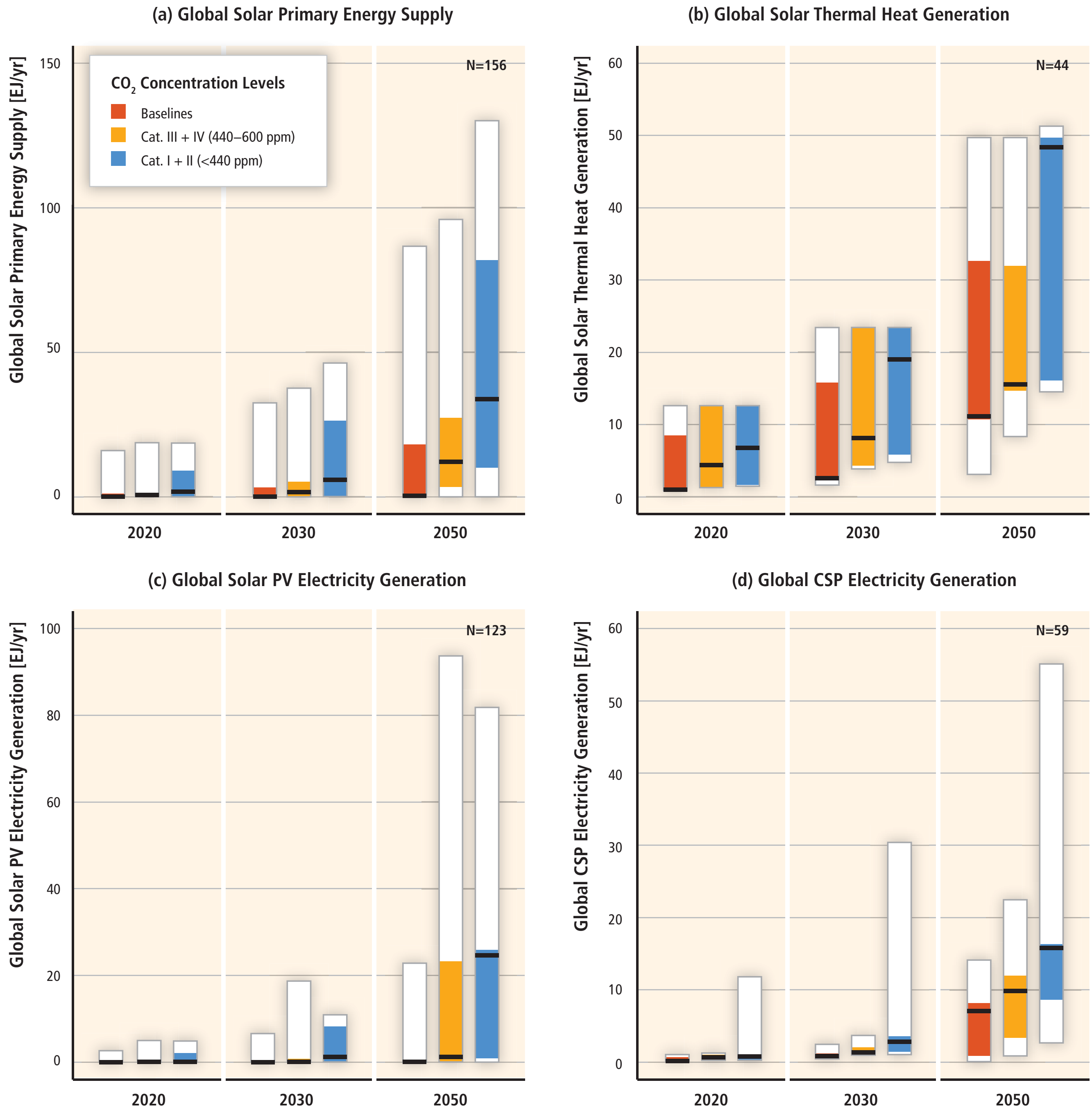


Figure TS.3.7 | Global solar supply and generation in long-term scenarios (median, 25th to 75th percentile range, and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration level in 2100; the specific number of scenarios underlying the figure is indicated in the upper right-hand corner). (a) Global solar primary energy supply; (b) global solar thermal heat generation; (c) global solar PV electricity generation; and (d) global CSP electricity generation. [Figure 3.22]

4.2 Resource potential

The accessible stored heat from hot dry rocks in the Earth is estimated to range from 110 to 403 x 10^6 EJ down to 10 km depth, 56 to 140 x 10^6 EJ down to 5 km depth, and around 34 x 10^6 EJ down to 3 km depth. Using previous estimates for hydrothermal resources and calculations for enhanced (or engineered) geothermal systems derived from stored heat estimates at depth, geothermal technical potentials for electric generation range from 118 to 146 EJ/yr (at 3 km depth) to 318 to 1,109 EJ/yr (at 10 km depth), and for direct uses range from 10 to 312 EJ/yr (Figure TS.4.1). [4.2.1]

Technical potentials are presented on a regional basis in Table TS.4.1. The regional breakdown is based on the methodology applied by the Electric Power Research Institute to estimate theoretical geothermal

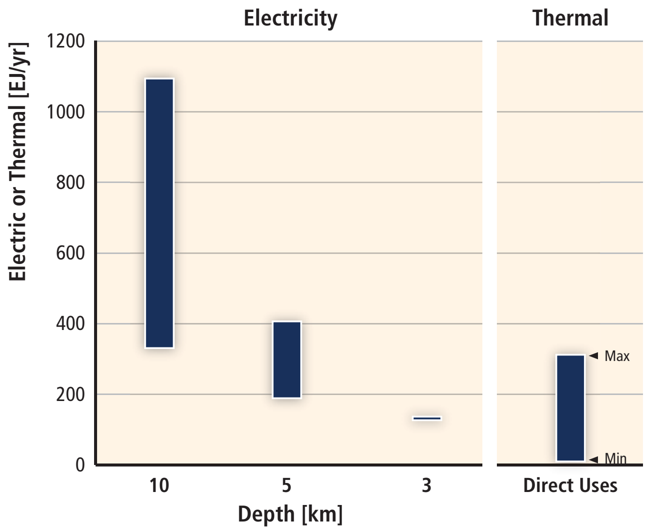


Figure TS.4.1 | Geothermal technical potentials for electricity and direct uses (heat). Direct uses usually do not require development to depths greater than about three km. [Figure 4.2]

potentials for each country, and then countries are grouped regionally. Thus, the present disaggregation of global technical potential is based on factors accounting for regional variations in the average geothermal gradient and the presence of either a diffuse geothermal anomaly or a high-temperature region associated with volcanism or plate boundaries. The separation into electric and thermal (direct uses) potentials is somewhat arbitrary in that most higher-temperature resources could be used for either, or both, in CHP applications depending on local market conditions. [4.2.2]

The heat extracted to achieve the technical potentials can be fully or partially replenished over the long term by the continental terrestrial heat flow of 315 EJ/yr at an average flux of 65 mW/m^2. [4.2.1]

4.3 Technology and applications

Geothermal energy is currently extracted using wells and other means that produce hot fluids from: (a) hydrothermal reservoirs with naturally high permeability, or (b) Enhanced or engineered geothermal systems (EGS) with artificial fluid pathways (Figure TS.4.2). Technology for electricity generation from hydrothermal reservoirs is mature and reliable, and has been operating for about 100 years. Technologies for direct heating using geothermal heat pumps (GHPs) for district heating and for other applications are also mature. Technologies for EGS are in the demonstration stage. [4.3]

Electric power from geothermal energy is especially suitable for supplying base-load power, but also can be dispatched and used to meet peak demand. Hence, geothermal electric power can complement variable electricity generation. [4.3]

Since geothermal resources are underground, exploration methods (including geological, geochemical and geophysical surveys) have been developed to locate and assess them. The objectives of geothermal exploration are to identify and rank prospective geothermal reservoirs prior to drilling. Today, geothermal wells are drilled over a range of depths up to 5 km using conventional rotary drilling methods similar to those for accessing oil and gas reservoirs. Advanced drilling technologies allow for high-temperature operation and provide directional capability. [4.3.1]

The basic types of geothermal power plants in use today are steam condensing turbines and binary cycle units. Condensing plants can be of the flash or dry-steam type (the latter do not require brine separation, resulting in simpler and cheaper plants) and are more common than binary units. They are installed in intermediate- and high-temperature resources (≥150°C) with capacities often between 20 and 110 MW$_e$.

Table TS.4.1 | Geothermal technical potentials on continents for the IEA regions. [Table 4.3]

REGION[1]	Electric technical potential (EJ/yr) at depths to:						Technical potentials (EJ/yr) for direct uses	
	3 km		5 km		10 km			
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
OECD North America	25.6	31.8	38.0	91.9	69.3	241.9	2.1	68.1
Latin America	15.5	19.3	23.0	55.7	42.0	146.5	1.3	41.3
OECD Europe	6.0	7.5	8.9	21.6	16.3	56.8	0.5	16.0
Africa	16.8	20.8	24.8	60.0	45.3	158.0	1.4	44.5
Transition Economies	19.5	24.3	29.0	70.0	52.8	184.4	1.6	51.9
Middle East	3.7	4.6	5.5	13.4	10.1	35.2	0.3	9.9
Developing Asia	22.9	28.5	34.2	82.4	62.1	216.9	1.8	61.0
OECD Pacific	7.3	9.1	10.8	26.2	19.7	68.9	0.6	19.4
Total	**117.5**	**145.9**	**174.3**	**421.0**	**317.5**	**1,108.6**	**9.5**	**312.2**

Note: 1. For regional definitions and country groupings see Annex II.

In binary cycle plants, the geothermal fluid passes through a heat exchanger heating another working fluid with a low boiling point, which vaporizes and drives a turbine. They allow for use of lower-temperature hydrothermal reservoirs and of EGS reservoirs (generally from 70°C to 170°C), and are often constructed as linked modular units of a few MW_e in capacity. Combined or hybrid plants comprise two or more of the above basic types to improve versatility, increase overall thermal efficiency, improve load-following capability, and efficiently cover a wide resource temperature range. Finally, cogeneration plants, or CHP plants, produce both electricity and hot water for direct use. [4.3.3]

EGS reservoirs require stimulation of subsurface regions where temperatures are high enough for effective utilization. A reservoir consisting of a fracture network is created or enhanced to provide well-connected fluid pathways between injection and production wells. Heat is extracted by circulating water through the reservoir in a closed loop and can be used for power generation and for industrial or residential heating (see Figure TS.4.2). [4.3.4]

Direct use provides heating and cooling for buildings including district heating, fish ponds, greenhouses, bathing, wellness and swimming pools, water purification/desalination and industrial and process heat for agricultural products and mineral drying. Although it can be debated whether GHPs are a 'true' application of geothermal energy, they can be utilized almost anywhere in the world for heating and cooling, and take advantage of the relatively constant ground or groundwater temperature in the range of 4°C to 30°C. [4.3.5]

4.4 Global and regional status of market and industry development

For nearly a century, geothermal resources have been used to generate electricity. In 2009, the global geothermal electric market had a wide range of participants with 10.7 GW_e of installed capacity. Over 67 TWh_e (0.24 EJ) of electricity were generated in 2008 in 24 countries (Figure TS.4.3), and provided more than 10% of total electricity demand in 6 of them. There were also 50.6 GW_{th} of direct geothermal applications operating in 78 countries, which generated 121.7 TWh_{th} (0.44 EJ) of heat in 2008. GHPs contributed 70% (35.2 GW_{th}) of this installed capacity for direct use. [4.4.1, 4.4.3]

The global average annual growth rate of installed geothermal electric capacity over the last five years (2005-2010) was 3.7%, and over the last 40 years (1970-2010), 7.0%. For geothermal direct uses rates were 12.7% (2005-2010), and 11% between 1975 and 2010. [4.4.1]

EGS is still in the demonstration phase, with one small plant in operation in France and one pilot project in Germany. In Australia considerable investment has been made in EGS exploration and development in recent years, and the USA has recently increased support for EGS research, development and demonstration as part of a revived national geothermal programme. [4.4.2]

(a)

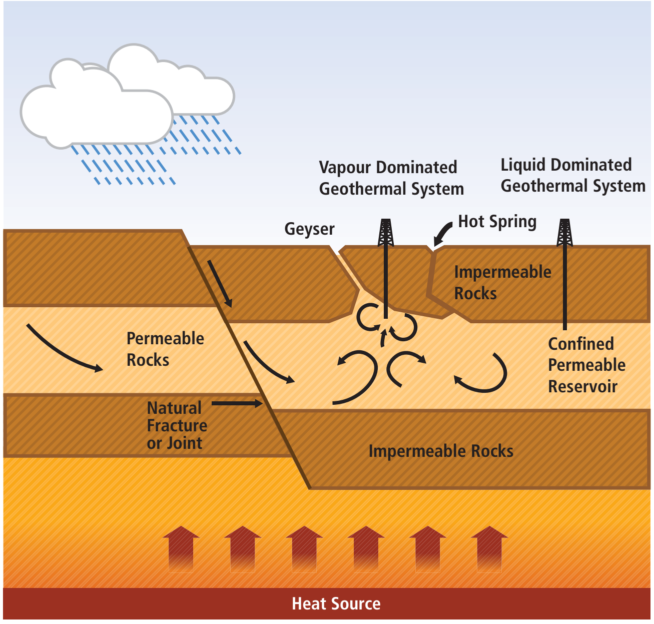


Figure TS.4.2a | Scheme showing convective (hydrothermal) resources. [Figure 4.1a]

In 2009, the main types (and relative percentages) of direct geothermal applications in annual energy use were: space heating of buildings (63%), bathing and balneology (25%), horticulture (greenhouses and soil heating) (5%), industrial process heat and agricultural drying (3%), aquaculture (fish farming) (3%) and snow melting (1%). [4.4.3]

For geothermal to reach its full capacity in climate change mitigation it is necessary to overcome technical and non-technical barriers. Policy measures specific to geothermal technology can help overcome these barriers. [4.4.4]

4.5 Environmental and social impacts

Environmental and social impacts related to geothermal energy do exist, and are typically site- and technology-specific. Usually, these impacts are manageable, and the negative environmental impacts are minor. The main GHG emission from geothermal operations is CO_2, although it is not created through combustion, but emitted from naturally occurring sources. A field survey of geothermal power plants operating in 2001 found a wide spread in the direct CO_2 emission rates, with values ranging from 4 to 740 g/kWh_e depending on technology design and composition of the geothermal fluid in the underground reservoir. Direct CO_2 emissions for direct use applications are negligible, while EGS power plants are likely to be designed as liquid-phase closed-loop circulation systems, with zero direct emissions. Lifecycle assessments anticipate that CO_2-equivalent emissions are less than 50 g/kWh_e for geothermal power plants; less than 80 g/kWh_e for projected EGS; and

(b)

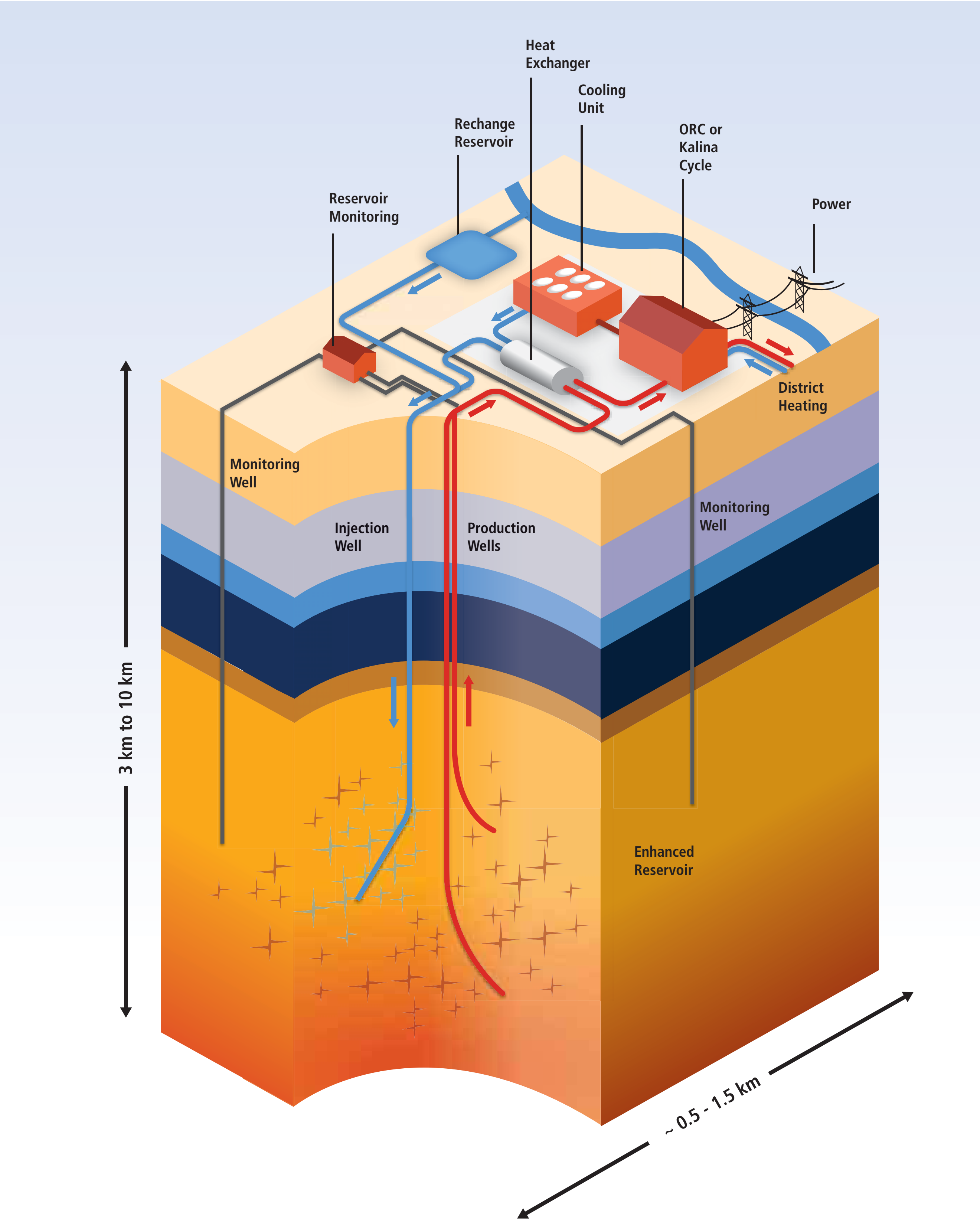


Figure TS.4.2b | Scheme showing conductive (EGS) resources. [Figure 4.1b]

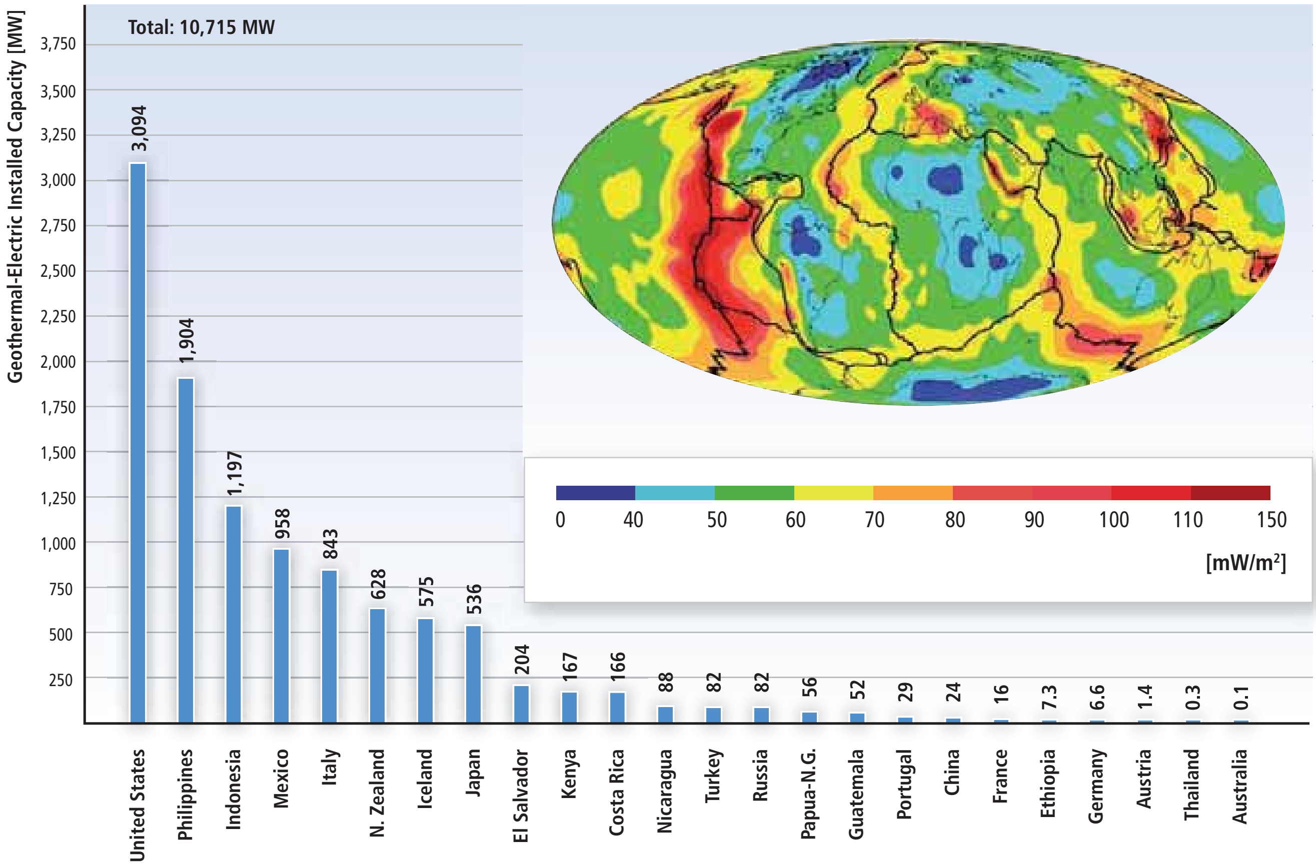


Figure TS.4.3 | Geothermal electric installed capacity by country in 2009. Figure shows worldwide average heat flow in mW/m² and tectonic plate boundaries. [Figure 4.5]

between 14 and 202 g/kWh$_{th}$ for district heating systems and GHPs. [4.5, 4.5.1, 4.5.2]

Environmental impacts associated with geothermal projects involve consideration of a range of local air, land and water use impacts during both construction and operational phases that are common to most energy projects as well as specific to geothermal energy. Geothermal systems involve natural phenomena, and typically discharge gases mixed with steam from surface features, and minerals dissolved in water from hot springs. Some gases may be dangerous, but are typically either treated or monitored during production. In the past, surface disposal of separated water was more common, but today happens only in exceptional circumstances. Geothermal brine is usually injected back into the reservoir to support reservoir pressures and to avoid adverse environmental effects. Surface disposal, if significantly in excess of natural hot-spring flow rates, and if not strongly diluted, can have adverse effects on the ecology of rivers, lakes or marine environments. [4.5.3.1]

Local hazards arising from natural phenomena, such as micro-earthquakes, hydrothermal steam eruptions and ground subsidence may be influenced by the operation of geothermal fields. During 100 years of development, no buildings or structures within a geothermal operation or local community have been significantly damaged by shallow earthquakes originating from either geothermal production or injection activities. Some EGS demonstration projects, particularly in populated areas of Europe, have raised social opposition. The process of high-pressure injection of cold water into hot rock generates small seismic events. Induced seismic events have not been large enough to lead to human injury or significant property damage, but proper management of this issue will be an important step to facilitating significant expansion of future EGS projects. [4.5.3.2]

Land use requirements range from 160 to 290 m²/GWh$_e$/yr excluding wells, and up to 900 m²/GWh/yr including wells. Specific geothermal impacts on land use include effects on outstanding natural features such as springs, geysers and fumaroles. Land use issues in many settings (e.g., Japan, the USA and New Zealand) can be a serious impediment to further expansion of geothermal development. [4.5.3.3]

Geothermal resources may also have significant environmental advantages compared to the energy use they otherwise offset. [4.5.1]

4.6 Prospects for technology improvement, innovation and integration

Geothermal resources can be integrated into all types of electrical power supply systems, from large, interconnected continental transmission grids to onsite use in small, isolated villages or autonomous buildings. Since geothermal energy typically provides base-load electric generation, integration of new power plants into existing power systems does not present a major challenge. For geothermal direct uses, no integration problems have been observed, and for heating and cooling, geothermal energy (including GHPs) is already widespread at the domestic, community and district scales. Section 8 of this summary addresses integration issues in greater depth. [4.6]

Several prospects for technology improvement and innovation can reduce the cost of producing geothermal energy and lead to higher energy recovery, longer field and plant lifetimes, and better reliability. Advanced geophysical surveys, injection optimization, scaling/corrosion inhibition, and better reservoir simulation modelling will help reduce the resource risks by better matching installed capacity to sustainable generation capacity. [4.6]

In exploration, R&D is required to locate hidden geothermal systems (e.g., with no surface manifestations) and for EGS prospects. Refinement and wider usage of rapid reconnaissance geothermal tools such as satellite- and airborne-based hyper-spectral, thermal infrared, high-resolution panchromatic and radar sensors could make exploration efforts more effective. [4.6.1]

Special research in drilling and well construction technology is needed to improve the rate of penetration when drilling hard rock and to develop advanced slim-hole technologies, with the general objectives of reducing the cost and increasing the useful life of geothermal production facilities. [4.6.1]

The efficiency of the different system components of geothermal power plants and direct uses can still be improved, and it is important to develop conversion systems that more efficiently utilize the energy in the produced geothermal fluid. Another possibility is the use of suitable oil and gas wells potentially capable of supplying geothermal energy for power generation. [4.6.2]

EGS projects are currently at a demonstration and experimental stage. EGS require innovative methods to hydraulically stimulate reservoir connectivity between injection and production wells to attain sustained, commercial production rates while reducing the risk of seismic hazard, and to improve numerical simulators and assessment methods to enable reliable predictions of chemical interaction between geo-fluids and geothermal reservoirs rocks. The possibility of using CO_2 as a working fluid in geothermal reservoirs, particularly in EGS, is also under investigation since it could provide a means for enhancing the effect of geothermal energy deployment, lowering CO_2 emissions beyond just generating electricity with a carbon-free renewable resource. [4.6.3]

Currently there are no technologies in use to tap submarine geothermal resources, but in theory electrical energy could be produced directly from a hydrothermal vent. [4.6.4]

4.7 Cost trends

Geothermal projects typically have high upfront investment costs, due to the need to drill wells and construct power plants, and relatively low operational costs. Though costs vary by project, the LCOE of power plants using hydrothermal resources are often competitive in today's electricity markets; the same is true for direct uses of geothermal heat. EGS plants remain in the demonstration phase, but estimates of EGS costs are higher than those for hydrothermal reservoirs. [4.7]

The investment costs of a typical geothermal electric project are: (a) exploration and resource confirmation (10 to 15% of the total); (b) drilling of production and injection wells (20 to 35% of the total); (c) surface facilities and infrastructure (10 to 20% of the total); and (d) power plant (40 to 81% of the total). Current investment costs vary worldwide between USD_{2005} 1,800 and 5,200/kW_e. [4.7.1]

Geothermal electric O&M costs, including make-up wells (i.e., new wells to replace failed wells and restore lost production or injection capacity), have been calculated to be USD_{2005} 152 to 187/kW_e/yr, but in some countries can be significantly lower (e.g., USD_{2005} 83 to 117/kW_e/yr in New Zealand). [4.7.2]

Power plant longevity and capacity factor are also important economic parameters. The worldwide capacity factor average in 2008 for existing geothermal power plants was 74.5%, with newer installations above 90%. [4.7.3]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for hydrothermal geothermal projects over a large set and range of input parameters has been calculated to range from US $cents_{2005}$ 3.1/kWh to US $cents_{2005}$ 17/kWh, depending on the particular type of technology and project-specific conditions. Using a narrower set and range of parameters, Figure TS.4.4 shows that, at a 7% discount rate, recently installed green-field hydrothermal projects operating at the global average capacity factor of 74.5% (and under other conditions specified in [4.7.4]) have LCOE in the range from US $cents_{2005}$ 4.9/kWh to US $cents_{2005}$ 7.2/kWh for condensing flash plants and, for binary cycle plants, from US $cents_{2005}$ 5.3/kWh to US $cents_{2005}$ 9.2/kWh. The LCOE is shown to vary substantially with capacity factor, investment cost and discount rate. No LCOE data exist for EGS, but some projections have been made using different models for several cases with diverse temperatures and depths, for example, US $cents_{2005}$ 10/kWh to US $cents_{2005}$ 17.5/kWh for relatively high-grade EGS resources. [1.3.2, 4.7.4, 10.5.1, Annex II, Annex III]

Estimates of possible cost reductions from design changes and technical advances rely solely on expert knowledge of the geothermal process

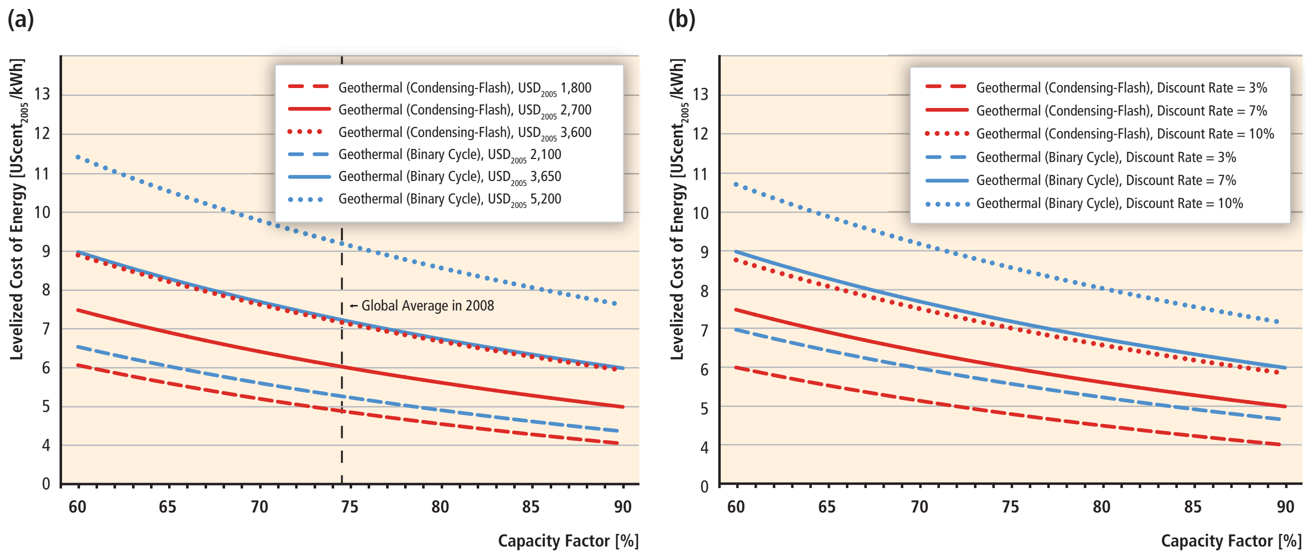


Figure TS.4.4 | Levelized cost of geothermal power, 2008: a) as a function of capacity factor and cost*,***; and b) as a function of capacity factor and discount rate**,***. [Figure 4.8]

Notes: * Discount rate assumed to equal 7%. ** Investment cost for condensing flash plants assumed at USD 2,700/kW and for binary-cycle plants at USD 3,650/kW. ***Annual O&M cost assumed to be USD 170/kW and lifetime 27.5 years.

value chain, as published learning curve studies are limited. Engineering improvements in design and stimulation of geothermal reservoirs, and improvements in materials, operation and maintenance are expected to have the greatest impact on LCOE in the near term, for example, leading to higher capacity factors and a lower contribution of drilling cost to overall investment costs. For green-field projects in 2020, the worldwide average projected LCOE is expected to range from US cents$_{2005}$ 4.5/kWh to US cents$_{2005}$ 6.6/kWh for condensing flash plants and from US cents$_{2005}$ 4.9/kWh to US cents$_{2005}$ 8.6/kWh for binary cycle plants ranges, given an average worldwide capacity factor of 80%, a 27.5-year lifetime and a discount rate of 7%. Therefore, a global average LCOE reduction of about 7% is expected for geothermal flash and binary plants by 2020. Future costs of EGS are expected to decline to lower levels as well. [4.7.5]

The LCOH for direct-use projects has a wide range, depending upon specific use, temperature and flow rate required, associated O&M and labour costs, and output of the produced product. In addition, costs for new construction are usually less than costs for retrofitting older structures. The cost figures given in Table TS.4.2 are based on a climate typical of the northern half of the USA or Europe. Heating loads would be higher for more northerly climates such as Iceland, Scandinavia and Russia. Most figures are based on cost in the USA, but would be similar in developed countries and lower in developing countries. [4.7.6]

Industrial applications are more difficult to quantify, as they vary widely depending upon the energy requirements and the product to be produced. These plants normally require higher temperatures and often compete with power plant use; however, they do have a high load factor of 0.40 to 0.70, which improves the economics. Industrial applications vary from large food, timber and mineral drying plants (USA and New Zealand) to pulp and paper plants (New Zealand). [4.7.6]

4.8 Potential deployment

Geothermal energy can contribute to near- and long-term carbon emissions reduction. In 2008, global geothermal energy use represented only about 0.1% of the global primary energy supply. However, by 2050, geothermal could meet roughly 3% of the global electricity demand and 5% of the global demand for heating and cooling. [4.8]

Taking into account the geothermal electric projects under construction or planned in the world, installed geothermal capacity is expected to reach 18.5 GW$_e$ by 2015. Practically all the new power plants expected to be on line by 2015 will be flash-condensing and binary utilizing hydrothermal resources, with a small contribution from EGS projects. Geothermal direct uses (heat applications including GHP) are expected to grow at the same historic annual rate (11% between 1975 and 2010) to reach 85.2 GW$_{th}$. By 2015, total electric generation could reach 121.6 TWh/yr (0.44 EJ/yr) while direct generation of heat could reach 224 TWh$_{th}$/yr (0.8 EJ/yr), with the regional breakdown presented in Table TS.4.3. [4.8.1]

The long-term potential deployment of geothermal energy based on a comprehensive assessment of numerous model-based scenarios is mentioned in Section 10 of this summary and spans a broad range. The scenario medians for three GHG concentration stabilization ranges, based

Table TS.4.2 | Investment costs and calculated levelized cost of heat (LCOH) for several direct geothermal applications. [Table 4.8]

Heat application	Investment cost (USD_{2005}/kW_{th})	LCOH (USD_{2005}/GJ) at discount rates of:		
		3%	7%	10%
Space heating (buildings)	1,600–3,940	20–50	24–65	28–77
Space heating (districts)	570–1,570	12–24	14–31	15–38
Greenhouses	500–1,000	7.7–13	8.6–14	9.3–16
Uncovered aquaculture ponds	50–100	8.5–11	8.6–12	8.6–12
GHP (residential and commercial)	940–3,750	14–42	17–56	19–68

Table TS.4.3 | Regional current and forecast installed capacity for geothermal power and direct uses (heat) and forecast generation of electricity and heat by 2015. [Table 4.9]

REGION[1]	Current capacity (2010)		Forecast capacity (2015)		Forecast generation (2015)	
	Direct (GW_{th})	Electric (GW_e)	Direct (GW_{th})	Electric (GW_e)	Direct (TW_{th})	Electric (TWh_e)
OECD North America	13.9	4.1	27.5	6.5	72.3	43.1
Latin America	0.8	0.5	1.1	1.1	2.9	7.2
OECD Europe	20.4	1.6	32.8	2.1	86.1	13.9
Africa	0.1	0.2	2.2	0.6	5.8	3.8
Transition Economies	1.1	0.1	1.6	0.2	4.3	1.3
Middle East	2.4	0	2.8	0	7.3	0
Developing Asia	9.2	3.2	14.0	6.1	36.7	40.4
OECD Pacific	2.8	1.2	3.3	1.8	8.7	11.9
TOTAL	**50.6**	**10.7**	**85.2**	**18.5**	**224.0**	**121.6**

Notes: 1. For regional definitions and country groupings see Annex II. Estimated average annual growth rate for 2010 to 2015 is 11.5% for power and 11% for direct uses. Average worldwide capacity factors of 75% (for electric) and 30% (for direct use) were assumed by 2015.

Table TS.4.4 | Potential geothermal deployments for electricity and direct uses in 2020 through 2050. [Table 4.10]

Year	Use	Capacity[1] (GW)	Generation (TWh/yr)	Generation (EJ/yr)	Total (EJ/yr)
2020	Electricity	25.9	181.8	0.65	2.01
	Direct	143.6	377.5	1.36	
2030	Electricity	51.0	380.0	1.37	5.23
	Direct	407.8	1,071.7	3.86	
2050	Electricity	150.0	1,182.8	4.26	11.83
	Direct	800.0	2,102.3	7.57	

Notes: 1. Installed capacities for 2020 and 2030 are extrapolated from 2015 estimates using a 7% annual growth rate for electricity and 11% for direct uses, and for 2050 are the middle value between projections cited in Chapter 4. Generation was estimated with average worldwide capacity factors of 80% (2020), 85% (2030) and 90% (2050) for electricity and of 30% for direct uses.

on the AR4 baselines (>600 ppm CO_2), 440 to 600 ppm (Categories III and IV) and <440 ppm (Categories I and II), range from 0.39 to 0.71 EJ/yr for 2020, 0.22 to 1.28 EJ/yr for 2030 and 1.16 to 3.85 EJ/yr for 2050.

Carbon policy is likely to be one of the main driving factors for future geothermal development, and under the most favourable GHG concentration stabilization policy (<440 ppm), geothermal deployment by 2020, 2030 and 2050 could be significantly higher than the median values noted above. By projecting the historic average annual growth rates of geothermal power plants (7%) and direct uses (11%) from the estimates for 2015, the installed geothermal capacity in 2020 and 2030 for electricity and direct uses could be as shown in Table TS.4.4.

By 2050, the geothermal-electric capacity would be as high as 150 GW_e (with half of that comprised of EGS plants), and up to an additional 800 GW_{th} of direct-use plants (Table TS.4.4). [4.8.2]

Even the highest estimates for the long-term contribution of geothermal energy to the global primary energy supply (52.5 EJ/yr by 2050) are within the technical potential ranges (118 to 1,109 EJ/yr for electricity and 10 to 312 EJ/yr for direct uses) and even within the upper range of hydrothermal resources (28.4 to 56.8 EJ/yr). Thus, technical potential is not likely to be a barrier to reaching more ambitious levels of geothermal deployment (electricity and direct uses), at least on a global basis. [4.8.2]

Evidence suggests that geothermal supply could meet the upper range of projections derived from a review of about 120 energy and GHG-reduction scenarios. With its natural thermal storage capacity, geothermal is especially suitable for supplying base-load power. Considering its technical potential and possible deployment, geothermal energy could meet roughly 3% of global electricity demand by 2050, and also has the potential to provide roughly 5% of the global demand for heating and cooling by 2050. [4.8.3]

5. Hydropower

5.1 Introduction

Hydropower is a renewable energy source where power is derived from the energy of water moving from higher to lower elevations. It is a proven, mature, predictable and cost-competitive technology. The mechanical power of falling water is an old tool used for various services from the time of the Greeks more than 2,000 years ago. The world's first hydroelectric station of 12.5 kW was commissioned on 30 September 1882 on Fox River at the Vulcan Street Plant in Appleton, Wisconsin, USA. Though the primary role of hydropower in global energy supply today is in providing centralized electricity generation, hydropower plants also operate in isolation and supply independent systems, often in rural and remote areas of the world. [5.1]

5.2 Resource potential

The annual global technical potential for hydropower generation is 14,576 TWh (52.47 EJ) with a corresponding estimated total capacity potential of 3,721 GW—four times the currently installed global hydropower capacity (Figure TS.5.1). Undeveloped capacity ranges from about 47% in Europe to 92% in Africa, indicating large and well-distributed opportunities for hydropower development worldwide (see Table TS.5.1). Asia and Latin America have the largest technical potentials and the largest undeveloped resources. Africa has highest portion of total potential that is still undeveloped. [5.2.1]

It is noteworthy that the total installed capacities of hydropower in North America, Latin America, Europe and Asia are of the same order of magnitude and, in Africa and Australasia/Oceania, an order of magnitude less; Africa due to underdevelopment and Australasia/Oceania because of size, climate and topography. The global average capacity factor for hydropower plants is 44%. Capacity factor can be indicative of how hydropower is employed in the energy mix (e.g., peaking versus base-load generation) or water availability, or can be an opportunity for increased generation through equipment upgrades and operational optimization. [5.2.1]

The resource potential for hydropower could change due to climate change. Based on a limited number of studies to date, the climate change impacts on existing global hydropower systems is expected to be slightly positive, even though individual countries and regions could have significant positive or negative changes in precipitation and runoff. Annual power production capacity in 2050 could increase by 2.7 TWh (9.72 PJ) in Asia under the SRES A1B scenario, and decrease by 0.8 TWh (2.88 PJ) in Europe. In other regions, changes are found to be even smaller. Globally, the changes caused by climate change in the existing hydropower production system are estimated to be less than 0.1%, although additional research is needed to lower the uncertainty of these projections. [5.2.2]

5.3 Technology and applications

Hydropower projects are usually designed to suit particular needs and specific site conditions, and are classified by project type, head (i.e., the vertical height of water above the turbine) or purpose (single- or multi-purpose). Size categories (installed capacity) are based on national definitions and differ worldwide due to varying policies. There is no immediate, direct link between installed capacity as a classification criterion and general properties common to all hydropower plants (HPPs) above or below that MW limit. All in all, classification according to size, while both common and administratively simple, is—to a degree—arbitrary: general concepts like 'small' or 'large' hydropower are not technically or scientifically rigorous indicators of impacts, economics or characteristics. It may be more useful to evaluate a hydropower project on its sustainability or economic performance thus setting out more realistic indicators. The cumulative relative environmental and social impacts of large versus small hydropower development remain unclear and context dependent. [5.3.1]

Hydropower plants come in three main project types: run-of-river (RoR), storage and pumped storage. RoR HPPs have small intake basins with no storage capacity. Power production therefore follows the hydrological cycle of the watershed. For RoR HPPs the generation varies as water availability changes and thus they may be operated as variable in small streams or as base-load power plants in large rivers. Large-scale RoR HPPs may have some limited ability to regulate water flow, and if they operate in cascades in unison with storage hydropower in upstream reaches, they may contribute to the overall regulating and balancing ability of a fleet of HPPs. A fourth category, in-stream (hydrokinetic) technology, is less mature and functions like RoR without any regulation. [5.3.2]

Hydropower projects with a reservoir (storage hydropower) deliver a broad range of energy services such as base load, peak, and energy storage, and act as a regulator for other sources. In addition they often deliver services that go beyond the energy sector, including flood control, water supply, navigation, tourism and irrigation. Pumped storage plants store water as a source for electricity generation. By reversing the

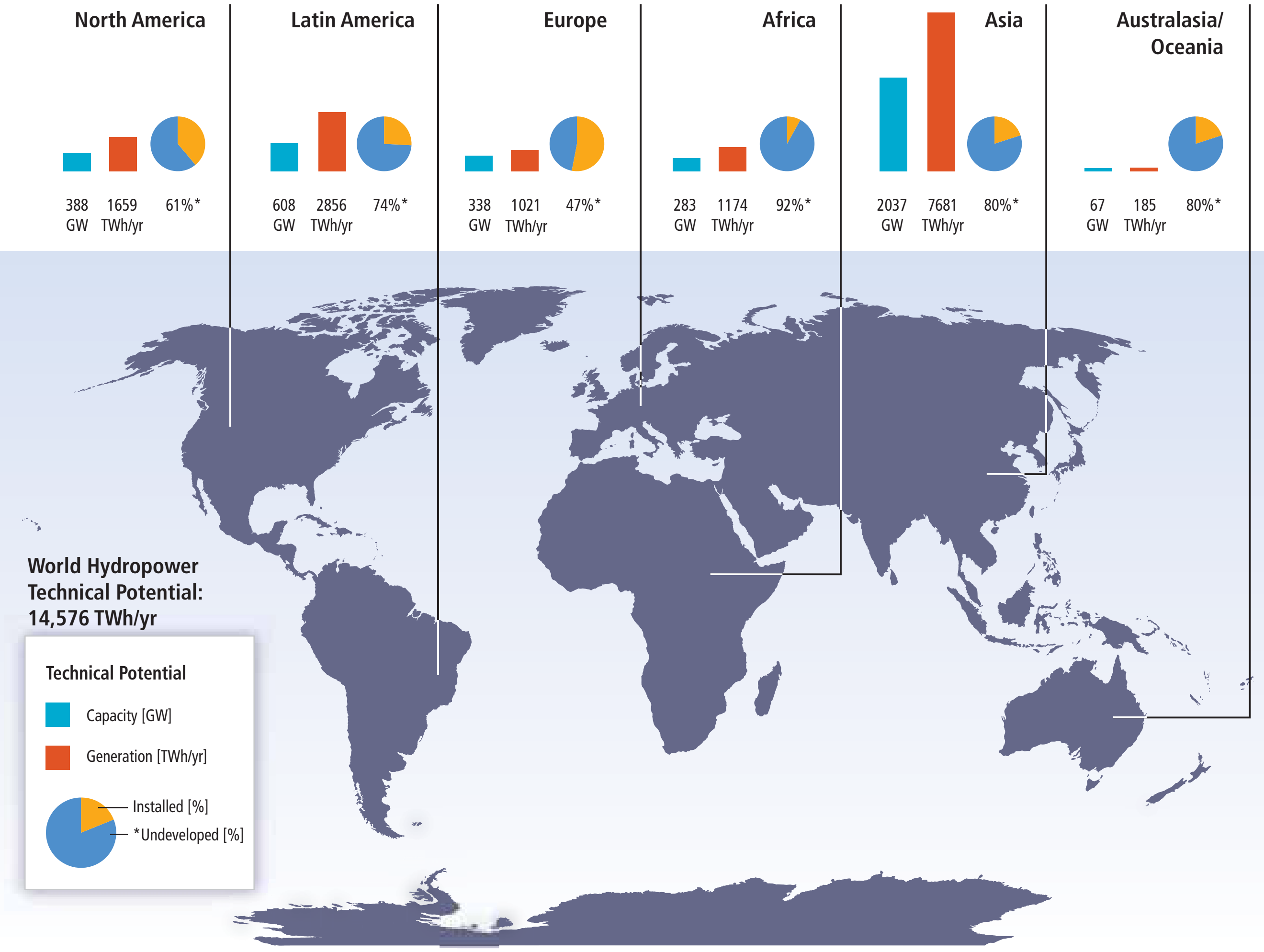


Figure TS.5.1 | Regional hydropower technical potential in terms of annual generation and installed capacity and the percentage of undeveloped technical potential in 2009. [Figure 5.2]

Table TS.5.1 | Regional hydro power technical potential in terms of annual generation and installed capacity (GW); and current generation, installed capacity, average capacity factors and resulting undeveloped potential as of 2009. [Table 5.1]

World region	Technical potential, annual generation TWh/yr (EJ/yr)	Technical potential, installed capacity (GW)	2009 Total generation TWh/yr (EJ/yr)	2009 Installed capacity (GW)	Undeveloped potential (%)	Average regional capacity factor (%)
North America	1,659 (5.971)	388	628 (2.261)	153	61	47
Latin America	2,856 (10.283)	608	732 (2.635)	156	74	54
Europe	1,021 (3.675)	338	542 (1.951)	179	47	35
Africa	1,174 (4.226)	283	98 (0.351)	23	92	47
Asia	7,681 (27.651)	2,037	1,514 (5.451)	402	80	43
Australasia/Oceania	185 (0.666)	67	37 (0.134)	13	80	32
World	**14,576 (52.470)**	**3,721**	**3,551 (12.783)**	**926**	**75**	**44**

flow of water, electrical energy can be produced on demand, with a very fast response time. Pumped storage is the largest-capacity form of grid energy storage now available. [5.3.2.2–5.3.2.3]

Sediment transport and reservoir sedimentation are problems that need to be understood as they have a number of negative effects on HPP performance: depletion of reservoir storage capacity over time; an increase in downstream degradation; increased flood risk upstream of reservoirs; generation losses due to reductions in turbine efficiency; increased frequency of repair and maintenance; and reductions in turbine lifetime and in regularity of power generation. The sedimentation problem may ultimately be controlled through land use policies and the protection of vegetation coverage. Hydropower has the best conversion efficiency of all known energy sources (about 90% efficiency, water to wire) and a very high energy payback ratio. [5.3.3]

Normally the life of a hydroelectric power plant is 40 to 80 years. Electrical and mechanical components and control equipment wear out early compared to civil structures, typically in 30 to 40 years, after which they require renovation. Upgrading/up-rating of HPPs calls for a systematic approach as there are a number of factors (hydraulic, mechanical, electrical and economic) that play a vital role in deciding the course of action. From a techno-economic viewpoint, up-rating should be considered along with renovation and modernization measures. Hydropower generating equipment with improved performance can be retrofitted, often to accommodate market demands for more flexible, peaking modes of operation. Most of the 926 GW of hydropower equipment in operation today (2010) will need to be modernized by 2030 to 2040. Refurbishment of existing hydropower plants often results in enhanced hydropower capacity, both where turbine capacity is being renovated/up-rated or where existing civil infrastructure (like barrages, weirs, dams, canal tunnels, etc.) is being reworked to add new hydropower facilities. [5.3.4]

5.4 Global and regional status of market and industry development

Hydropower is a mature, predictable and price-competitive technology. It currently provides approximately 16% of the world's total electricity production and 86% of all electricity from renewable sources. While hydropower contributes to some level of power generation in 159 countries, 5 countries make up more than half of the world's hydropower production: China, Canada, Brazil, the USA and Russia. The importance of hydroelectricity in the electricity matrix of these countries differs widely, however. While Brazil and Canada are heavily dependent on hydropower to produce 84% and 59% of total generation, respectively, Russia and China produce only 19% and 16% of their total electricity from hydropower, respectively. Despite the significant growth of hydroelectric production around the globe, the percentage share of hydroelectricity has dropped during the last three decades (1973 to 2008) from 21 to 16%, because electricity load and other generation sources have grown more rapidly than has hydropower. [5.4.1]

Carbon credits benefit hydropower projects by helping to secure financing and to reduce risks. Financing is the most decisive step in the entire project development process. Hydropower projects are one of the largest contributors to the flexible mechanisms of the Kyoto Protocol and therefore to existing carbon credit markets. Out of the 2,062 projects registered by the Clean Development Mechanism (CDM) Executive Board by 1 March 2010, 562 are hydropower projects. With 27% of the total number of projects, hydropower is the CDM's leading deployed RE source. China, India, Brazil and Mexico represent roughly 75% of the hosted projects. [5.4.3.1]

Many economical hydropower projects are financially challenged. High up-front costs are a deterrent for investment. Also, hydropower tends to have lengthy lead times for planning, permitting and construction. In the evaluation of lifecycle costs, hydropower often has a very high performance, with annual O&M costs being a fraction of the capital investment. As hydropower and its industry are old and mature, it is expected that the hydropower industry will be able to meet the demand that will be created by the predicted deployment rate in the years to come. For example, in 2008 the hydropower industry managed to install more than 41 GW of new capacity worldwide. [5.4.3.2]

The development of more appropriate financing models is a major challenge for the hydropower sector, as is finding the optimum roles for the public and private sectors. The main challenges for hydropower relate to creating private-sector confidence and reducing risk, especially prior to project permitting. Green markets and trading in emissions reductions will undoubtedly provide incentives. Also, in developing regions, such as Africa, interconnection between countries and the formation of power pools is building investor confidence in these emerging markets. [5.4.3.2]

The concepts of classifying HPPs as 'small' or 'large', as defined by installed capacity (MW), can act as a barrier to the development of hydropower. For example, these classifications can impact the financing of new hydropower plants, determining how hydropower is treated in climate change and energy policies. Different incentives are used for small-scale hydropower (FITs, green certificates and bonuses) depending on the country, but no incentives are available for large-scale HPPs. The EU Linking Directive sets a limit for carbon credits issued from HPPs to 20 MW. The same limit is found in the UK Renewables Obligation, a green certificate market-based mechanism. Likewise, in several countries FITs do not apply to hydropower above a certain size limit (e.g., France 12 MW, Germany 5 MW, India 5 and 25 MW). [5.4.3.4]

The UNFCCC CDM Executive Board has decided that storage hydropower projects will have to follow the power density indicator (PDI: installed capacity/reservoir area in W/m^2) to be eligible for CDM credits. The PDI rule seems to presently exclude storage hydropower from qualifying for CDM (or Joint Implementation) credits and may lead to suboptimal development of hydropower resources as the non-storage RoR option will be favoured.

5.5 Integration into broader energy systems

Hydropower's large capacity range, its flexibility, storage capability (when coupled with a reservoir), and ability to operate in a stand-alone mode or in grids of all sizes enables it to deliver a broad range of services. [5.5]

Hydropower can be delivered through the national and regional electric grid, mini-grids and also in isolated mode. Realization has been growing in developing countries that small-scale hydropower schemes have an important role to play in the socioeconomic development of remote rural, especially hilly, areas as those can provide power for industrial, agricultural and domestic uses. In China, small-scale HPPs have been one of the most successful examples of rural electrification, where over 45,000 small HPPs totalling over 55,000 MW of capacity and producing 160 TWh (576 PJ) of generation annually benefit over 300 million people. [5.5.2]

With a very large reservoir relative to the size of the hydropower plant (or very consistent river flows), HPPs can generate power at a near-constant level throughout the year (i.e., operate as a base-load plant). Alternatively, in the case that the hydropower capacity far exceeds the amount of reservoir storage, the hydropower plant is sometimes referred to as energy-limited. An energy-limited hydro plant would exhaust its 'fuel supply' by consistently operating at its rated capacity throughout the year. In this case, the use of reservoir storage allows hydropower generation to occur at times that are most valuable from the perspective of the power system rather than at times dictated solely by river flows. Since electrical demand varies during the day and night, during the week and seasonally, storage hydropower generation can be timed to coincide with times where the power system needs are the greatest. In part, these times will occur during periods of peak electrical demand. Operating hydropower plants in a way to generate power during times of high demand is referred to as peaking operation (in contrast to base-load). Even with storage, however, hydropower generation will still be limited by the size of the storage, the rated electrical capacity of the hydropower plant, and downstream flow constraints for irrigation, recreation or environmental uses of the river flows. Hydropower peaking may, if the outlet is directed to a river, lead to rapid fluctuations in river flow, water-covered area, depth and velocity. In turn this may, depending on local conditions, lead to negative impacts in the river unless properly managed. [5.5.3]

In addition to hydropower supporting fossil and nuclear generation technologies, it can also help reduce the challenges with integrating variable renewable resources. In Denmark, for example, the high level of variable wind energy (>20% of the annual energy demand) is managed in part through strong interconnections (1 GW) to Norway, which has substantial storage hydropower. More interconnectors to Europe may further support increasing the share of wind power in Denmark and Germany. Increasing variable generation will also increase the amount of balancing services, including regulation and load following, required by the power system. In regions with new and existing hydropower facilities, providing these services from hydropower may avoid the need to rely on increased part-load and cycling of conventional thermal plants to provide these services. [5.5.4]

Though hydro has the potential to offer significant power system services in addition to energy and capacity, interconnecting and reliably utilizing HPPs may also require changes to power systems. The interconnection of hydropower to the power system requires adequate transmission capacity from HPPs to demand centres. Adding new HPPs has in the past required network investments to extend the transmission network. Without adequate transmission capacity, HPP operation can be constrained such that the services offered by the plant are less than what it could offer in an unconstrained system. [5.5.5]

5.6 Environmental and social impacts

Like all energy and water management options, hydropower projects have negative and positive environmental and social impacts. On the environmental side, hydropower may have a significant environmental footprint at local and regional levels but offers advantages at the macro-ecological level. With respect to social impacts, hydropower projects may entail the relocation of communities living within or nearby the reservoir or the construction sites, compensation for downstream communities, public health issues, and others. A properly designed hydropower project may, however, be a driving force for socioeconomic development, though a critical question remains about how these benefits are shared. [5.6]

All hydroelectric structures affect a river's ecology, mainly by inducing a change into its hydrologic characteristics and by disrupting the ecological continuity of sediment transport and fish migration through the building of dams, dikes and weirs. However, the extent to which a river's physical, chemical, biological and ecosystem characteristics are modified depends largely on the type of HPP. Whereas RoR hydropower projects do not alter a river's flow regime, the creation of a reservoir for storage hydropower entails a major environmental change by transforming a fast-running river ecosystem into a still-standing artificial lake. [5.6.1.1–5.6.1.6]

Similar to a hydropower project's ecological effects, the extent of its social impacts on the local and regional communities, land use, economy, health and safety or heritage varies according to project type and site-specific conditions. While RoR projects generally introduce little social change, the creation of a reservoir in a densely populated area can entail significant challenges related to resettlement and impacts on the livelihoods of the downstream populations. Restoration and improvement of living standards of affected communities is a long-term and challenging task that has been managed with variable success in the past. Whether HPPs can contribute to fostering socioeconomic development depends largely on how the generated services and revenues are shared and distributed among different stakeholders. HPPs can also have positive impacts on the living conditions of local communities and the regional economy, not only by generating electricity but also by facilitating through the creation of freshwater storage schemes multiple other water-dependent activities, such as irrigation, navigation, tourism, fisheries or sufficient water supply to municipalities and industries while protecting against floods and droughts. [5.6.1.7–5.6.1.11]

The assessment and management of environmental and social impacts associated with, especially, larger HPPs represent a key challenge for hydropower development. Emphasizing transparency and an open, participatory decision-making process, the stakeholder consultation approach is driving both present-day and future hydropower projects towards increasingly more environmentally friendly and sustainable solutions. In many countries, a national legal and regulatory framework has been put in place to determine how hydropower projects shall be developed and operated, while numerous multilateral financing agencies have developed their own guidelines and requirements to assess the economic, social and environmental performance of hydropower projects. [5.6.2]

One of hydropower's main environmental advantages is that it creates no atmospheric pollutants or waste associated with fuel combustion. However, all freshwater systems, whether they are natural or man-made, emit GHGs (e.g., CO_2, methane) due to decomposing organic material. Lifecycle assessments (LCAs) carried out on hydropower projects have so far demonstrated the difficulty of generalizing estimates of lifecycle GHG emissions for hydropower projects in all climatic conditions, pre-impoundment land cover types, ages, hydropower technologies, and other project-specific circumstances. The multipurpose nature of most hydropower projects makes allocation of total impacts to the several purposes challenging. Many LCAs to date allocate all impacts of hydropower projects to the electricity generation function, which in some cases may overstate the emissions for which they are 'responsible'. LCAs (Figure TS.5.2) that evaluate GHG emissions of HPPs during construction, operation and maintenance, and dismantling, show that the majority of lifecycle GHG emission estimates for hydropower cluster between about 4 and 14 g CO_2eq/kWh, but under certain scenarios there is potential to emit much larger quantities of GHGs, as shown by the outliers. [5.6.3.1]

While some natural water bodies and freshwater reservoirs may even absorb more GHGs than they emit, there is a definite need to properly assess the net change in GHG emissions induced by the creation of such reservoirs. All LCAs included in these assessments evaluated only gross GHG emissions from reservoirs. Whether reservoirs are net emitters of GHGs, considering emissions that would have occurred without the reservoir, is an area of active research. When considering net anthropogenic emissions as the difference in the overall carbon cycle between the situations with and without the reservoir, there is currently no consensus on whether reservoirs are net emitters or net sinks. Presently two international processes are investigating this issue: the UN Educational, Scientific and Cultural Organization/International Hydrological Programme research project and the IEA Hydropower Agreement Annex XII. [5.6.3.2]

5.7 Prospects for technology improvement and innovation

Though hydropower is a proven and well-advanced technology, there is still room for further improvement, for example, by optimizing operations, mitigating or reducing environmental impacts, adapting to new social and environmental requirements and implementing more robust and cost-effective technological solutions. Large hydropower turbines are now close to the theoretical limit for efficiency, with up to 96% efficiency when operated at the best efficiency point, but this is not always possible and continued research is needed to make more efficient operation possible over a broader range of flows. Older turbines can have lower efficiency by design or reduced efficiency due to corrosion and cavitation. There is therefore the potential to increase energy output by retrofitting with new higher efficiency equipment and usually also with increased capacity. Most of the existing electrical and mechanical equipment in operation today will need to be modernized during the next three decades, allowing for improved efficiency and higher power and energy output. Typically, generating equipment can be upgraded or replaced with more technologically advanced electro-mechanical equipment two or three times during the lifetime of the project, making more effective use of the same flow of water. [5.7]

There is much ongoing technology innovation and material research aiming to extend the operational range in terms of head and discharge, and also to improve environmental performance, reliability and reduce costs. Some of the promising technologies under development are variable-speed and matrix technologies, fish-friendly turbines, hydrokinetic turbines, abrasive-resistant turbines, and new tunnelling and dam technologies. New technologies aiming at utilizing low (<15 m) or very low (<5 m) head may open up many sites for hydropower that have not been within reach of conventional technology. As most of the data available on hydropower potential are based on field work produced several decades ago, when low-head hydropower was not a high priority, existing data on low-head hydropower potential may not be complete. Finally, there is a significant potential for improving operation of HPPs by utilizing new methods for optimizing plant operation. [5.7.1–5.7.8]

5.8 Cost trends

Hydropower is often economically competitive with current market energy prices, though the cost of developing, deploying and operating new hydropower projects will vary from project to project. Hydropower projects often require a high initial investment, but have the advantage of very low O&M costs and a long lifespan. [5.8]

Investment costs for hydropower include costs of planning; licensing; plant construction; impact reductions for fish and wildlife, recreational, historical and archaeological sites; and water quality monitoring. Overall, there are two major cost groups: the civil construction costs, which normally are the greatest costs of the hydropower project; and electromechanical equipment costs. The civil construction costs follow the price trends in the country where the project is going to be developed. In the case of countries with economies in transition, the costs are likely to be relatively low due to the use of local labour and local materials. The costs of electromechanical equipment follow the tendency of prices at a global level. [5.8.1]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for hydropower projects over a large set and range of input parameters has been

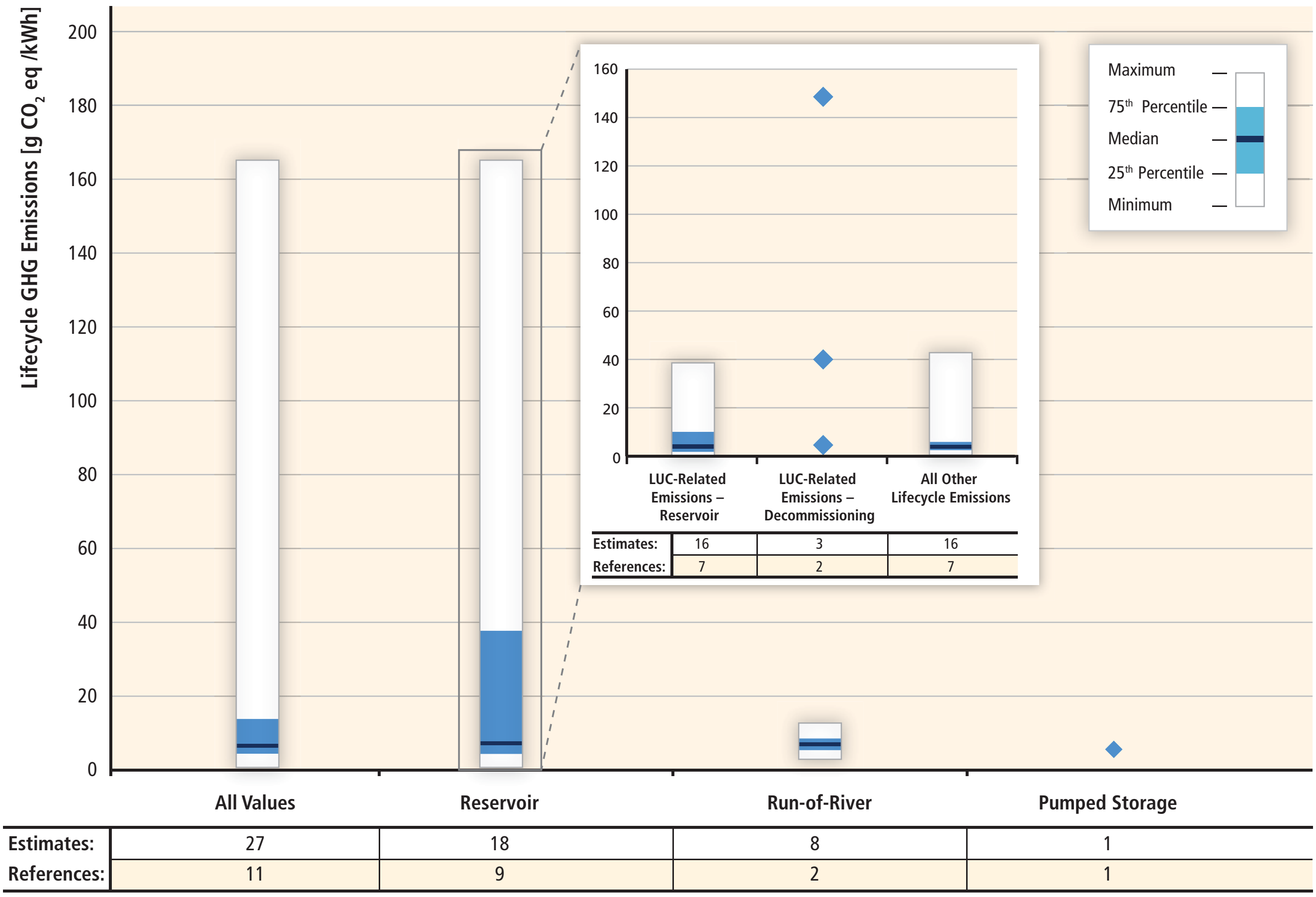


Figure TS.5.2 | Life-cycle GHG emissions of hydropower technologies (unmodified literature values, after quality screen). See Annex I for details of literature search and citations of literature contributing to the estimates displayed. Surface emissions from reservoirs are referred to as gross GHG emissions. [Figure 5.15]

calculated to range from as low as US $cent_{2005}$ 1.1/kWh to US $cent_{2005}$ 15/kWh, depending on site-specific parameters for investment costs of each project and on assumptions regarding the discount rate, capacity factor, lifetime and O&M costs. [1.3.2, 5.8, 10.5.1, Annex II, Annex III]

Figure TS.5.3 presents the LCOE for hydropower projects over a somewhat different and more typical set and range of parameters consistent with the majority of hydropower projects, and does so as a function of capacity factor while applying different investment costs and discount rates.

Capacity factors will be determined by hydrological conditions, installed capacity and plant design, and the way the plant is operated. For power plant designs intended for maximum energy production (base-load) and/or with some regulation, capacity factors will often be from 30 to 60%, with average capacity factors for different world regions shown in the graph. For peaking-type power plants, the capacity factor can be even lower, whereas capacity factors for RoR systems vary across a wide range (20 to 95%) depending on the geographical and climatological conditions, technology, and operational characteristics. For an average capacity factor of 44% and investment costs between USD_{2005} 1,000/kW and USD_{2005} 3,000/kW, the LCOE ranges from US $cent_{2005}$ 2.5/kWh to US $cent_{2005}$ 7.5/kWh.

Most of the projects developed in the near-term future (up to 2020) are expected to have investment costs and LCOE in this range, though projects with both lower and higher costs are possible. Under good conditions, the LCOE of hydropower can be in the range of US $cent_{2005}$ 3/kWh to US $cent_{2005}$ 5/kWh. [5.8.3, 8.2.1.2, Annex III]

There is relatively little information on historical trends in hydropower costs in the literature. One reason for this—besides the fact that project costs are highly site-specific—may be the complex cost structure for hydropower plants, where some components may have decreasing cost trends (e.g., tunnelling costs), while others may have increasing cost trends (e.g., social and environmental mitigation costs). [5.8.4]

One complicating factor when considering the cost of hydropower is that, for multipurpose reservoirs, there is a need to share or allocate the cost of serving other water uses like irrigation, flood control, navigation, roads, drinking water supply, fish, and recreation. There are

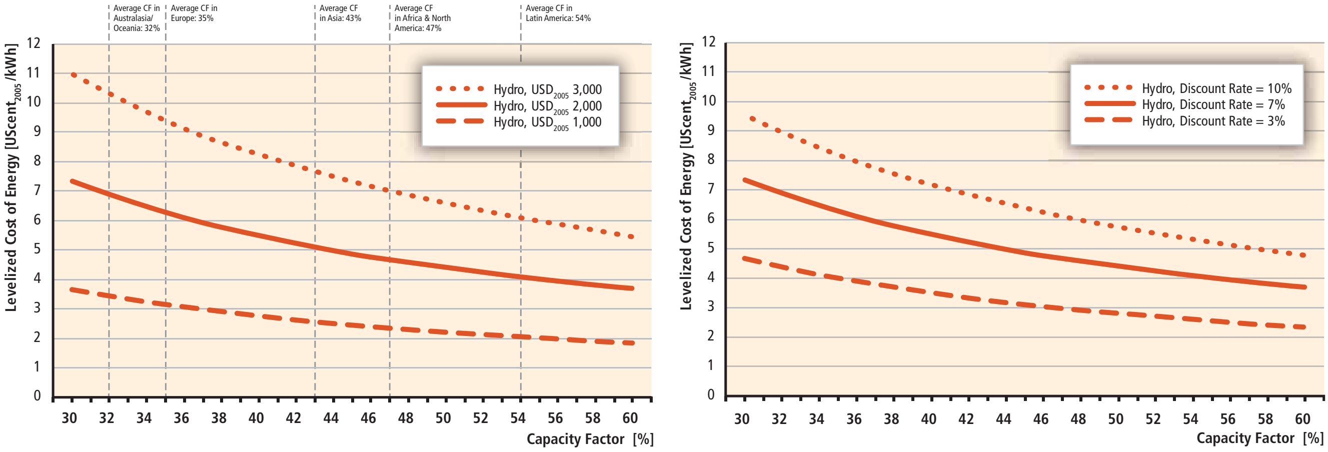


Figure TS.5.3 | Recent and near-term estimated levelized cost of hydropower (a) as a function of capacity factor and investment cost*, ***; and (b) as a function of capacity factor and discount rate**,***. [Figure 5.20]

Notes: * Discount rate is assumed to equal 7%. ** Investment cost is assumed to be USD 2,000/kW. *** Annual O&M cost is assumed at 2.5%/yr of investment cost and plant lifetime as 60 years.

different methods of allocating the cost to individual purposes, each of which has advantages and drawbacks. The basic rules are that the allocated cost to any purpose does not exceed that benefit of that purpose and each purpose will be carried out at its separable cost. Separable cost for any purpose is obtained by subtracting the cost of a multipurpose project without that purpose from the total cost of the project with the purpose included. Merging economic elements (energy and water selling prices) with social benefits (supplying water to farmers in case of lack of water) and the value of the environment (to preserve a minimum environmental flow) is becoming a tool for consideration of cost sharing for multipurpose reservoirs. [5.8.5]

5.9 Potential deployment

Hydropower offers a significant potential for near- and long-term carbon emissions reduction. On a global basis, the hydropower resource is unlikely to constrain further development in the near to medium term, though environmental and social concerns may limit deployment opportunities if not carefully managed. [5.9]

So far, only 25% of the hydropower potential has been developed across the world (that is, 3,551 TWh out of 14,575 TWh) (12.78 EJ out of 52.47 EJ). The different long-term prospective scenarios propose a continuous increase for the next decades. The increase in hydropower capacity over the last 10 years is expected by several studies to continue in the near to medium term: from 926 GW in 2009 to between 1,047 and 1,119 GW by 2015; an annual addition ranging from 14 to 25 GW. [5.9, 5.9.1]

The reference-case projections presented in Chapter 10 (based on 164 analyzed longer-term scenarios) show hydropower's role in the global energy supply covering a broad range, with a median of roughly 13 EJ (3,600 TWh) in 2020, 16 EJ (4,450 TWh) in 2030 and 19 EJ (5,300 TWh) in 2050. 12.78 EJ was reached already in 2009 and thus the average estimate of 13 EJ for 2020 has probably been exceeded today. Also, some scenario results provide lower values than the current installed capacity for 2020, 2030 and 2050, which is counterintuitive given, for example, hydropower's long lifetimes, its significant market potential and other important services. These results could maybe be explained by model/scenario weaknesses (see discussions in Section 10.2.1.2 of this report). Growth of hydropower is therefore projected to occur even in the absence of GHG mitigation policies, even with hydropower's median contribution to global electricity supply dropping from about 16% today to less than 10% by 2050. As GHG mitigation policies are assumed to become more stringent in the alternative scenarios, the contribution of hydropower grows: by 2030, hydropower's median contribution equals roughly 16.5 EJ (4,600 TWh) in the 440 to 600 and <440 ppm CO_2 stabilization ranges (compared to the median of 15 EJ in the baseline cases), increasing to about 19 EJ by 2050 (compared to the median of 18 EJ in the baseline cases). [5.9.2]

Regional projections of hydropower generation in 2035 show a 98% increase in the Asia Pacific region compared to 2008 levels and a 104% increase in Africa. Brazil is the main driving force behind the projected 46% increase in hydropower generation in the South and Central America region over the same time period. North America and Europe/Eurasia expect more modest increases of 13 and 27%, respectively, over the period. [5.9.2]

Overall, evidence suggests that relatively high levels of deployment in the next 20 years are feasible. Even if hydropower's share in global electricity supply decreases by 2050, hydropower would remain an attractive RE source within the context of global carbon mitigation scenarios. Furthermore, increased development of storage hydropower may enable investment into water management infrastructure, which is needed in response to growing problems related to water resources. [5.9.3]

5.10 Integration into water management systems

Water, energy and climate change are inextricably linked. Water availability is crucial for many energy technologies, including hydropower, while energy is needed to secure water supply for agriculture, industries and households, in particular in water-scarce areas in developing countries. This close relationship has led to the understanding that the water-energy nexus must be addressed in a holistic way, in particular with regard to climate change and sustainable development. Providing energy and water for sustainable development may require improved regional and global water governance. As it is often associated with the creation of water storage facilities, hydropower is at the crossroads of these issues and can play an important role in enhancing both energy and water security. [5.10]

Today, about 700 million people live in countries experiencing water stress or scarcity. By 2035, it is projected that three billion people will be living in conditions of severe water stress. Many countries with limited water availability depend on shared water resources, increasing the risk of conflict over these scarce resources. Therefore, adaptation to climate change impacts will become very important in water management. [5.10.1]

In a context where multipurpose hydropower can be a tool to mitigate both climate change and water scarcity, these projects may have an enabling role beyond the electricity sector as a financing instrument for reservoirs, helping to secure freshwater availability. However, multiple uses may increase the potential for conflicts and reduce energy production during times of low water levels. As major watersheds are shared by several nations, regional and international cooperation is crucial. Both intergovernmental agreements and initiatives by international institutions are actively supporting these important processes. [5.10.2, 5.10.3]

6. Ocean Energy

6.1 Introduction

Ocean energy offers the potential for long-term carbon emissions reduction but is unlikely to make a significant short-term contribution before 2020 due to its nascent stage of development. The theoretical potential of 7,400 EJ/yr contained in the world's oceans easily exceeds present human energy requirements. Government policies are contributing to accelerate the deployment of ocean energy technologies, heightening expectations that rapid progress may be possible. The six main classes of ocean energy technology offer a diversity of potential development pathways, and most offer potentially low environmental impacts as currently understood. There are encouraging signs that the investment cost of ocean energy technologies and the levelized cost of electricity generated will decline from their present non-competitive levels as R&D and demonstrations proceed, and as deployment occurs. Whether these cost reductions are sufficient to enable broad-scale deployment of ocean energy is the most critical uncertainty in assessing the future role of ocean energy in mitigating climate change. [6 ES, 6.1]

6.2 Resource potential

Ocean energy can be defined as energy derived from technologies that utilize seawater as their motive power or harness the water's chemical or heat potential. The RE resource in the ocean comes from six distinct sources, each with different origins and each requiring different technologies for conversion. These sources are:

Wave energy derived from the transfer of the kinetic energy of the wind to the upper surface of the ocean. The total theoretical wave energy resource is 32,000 TWh/yr (115 EJ/yr), but the technical potential is likely to be substantially less and will depend on development of wave energy technologies. [6.2.1]

Tidal range (tidal rise and fall) derived from gravitational forces of the Earth-Moon-Sun system. The world's theoretical tidal power potential is in the range of 1 to 3 TW, located in relatively shallow waters. Again, technical potential is likely to be significantly less than theoretical potential. [6.2.2]

Tidal currents derived from water flow that results from the filling and emptying of coastal regions associated with tides. Current regional estimates of tidal current technical potential include 48 TWh/yr (0.17 EJ) for Europe and 30 TWh/yr (0.11 EJ/yr) for China. Commercially attractive sites have also been identified in the Republic of Korea, Canada, Japan, the Philippines, New Zealand and South America. [6.2.3]

Ocean currents derived from wind-driven and thermohaline ocean circulation. The best-characterized system of ocean currents is the Gulf Stream in North America, where the Florida Current has a technical potential for 25 GW of electricity capacity. Other regions with potentially promising ocean circulation include the Agulhas/Mozambique Currents off South Africa, the Kuroshio Current off East Asia and the East Australian Current. [6.2.4]

Ocean thermal energy conversion (OTEC) derived from temperature differences arising from solar energy stored as heat in upper ocean layers and colder seawater, generally below 1,000 m. Although the energy density of OTEC is relatively low, the overall resource potential is much larger than for other forms of ocean energy. One 2007 study estimates that about 44,000 TWh/yr (159 EJ/yr) of steady-state power may be possible. [6.2.5]

Salinity gradients (osmotic power) derived from salinity differences between fresh and ocean water at river mouths. The theoretical potential of salinity gradients is estimated at 1,650 TWh/yr (6 EJ/yr). [6.2.6]

Figure TS.6.1 provides examples of how selected ocean energy resources are distributed across the globe. Some ocean energy resources, such as ocean currents or power from salinity gradients, are globally distributed. Ocean thermal energy is principally located in the Tropics around the equatorial latitudes (latitudes 0° to 35°), whilst the highest annual wave power occurs between latitudes of 30° to 60°. Wave power in the southern hemisphere undergoes smaller seasonal variation than in the northern hemisphere. Ocean currents, ocean thermal energy, salinity gradients and, to some extent, wave energy are consistent enough to generate base-load power. Given the early state of the available literature and the substantial uncertainty in ocean energy's technical potential, the estimates for technical ocean energy potential vary widely. [6.2.1–6.2.6]

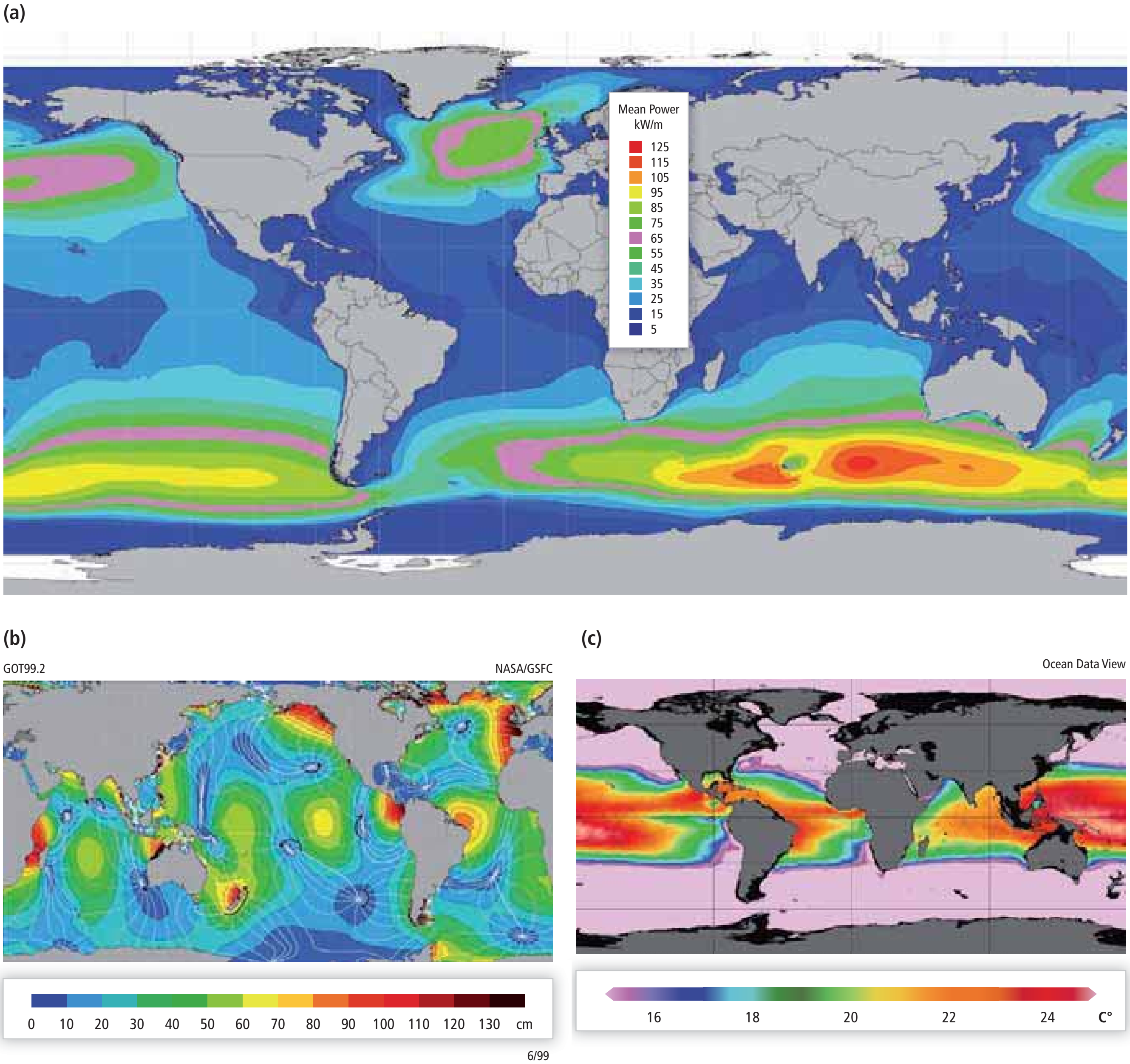


Figure TS.6.1a-c | Global distribution of various ocean energy resources: (a) Wave power; (b) Tidal range, (c) Ocean thermal energy. [Figures 6.1, 6.2, 6.4]

(d)

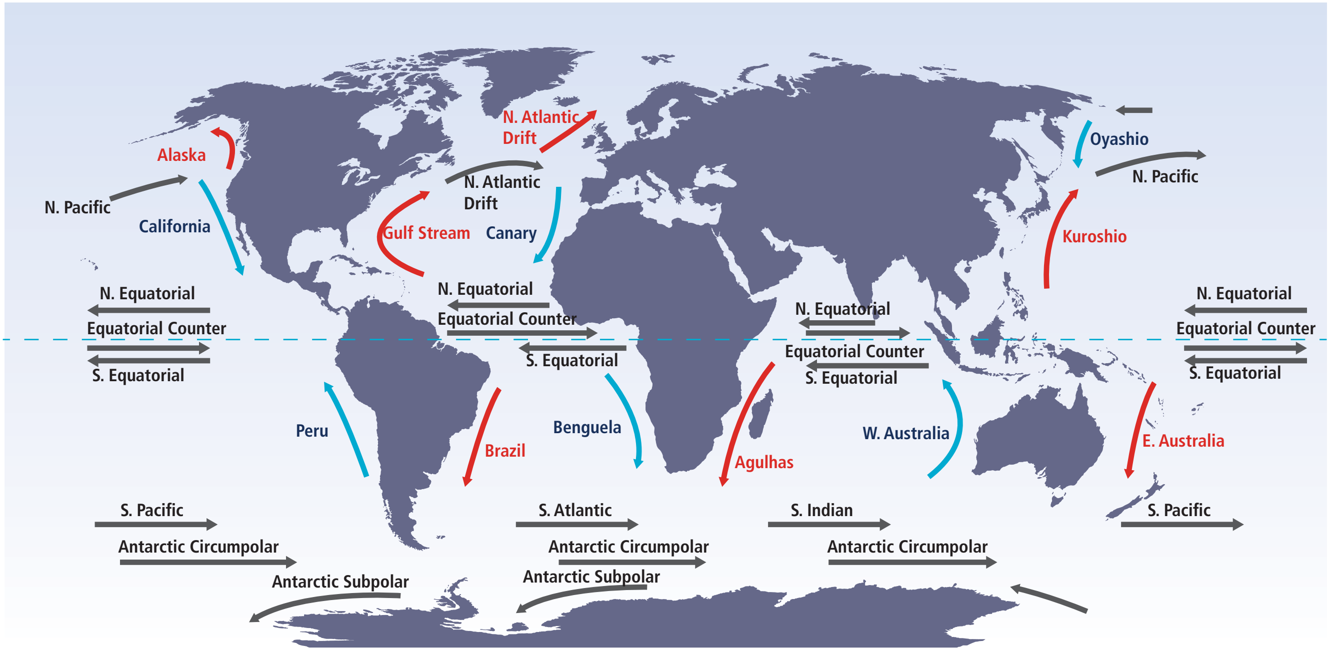


Figure TS.6.1d | Global distribution of various ocean energy resources: (d) Ocean currents. [Figure 6.3]

6.3 Technology and applications

The current development status of ocean energy technologies ranges from the conceptual and pure R&D stages to the prototype and demonstration stage, and only tidal range technology can be considered mature. Presently there are many technology options for each ocean energy source and, with the exception of tidal range barrages, technology convergence has not yet occurred. Over the past four decades, other marine industries (primarily offshore oil and gas) have made significant advances in the fields of materials, construction, corrosion, submarine cables and communications. Ocean energy is expected to directly benefit from these advances. [6.3.1]

Many wave energy technologies representing a range of operating principles have been conceived, and in many cases demonstrated, to convert energy from waves into a usable form of energy. Major variables include the method of wave interaction with respective motions (heaving, surging, pitching) as well as water depth (deep, intermediate, shallow) and distance from shore (shoreline, near-shore, offshore). Wave energy technologies can be classified into three groups: oscillating water columns (OWC: shore-based, floating), oscillating bodies (surface buoyant, submerged), and overtopping devices (shore-based, floating). [6.2.3] Principles of operation are presented in Figure TS.6.2.

Tidal range energy can be harnessed by the adaptation of river-based hydroelectric dams to estuarine situations, where a barrage encloses an estuary. The barrage may generate electricity on both the ebb and flood tides and some future barrages may have multiple basins to enable almost continuous generation. The most recent technical concepts are stand-alone offshore 'tidal lagoons'. [6.3.3]

Technologies to harness power from tidal and ocean currents are also under development, but tidal energy turbines are more advanced. Some of the tidal/ocean current energy technologies are similar to mature wind turbine generators but submarine turbines must also account for reversing flow, cavitation at blade tips and harsh underwater marine conditions. Tidal currents tend to be bidirectional, varying with the tidal cycle, and relatively fast-flowing, compared with ocean currents, which are usually unidirectional and slow-moving but continuous. Converters are classified by their principle of operation into axial flow turbines, cross flow turbines and reciprocating devices as presented in Figure TS.6.3. [6.3.4]

Ocean thermal energy conversion (OTEC) plants use the temperature differences between warm seawater from the ocean surface and cool seawater from depth (1,000 m is often used as a reference level) to produce electricity. Open-cycle OTEC systems use seawater directly as the circulating fluid, whilst closed-cycle systems use heat exchangers and a secondary working fluid (most commonly ammonia) to drive a turbine. Hybrid systems use both open- and closed-cycle operation. Although there have been trials of OTEC technologies, problems have been encountered with maintenance of vacuums, heat exchanger biofouling and corrosion issues. Current research is focused on overcoming these problems. [6.3.5]

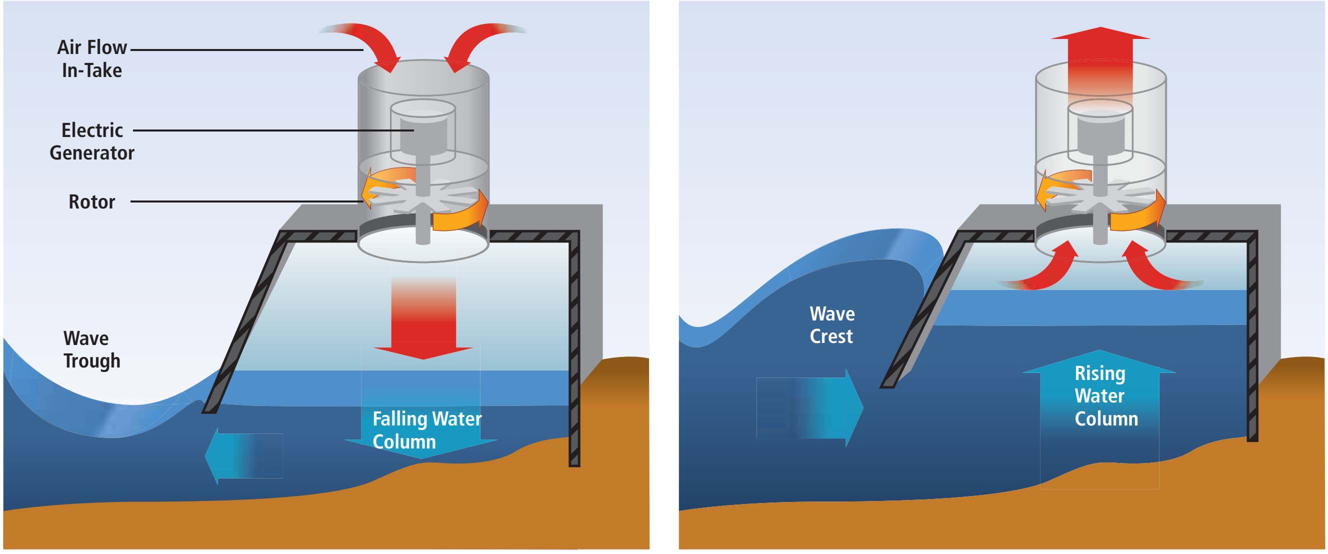


Figure TS.6.2a/b | Type of wave energy converter and its operation: oscillating water column device. [Figure 6.6] (design by the National Renewable Energy Laboratory (NREL))

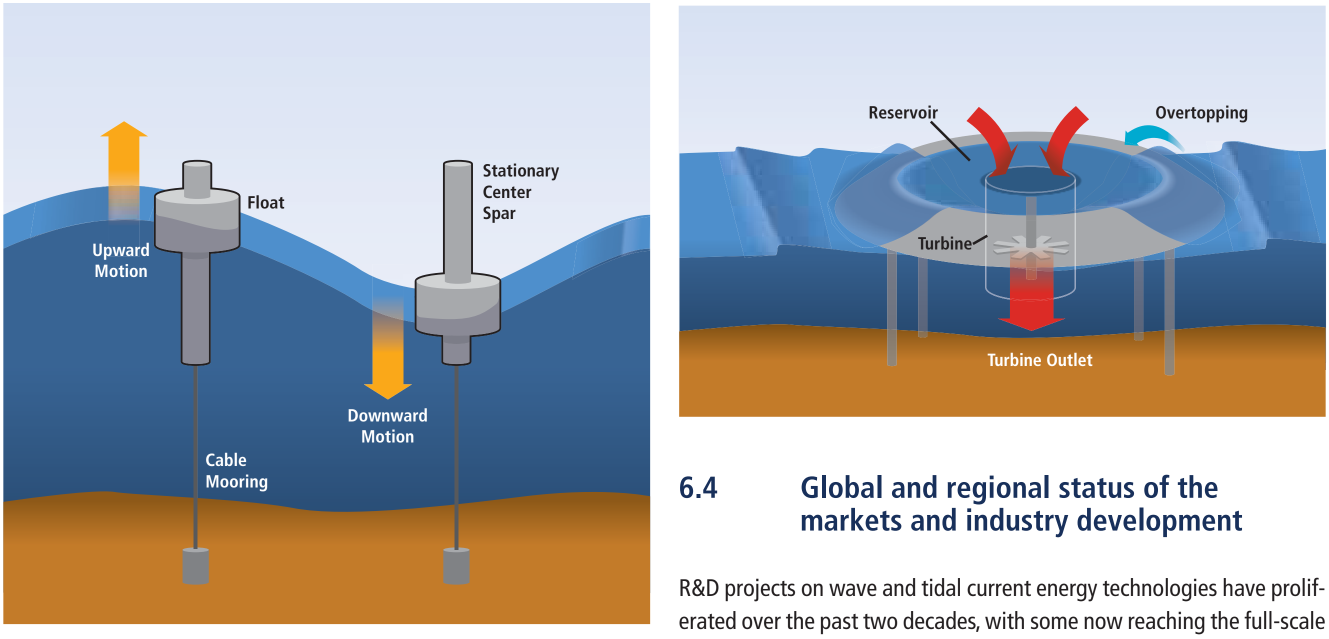


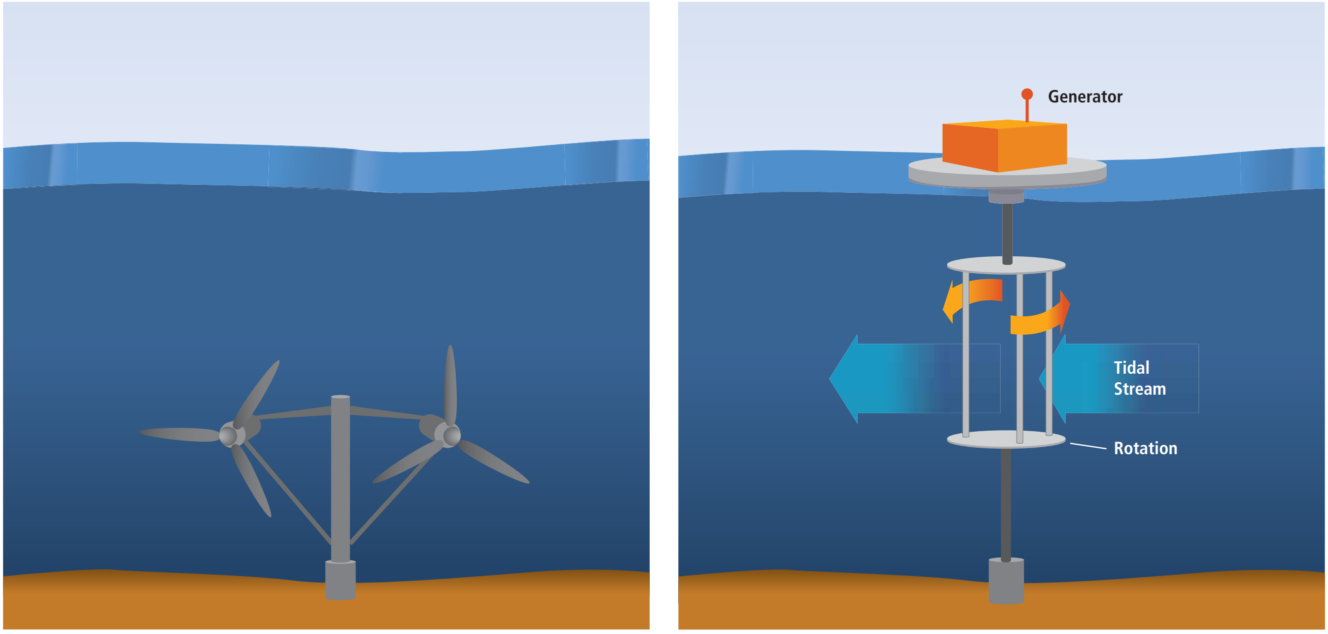
Figure TS.6.2c/d | Wave energy converters and their operation: (left) oscillating body device; and (right) overtopping device. [Figure 6.6] (design by the National Renewable Energy Laboratory (NREL))

The salinity gradient between freshwater from rivers and seawater can be utilized as a source of power with at least two concepts under development. The reversed electro dialysis (RED) process is a concept in which the difference in chemical potential between the two solutions is the driving force (Figure TS.6.4). The pressure-retarded osmosis, or osmotic power process, utilizes the concept of naturally occurring osmosis, a hydraulic pressure potential, caused by the tendency of freshwater to mix with seawater due to the difference in salt concentration (Figure TS.6.5). [6.3.6]

6.4 Global and regional status of the markets and industry development

R&D projects on wave and tidal current energy technologies have proliferated over the past two decades, with some now reaching the full-scale pre-commercial prototype stage. Presently, the only full-size and operational ocean energy technology available is the tidal barrage, of which the best example is the 240 MW La Rance Barrage in north-western France, completed in 1966. The 254 MW Sihwa Barrage (South Korea) is due to become operational in 2011. Technologies to develop other ocean energy sources including OTEC, salinity gradients and ocean currents are still at the conceptual, R&D or early prototype stages. Currently, more than 100 different ocean energy technologies are under development in over 30 countries. [6.4.1]

The principal investors in ocean energy R&D and deployments are national, federal and state governments, followed by major energy utilities and investment companies. National and regional governments are



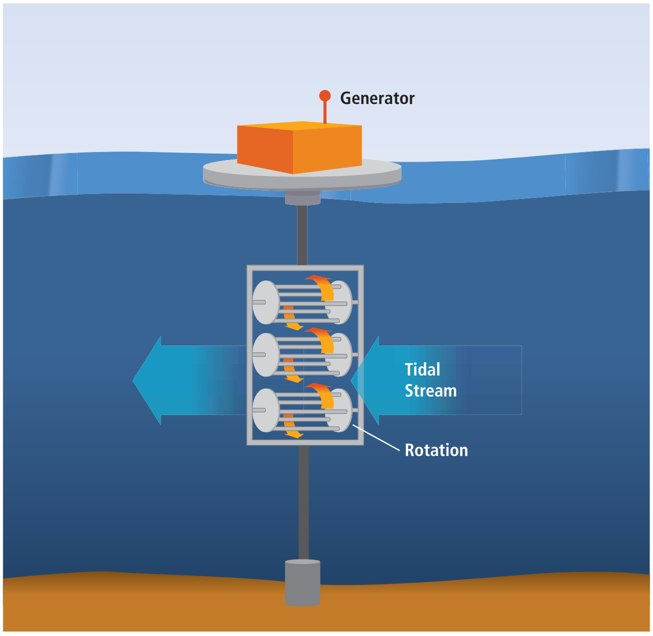


Figure TS.6.3 | Tidal current energy converters and their operation: (Top left) twin turbine horizontal axis device; (Bottom left) cross-flow device; and (Top right) vertical axis device. [Figure 6.8]

particularly supportive of ocean energy through a range of financial, regulatory and legislative initiatives to support developments. [6.4.7]

Industrial involvement in ocean energy is at a very early stage and there is no manufacturing industry for these technologies at present. The growth of interest may lead to the transfer of capacity, skills and capabilities from related industries, combined with new specific innovative aspects. One interesting feature of ocean energy is the development of a number of national marine energy testing centres and these are becoming foci for device testing, certification and advanced R&D. [6.4.1.2]

The status of industry development can be assessed by the current and recent deployments of ocean energy systems.

Wave energy: A number of shore-based wave energy prototypes are operating around the world. Two OWC devices have been operational in Portugal and Scotland for approximately a decade, while two other offshore OWC devices have been tested at prototype scale in Australia and Ireland. Another OWC was operational off the southern coast of India between 1990 and 2005. A number of companies in Australia, Brazil, Denmark, Finland, Ireland, Norway, Portugal, Spain, Sweden, New Zealand, the UK and the USA have been testing pilot scale or pre-commercial prototypes at sea, with the largest being 750 kW. [6.4.2]

Tidal range: The La Rance 240 MW plant in France has been operational since 1966. Other smaller projects have been commissioned since then in China, Canada and Russia. The Sihwa barrage 254 MW plant in Korea will be commissioned during 2011, and several other large projects are under consideration. [6.4.3]

Tidal and ocean currents: There are probably more than 50 tidal current devices at the proof-of-concept or prototype development stage, but large-scale deployment costs are yet to be demonstrated. The most advanced example is the SeaGen tidal turbine, which was installed near Northern Ireland and has delivered electricity into the electricity grid for more than one year. An Irish company has tested its open-ring turbine in Scotland, and more recently in Canada. Two companies have demonstrated horizontal-axis turbines at full scale in Norway and Scotland, whilst another has demonstrated a vertical-axis turbine in Italy. Lastly,

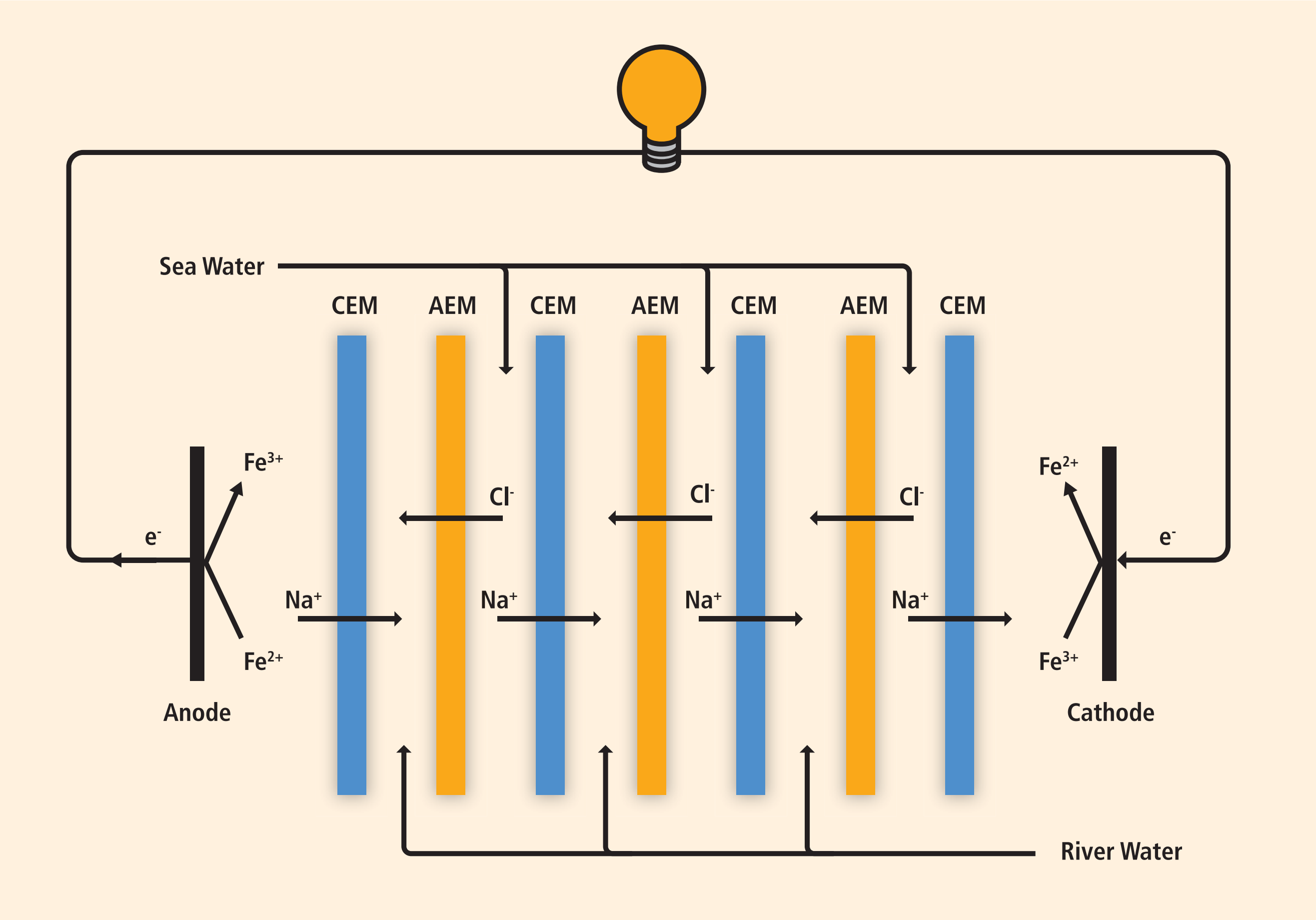


Figure TS.6.4 | Reversed electro dialysis (RED) system. [Figure 6.9]

Notes: CEM = cation exchange membrane; AEM = anion exchange membrane, Na = sodium, Cl = Chlorine, Fe = iron.

a reciprocating device was demonstrated in the UK in 2009. No pilot or demonstration plants have been deployed for ocean currents to date, although much larger scales are envisioned if technologies are able to capture the slower-velocity currents. [6.4.4]

OTEC: Japan, India, the USA and several other countries have tested pilot OTEC projects. Many have experienced engineering challenges related to pumping, vacuum retention and piping. Larger-scale OTEC developments could have significant markets in tropical maritime nations, including the Pacific Islands, Caribbean Islands, and Central American and African nations if the technology develops to the point of being a cost-effective energy supply option. [6.4.5]

Salinity gradients: Research into osmotic power is being pursued in Norway, with a prototype in operation since 2009 as part of a drive to deliver a commercial osmotic power plant. At the same time, the RED technology has been proposed for retrofitting the 75-year-old Afsluitdijk dike in The Netherlands. [6.4.6]

6.5 Environmental and social impacts

Ocean energy does not directly emit CO_2 during operation; however, GHG emissions may arise from different aspects of the lifecycle of ocean energy systems, including raw material extraction, component manufacturing, construction, maintenance and decommissioning. A comprehensive review of lifecycle assessment studies published since 1980 suggests that lifecycle GHG emissions from wave and tidal energy systems are less than 23 g CO_2eq/kWh, with a median estimate of lifecycle GHG emissions of around 8 g CO_2eq/kWh for wave energy. Insufficient studies are available to estimate lifecycle emissions from the other classes of ocean energy technology. Regardless, in comparison to fossil energy generation technologies, the lifecycle GHG emissions from ocean energy devices appear low. [6.5.1]

The local social and environmental impacts of ocean energy projects are being evaluated as actual deployments multiply, but can be estimated based on the experience of other maritime and offshore

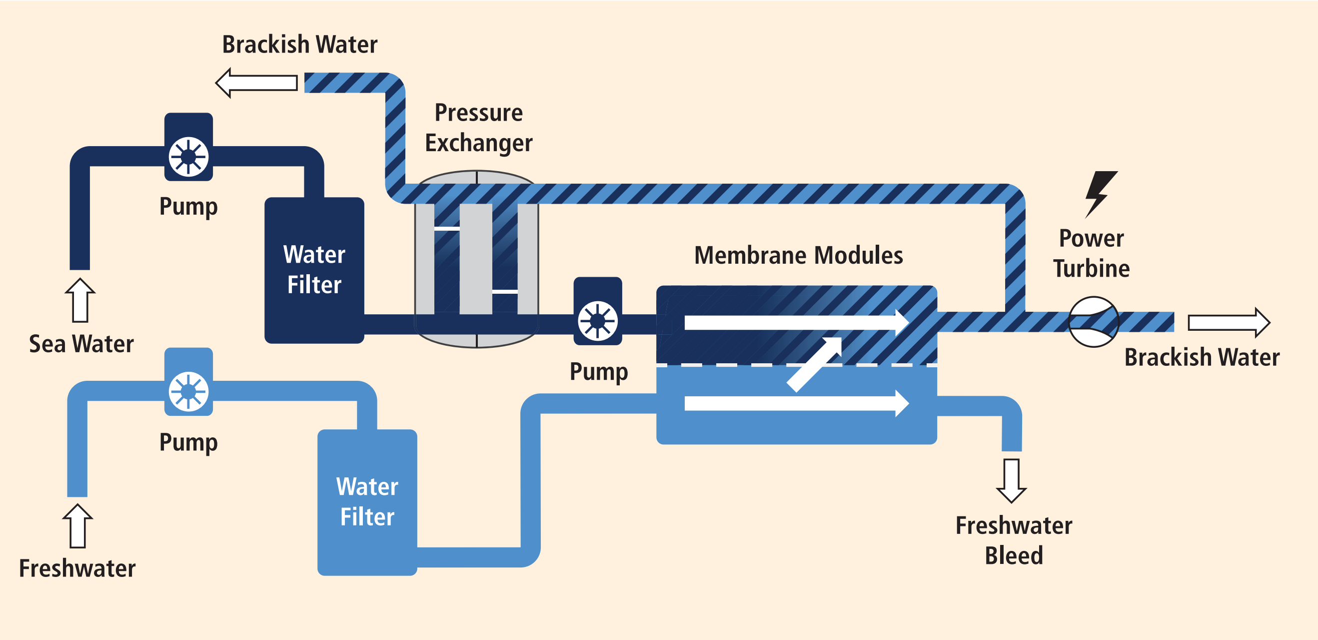


Figure TS.6.5 | Pressure-retarded osmosis (PRO) process. [Figure 6.10]

industries. Environmental risks from ocean energy technologies appear to be relatively low, but the early stage of ocean energy deployment creates uncertainty about the degree to which social and environmental concerns might eventually constrain development. [6 ES]

Each ocean power technology has its own specific set of environmental and social impacts. Possible positive effects from ocean energy may include avoidance of adverse effects on marine life by virtue of reducing other human activities in the area around the ocean devices, and the strengthening of energy supply and regional economic growth, employment and tourism. Negative effects may include a reduction in visual amenity and loss of access to space for competing users, noise during construction, noise and vibration during operation, electromagnetic fields, disruption to biota and habitats, water quality changes and possible pollution, for instance from chemical or oil leaks, and other limited specific impacts on local ecosystems. [6.5.2]

6.6 Prospects for technology improvement, innovation and integration

As emerging technologies, ocean energy devices have the potential for significant technological advances. Not only will device-specific R&D and deployment be important to achieving these advances, but technology improvements and innovation in ocean energy converters are also likely to be influenced by developments in related fields. [6.6]

Integration of ocean energy into wider energy networks will need to recognize the widely varying generation characteristics arising from the different resources. For example, electricity generation from tidal stream resources shows very high variability over one to four hours, yet extremely limited variability over monthly or longer time horizons. [6.6]

6.7 Cost trends

Commercial markets are not yet driving marine energy technology development. Government-supported R&D and national policy incentives are the key motivations. Because none of the ocean energy technologies but tidal barrages are mature (experience with other technologies is only now becoming available for validation of demonstration/prototype devices), it is difficult to accurately assess the economic viability of most ocean energy technologies. [6.7.1]

Table TS.6.1 shows the best available data for some of the primary cost factors that affect the levelized cost of electricity by each of the ocean energy sub-types. In most cases, these cost and performance parameters are based on sparse information due to the lack of peer-reviewed reference data and actual operating experience, and in many cases therefore reflect estimated cost and performance assumptions based on engineering knowledge. Present-day investment costs were found in a few instances but are based on a small sample of projects and studies, which may not be representative of the entire industry. [6.7.1]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for tidal barrages (which is currently the only commercially available ocean energy technology) over a large set and range of input parameters has been

Table TS.6.1 | Summary of core available cost and performance parameters for all ocean energy technology sub-types. [Table 6.3]

Ocean Energy Technology	Investment Costs (USD_{2005}/kW)	Annual O&M Costs (USD_{2005}/kW)	Capacity Factor (CF) (%)	Design Life (years)
Wave	6,200–16,100	180	25–40	20
Tidal Range	4,500–5,000	100	22.5–28.5	40
Tidal Current	5,400–14,300	140	26–40	20
Ocean Current	N/A	N/A	N/A	20
Ocean Thermal	4,200–12,300[1]	N/A	N/A	20
Salinity Gradient	N/A	N/A	N/A	20

Note: 1. Cost figures for ocean thermal energy have not been converted to 2005 USD.

calculated to range from US $cent_{2005}$ 12/kWh to US $cent_{2005}$ 32/kWh. This range should, however, only be considered as indicative given the present state of deployment experience. [1.3.2, 6.7.1, 6.7.3, 10.5.1, Annex II, Annex III]

Because of the early stage of technology development, estimates of future costs for ocean energy should be considered speculative. Nonetheless, the cost of ocean energy is expected to decline over time as R&D, demonstrations, and deployments proceed. [6.7.1–6.7.5]

6.8 Potential deployment

Until about 2008, ocean energy was not considered in any of the major global energy scenario modelling activities and therefore its potential impact on future world energy supplies and climate change mitigation is just now beginning to be investigated. As such, the results of the published scenarios literature as they relate to ocean energy are sparse and preliminary, reflecting a wide range of possible outcomes. Specifically, scenarios for ocean energy deployment are considered in only three major sources here: Energy [R]evolution (E[R]) 2010, IEA World Energy Outlook (WEO) 2009 and Energy Technology Perspectives (ETP) 2010. Multiple scenarios were considered in the E[R] and the ETP reports and a single reference scenario was documented in the WEO report. Each scenario is summarized in Table TS.6.2.

This preliminary presentation of scenarios that describe alternative levels of ocean energy deployment is among the first attempts to review the potential role of ocean energy in the medium- to long-term scenarios literature with the intention of establishing the potential contribution of ocean energy to future energy supplies and climate change mitigation. As shown by the limited number of existing scenarios, ocean energy has the potential to help mitigate long-term climate change by offsetting GHG emissions with projected deployments resulting in energy delivery of up to 1,943 TWh/yr (~7 EJ/yr) by 2050. Other scenarios have been developed that indicate deployment as low as 25 TWh/yr (0.9 EJ/yr) from ocean energy. The wide range in results is based in part on uncertainty about the degree to which climate change mitigation will drive energy

Table TS.6.2 | Main characteristics of medium- to long-term scenarios from major published studies that include ocean energy. [Table 6.5]

	Deployment TWh/yr (PJ/yr)				GW	
Scenario	**2010**	**2020**	**2030**	**2050**	**2050**	**Notes**
Energy [R]evolution - Reference	N/A	3 (10.8)	11 (36.6)	25 (90)	N/A	No policy changes
Energy [R]evolution	N/A	53 (191)	128 (461)	678 (2,440)	303	Assumes 50% carbon reduction
Energy [R]evolution – Advanced	N/A	119 (428)	420 (1,512)	1,943 (6,994)	748	Assumes 80% carbon reduction
WEO 2009	N/A	3 (10.8)	13 (46.8)	N/A	N/A	Basis for E[R] reference case
ETP BLUE map 2050	N/A	N/A	N/A	133 (479)	N/A	Power sector is virtually decarbonized
ETP BLUE map no CCS 2050	N/A	N/A	N/A	274 (986)	N/A	BLUE Map Variant – Carbon capture and storage is found to not be possible
ETP BLUE map hi NUC 2050	N/A	N/A	N/A	99 (356)	N/A	BLUE Map Variant – Nuclear share is increased to 2,000 GW
ETP BLUE Map hi REN 2050	N/A	N/A	N/A	552 (1,987)	N/A	BLUE Map Variant – Renewable share is increased to 75%
ETP BLUE map 3%	N/A	N/A	N/A	401 (1,444)	N/A	BLUE Map Variant – Discount rates are set to 3% for energy generation projects.

sector transformation, but for ocean energy, is also based on inherent uncertainty as to when and if various ocean energy technologies become commercially available at attractive costs. To better understand the possible role of ocean energy in climate change mitigation, not only will continued technical advances be necessary, but the scenarios modelling process will need to increasingly incorporate the range of potential ocean energy technology sub-types, with better data for resource potential, present and future investment costs, O&M costs, and anticipated capacity factors. Improving the availability of the data at global and regional scales will be an important ingredient to improving coverage of ocean energy in the scenarios literature. [6.8.4]

7. Wind Energy

7.1 Introduction

Wind energy has been used for millennia in a wide range of applications. The use of wind energy to generate electricity on a commercial scale, however, became viable only in the 1970s as a result of technical advances and government support. A number of different wind energy technologies are available across a range of applications, but the primary use of wind energy of relevance to climate change mitigation is to generate electricity from larger, grid-connected wind turbines, deployed either on land ('onshore') or in sea- or freshwater ('offshore').[11] [7.1]

Wind energy offers significant potential for near-term (2020) and long-term (2050) GHG emissions reductions. The wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand, and that contribution could grow to in excess of 20% by 2050 if ambitious efforts are made to reduce GHG emissions and to address other impediments to increased wind energy deployment. Onshore wind energy is already being deployed at a rapid pace in many countries, and no insurmountable technical barriers exist that preclude increased levels of wind energy penetration into electricity supply systems. Moreover, though average wind speeds vary considerably by location, ample technical potential exists in most regions of the world to enable significant wind energy deployment. In some areas with good wind resources, the cost of wind energy is already competitive with current energy market prices, even without considering relative environmental impacts. Nonetheless, in most regions of the world, policy measures are still required to ensure rapid deployment. Continued advancements in on- and offshore wind energy technology are expected, however, further reducing the cost of wind energy and improving wind energy's GHG emissions reduction potential. [7.9]

11 Smaller wind turbines, higher-altitude wind electricity, and the use of wind energy in mechanical and propulsion applications are only briefly discussed in Chapter 7.

7.2 Resource potential

The global technical potential for wind energy is not fixed, but is instead related to the status of the technology and assumptions made regarding other constraints to wind energy development. Nonetheless, a growing number of global wind resource assessments have demonstrated that the world's technical potential exceeds current global electricity production. [7.2]

No standardized approach has been developed to estimate the global technical potential of wind energy: the diversity in data, methods, assumptions, and even definitions for technical potential complicate comparisons. The AR4 identified the technical potential for onshore wind energy as 180 EJ/yr (50,000 TWh/yr). Other estimates of the global technical potential for wind energy that consider relatively more development constraints range from a low of 70 EJ/yr (19,400 TWh/yr) (onshore only) to a high of 450 EJ/yr (125,000 TWh/yr) (on- and near-shore). This range corresponds to roughly one to six times global electricity production in 2008, and may understate the technical potential due to several of the studies relying on outdated assumptions, the exclusion or only partial inclusion of offshore wind energy in some of the studies, and methodological and computing limitations. Estimates of the technical potential for offshore wind energy alone range from 15 EJ/yr to 130 EJ/yr (4,000 to 37,000 TWh/yr) when only considering relatively shallower and near-shore applications; greater technical potential is available if also considering deeper-water applications that might rely on floating wind turbine designs. [7.2.1]

Regardless of whether existing estimates under- or overstate the technical potential for wind energy, and although further advances in wind resource assessment methods are needed, it is evident that the technical potential of the resource itself is unlikely to be a limiting factor for global wind energy deployment. Instead, economic constraints associated with the cost of wind energy, institutional constraints and costs associated with transmission access and operational integration, and issues associated with social acceptance and environmental impacts are likely to restrict growth well before any absolute limit to the global technical potential is encountered. [7.2.1]

In addition, ample technical potential exists in most regions of the world to enable significant wind energy deployment. The wind resource is not evenly distributed across the globe nor uniformly located near population centres, however, and wind energy will therefore not contribute equally in meeting the needs of every country. The technical potentials for onshore wind energy in OECD North America and Eastern Europe/Eurasia are found to be particularly sizable, whereas some areas of non-OECD Asia and OECD Europe appear to have more limited onshore technical potential. Figure TS.7.1, a global wind resource map, also shows limited technical potential in certain areas of Latin America and Africa, though other portions of those continents have significant

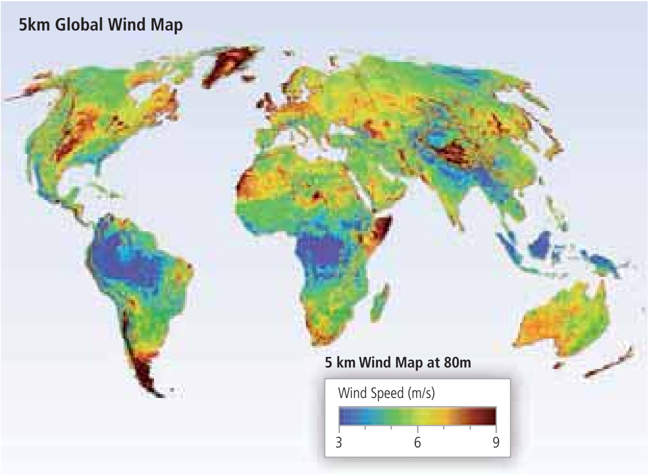


Figure TS.7.1 | Example global wind resource map with 5 km x 5 km resolution. [Figure 7.1]

technical potential. Recent, detailed regional assessments have generally found the size of the wind resource to be greater than estimated in previous assessments. [7.2.2]

Global climate change may alter the geographic distribution and/or the inter- and intra-annual variability of the wind resource, and/or the quality of the wind resource, and/or the prevalence of extreme weather events that may impact wind turbine design and operation. Research to date suggests that it is unlikely that multi-year annual mean wind speeds will change by more than a maximum of ±25% over most of Europe and North America during the present century, while research covering northern Europe suggests that multi-year annual mean wind power densities will likely remain within ±50% of current values. Fewer studies have been conducted for other regions of the world. Though research in this field is nascent and additional study is warranted, research to date suggests that global climate change may alter the geographic distribution of the wind resource, but that those effects are unlikely to be of a magnitude to greatly impact the global potential for wind energy deployment. [7.2.3]

7.3 Technology and applications

Modern, commercial grid-connected wind turbines have evolved from small, simple machines to large, highly sophisticated devices. Scientific and engineering expertise and advances, as well as improved computational tools, design standards, manufacturing methods and O&M procedures, have all supported these technology developments. [7.3]

Generating electricity from the wind requires that the kinetic energy of moving air be converted to electrical energy, and the engineering challenge for the wind energy industry is to design cost-effective wind turbines and power plants to perform this conversion. Though a variety of turbine configurations have been investigated, commercially available turbines are primarily horizontal-axis machines with three blades positioned upwind of the tower. In order to reduce the levelized cost of wind energy, typical wind turbine sizes have grown significantly (Figure TS.7.2), with the largest fraction of onshore wind turbines installed globally in 2009 having a rated capacity of 1.5 to 2.5 MW. As of 2010, onshore wind turbines typically stand on 50- to 100-m towers, with rotors that are often 50 to 100 m in diameter; commercial machines

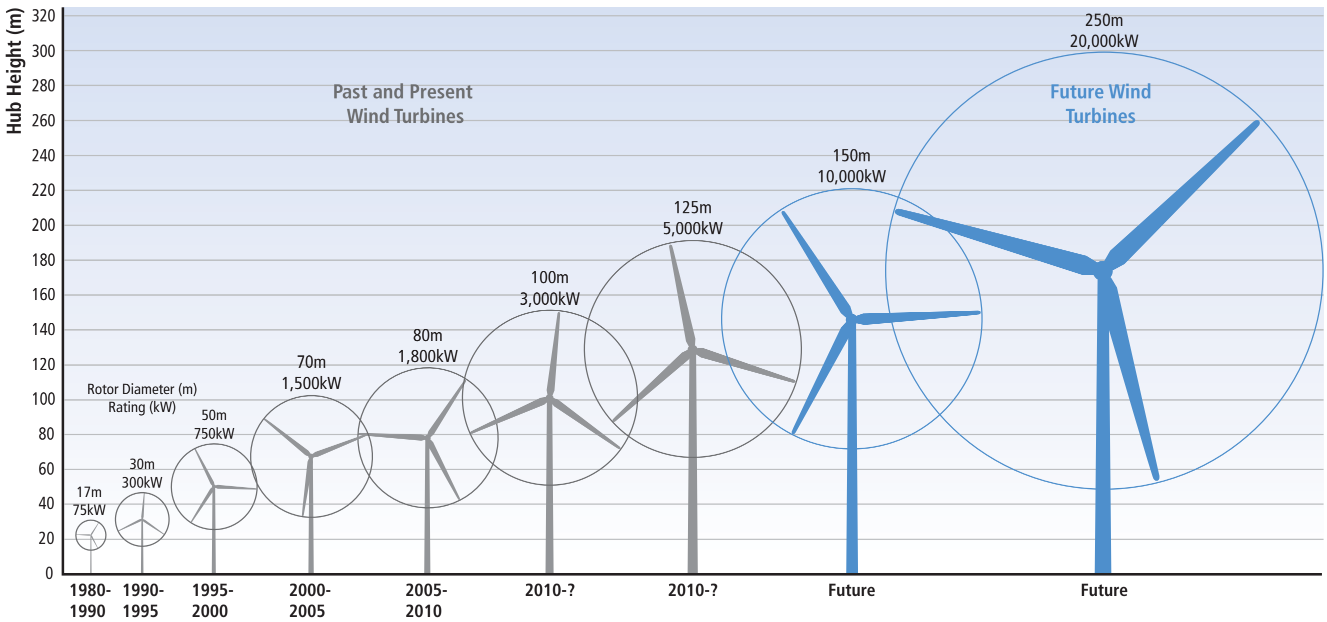


Figure TS.7.2 | Growth in size of typical commercial wind turbines. [Figure 7.6] with rotor diameters and tower heights in excess of 125 m are operating, and even larger machines are under development. Onshore wind energy technology is already being commercially manufactured and deployed at a large scale. [7.3.1]

Offshore wind energy technology is less mature than onshore, with higher investment costs. Lower power plant availabilities and higher O&M costs have also been common both because of the comparatively less mature state of the technology and because of the inherently greater logistical challenges of maintaining and servicing offshore turbines. Nonetheless, considerable interest in offshore wind energy exists in the EU and, increasingly, in other regions. The primary motivation to develop offshore wind energy is to provide access to additional wind resources in areas where onshore wind energy development is constrained by limited technical potential and/or by planning and siting conflicts with other land uses. Other motivations include the higher-quality wind resources located at sea; the ability to use even larger wind turbines and the potential to thereby gain additional economies of scale; the ability to build larger power plants than onshore, gaining plant-level economies of scale; and a potential reduction in the need for new, long-distance, land-based transmission infrastructure to access distant onshore wind energy. To date, offshore wind turbine technology has been very similar to onshore designs, with some modifications and with special foundations. As experience is gained, water depths are expected to increase and more exposed locations with higher winds will be utilized. Wind energy technology specifically tailored for offshore applications will become more prevalent as the offshore market expands, and it is expected that larger turbines in the 5 to 10 MW range may come to dominate this segment. [7.3.1.3]

Alongside the evolution of wind turbine design, improved design and testing methods have been codified in International Electrotechnical Commission standards. Certification agencies rely on accredited design and testing bodies to provide traceable documentation demonstrating conformity with the standards in order to certify that turbines, components or entire wind power plants meet common guidelines relating to safety, reliability, performance and testing. [7.3.2]

From an electric system reliability perspective, an important part of the wind turbine is the electrical conversion system. For modern turbines, variable-speed machines now dominate the market, allowing for the provision of real and reactive power as well as some fault ride-through capability, but no intrinsic inertial response (i.e., turbines do not increase or decrease power output in synchronism with system power imbalances); wind turbine manufacturers have recognized this latter limitation and are pursuing a variety of solutions. [7.3.3]

7.4 Global and regional status of market and industry development

The wind energy market has expanded substantially, demonstrating the commercial and economic viability of the technology and industry. Wind energy expansion has been concentrated in a limited number of regions, however, and further expansion, especially in regions with little wind energy deployment to date and in offshore locations, is likely to require additional policy measures. [7.4]

Wind energy has quickly established itself as part of the mainstream electricity industry. From a cumulative capacity of 14 GW at the end of 1999, global installed capacity increased twelve-fold in 10 years to reach almost 160 GW by the end of 2009. The majority of the capacity has been installed onshore, with offshore installations primarily in Europe and totalling a cumulative 2.1 GW. The countries with the highest installed capacity by the end of 2009 were the USA (35 GW), China (26 GW), Germany (26 GW), Spain (19 GW) and India (11 GW). The total investment cost of new wind power plants installed in 2009 was USD_{2005} 57 billion, while worldwide direct employment in the sector in 2009 has been estimated at approximately 500,000. [7.4.1, 7.4.2]

In both Europe and the USA, wind energy represents a major new source of electric capacity additions. In 2009, roughly 39% of all capacity additions in the USA and the EU came from wind energy; in China, 16% of the net capacity additions in 2009 came from wind energy. On a global basis, from 2000 through 2009, roughly 11% of all newly installed net electric capacity additions came from new wind power plants; in 2009 alone, that figure was probably more than 20%. As a result, a number of countries are beginning to achieve relatively high levels of annual wind electricity penetration in their respective electric systems. By the end of 2009, wind power capacity was capable of supplying electricity equal to roughly 20% of Denmark's annual electricity demand, 14% of Portugal's, 14% of Spain's, 11% of Ireland's and 8% of Germany's. [7.4.2]

Despite these trends, wind energy remains a relatively small fraction of worldwide electricity supply. The total wind power capacity installed by the end of 2009 would, in an average year, meet roughly 1.8% of worldwide electricity demand. Additionally, though the trend over time has been for the wind energy industry to become less reliant on European markets, with significant recent expansion in the USA and China, the market remains concentrated regionally: Latin America, Africa and the Middle East, and the Pacific regions have installed relatively little wind power capacity despite significant technical potential for wind energy in each region (Figure TS.7.3). [7.4.1, 7.4.2]

The deployment of wind energy must overcome a number of challenges, including: the relative cost of wind energy compared to energy market prices, at least if environmental impacts are not internalized and monetized; concerns about the impact of wind energy's variability; challenges of building new transmission; cumbersome and slow planning, siting and permitting procedures; the technical advancement needs and higher cost of offshore wind energy technology; and lack of institutional and technical knowledge in regions that have not yet experienced substantial wind energy deployment. As a result, growth is affected by a wide range of government policies. [7.4.4]

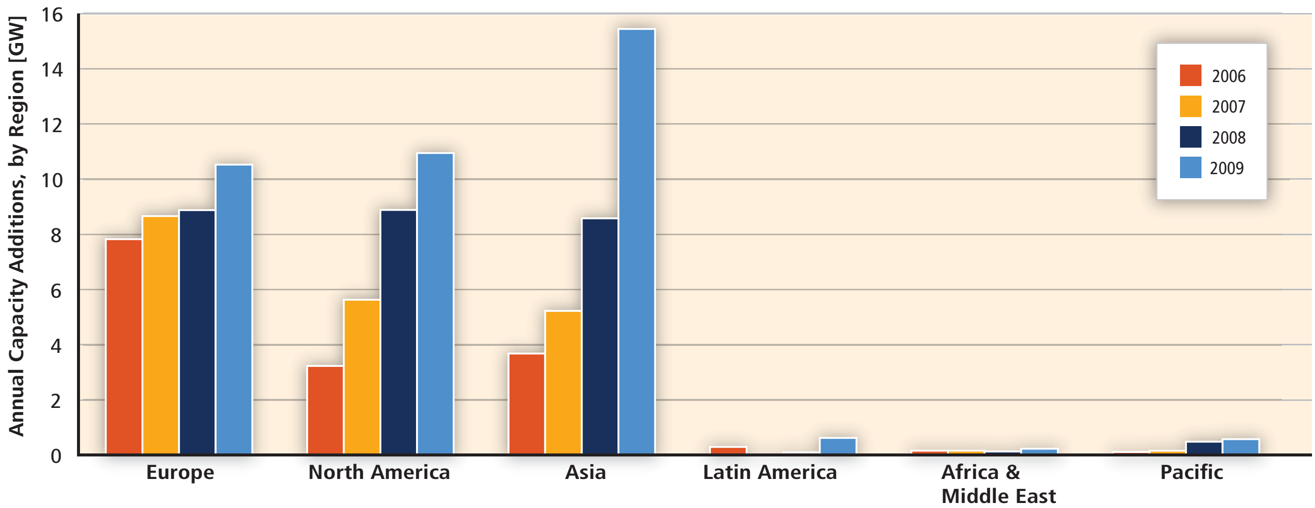


Figure TS.7.3 | Annual wind power capacity additions by region. [Figure 7.10]

Note: Regions shown in the figure are defined by the study.

7.5 Near-term grid integration issues

As wind energy deployment has increased, so have concerns about the integration of that energy into electric systems. The nature and magnitude of the integration challenge will depend on the characteristics of the existing electric system and the level of wind electricity penetration. Moreover, as discussed in Chapter 8, integration challenges are not unique to wind energy. Nevertheless, analysis and operating experience primarily from certain OECD countries suggests that, at low to medium levels of wind electricity penetration (defined here as up to 20% of total annual average electrical energy demand)[12], the integration of wind energy generally poses no insurmountable technical barriers and is economically manageable. At the same time, even at low to medium levels of wind electricity penetration, certain (and sometimes system-specific) technical and/or institutional challenges must be addressed. Concerns about (and the costs of) wind energy integration will grow with wind energy deployment, and even higher levels of penetration may depend on or benefit from the availability of additional technological and institutional options to increase flexibility and maintain a balance between supply and demand, as discussed further in Chapter 8 (Section 8.2). [7.5]

Wind energy has characteristics that present integration challenges, and that must be considered in electric system planning and operation to ensure the reliable and economical operation of the electric power system. These include: the localized nature of the wind resource with possible implications for new transmission for both on- and offshore wind energy; the variability of wind power output over multiple time scales; and the lower levels of predictability of wind power output than are common for many other types of power plants. The aggregate variability and uncertainty of wind power output depends, in part, on the degree of correlation between the output of different geographically dispersed wind power plants: generally, the outputs of wind power plants that are farther apart are less correlated with each other, and variability over shorter time periods (minutes) is less correlated than variability over longer time periods (multiple hours). Forecasts of wind power output are also more accurate over shorter time periods, and when multiple plants are considered together. [7.5.2]

Detailed system planning for new generation and transmission infrastructure is used to ensure that the electric system can be operated reliably and economically in the future. To do so, planners need computer-based simulation models that accurately characterize wind energy. Additionally, as wind power capacity has increased, so has the need for wind power plants to become more active participants in maintaining the operability and power quality of the electric system, and technical standards for grid connection have been implemented to help prevent wind power plants from adversely affecting the electric system during normal operation and contingencies. Transmission adequacy evaluations, meanwhile, must account for the location dependence of the wind resource, and consider any trade-offs between the costs of expanding the transmission system to access higher-quality wind resources in comparison to the costs of accessing lower-quality wind resources that require less transmission investment. Even at low to medium levels of wind electricity penetration, the addition of large quantities of on- or offshore wind energy in areas with higher-quality wind resources may require significant new additions or upgrades to the transmission system. Depending on the legal and regulatory framework in any particular region, the institutional challenges of transmission expansion can be substantial. Finally, planners need to account for wind

12 This level of penetration was chosen to loosely separate the integration needs for wind energy in the relatively near term from the broader, longer- term, and non-wind-specific discussion of power system changes provided in Chapter 8.

power output variability in assessing the contribution of wind energy to generation adequacy and therefore the long-term reliability of the electric system. Though methods and objectives vary from region to region, the contribution of wind energy to generation adequacy usually depends on the correlation of wind power output with the periods of time when there is a higher risk of a supply shortage, typically periods of high electricity demand. The marginal contribution of wind energy to generation adequacy typically declines as wind electricity penetration increases, but aggregating wind power plants over larger areas may slow this decline if adequate transmission capacity is available. The relatively low average contribution of wind energy to generation adequacy (compared to fossil units) suggests that electric systems with large amounts of wind energy will also tend to have significantly more total nameplate generation capacity to meet the same peak electricity demand than will electric systems without large amounts of wind energy. Some of this generation capacity will operate infrequently, however, and the mix of other generation will therefore tend (on economic grounds) to increasingly shift towards flexible 'peaking' and 'intermediate' resources and away from 'base-load' resources. [7.5.2]

The unique characteristics of wind energy also have important implications for electric system operations. Because wind energy is generated with a very low marginal operating cost, it is typically used to meet demand when it is available; other generators are then dispatched to meet demand minus any available wind energy (i.e., 'net demand'). As wind electricity penetration grows, the variability of wind energy results in an overall increase in the magnitude of changes in net demand, and also a decrease in the minimum net demand. As a result of these trends, wholesale electricity prices will tend to decline when wind power output is high and transmission interconnector capacity to other energy markets is constrained, and other generating units will be called upon to operate in a more flexible manner than required without wind energy. At low to medium levels of wind electricity penetration, the increase in minute-to-minute variability is expected to be relatively small. The more significant operational challenges relate to the need to manage changes in wind power output over one to six hours. Incorporating wind energy forecasts into electric system operations can reduce the need for flexibility from other generators, but even with high-quality forecasts, system operators will need a broad range of strategies to actively maintain the supply/demand balance, including the use of flexible power generation technologies, wind energy output curtailment, and increased coordination and interconnection between electric systems. Mass-market demand response, bulk energy storage technologies, large-scale deployment of electric vehicles and their associated contributions to system flexibility through controlled battery charging, diverting excess wind energy to fuel production or local heating, and geographic diversification of wind power plant siting will also become increasingly beneficial as wind electricity penetration rises. Despite the challenges, actual operating experience in different parts of the world demonstrates that electric systems can operate reliably with increased contributions of wind energy; in four countries (Denmark, Portugal, Spain, Ireland), wind energy in 2010 was already able to supply from 10 to roughly 20% of annual electricity demand. Experience is limited, in particular with regard to system faults at high instantaneous penetration levels, however, and as more wind energy is deployed in diverse regions and electric systems, additional knowledge about wind energy integration will be gained. [7.5.3]

In addition to actual operating experience, a number of high-quality studies of the increased transmission and generation resources required to accommodate wind energy have been completed, primarily covering OECD countries. These studies employ a wide variety of methodologies and have diverse objectives, but the results demonstrate that the cost of integrating up to 20% wind energy into electric systems is, in most cases, modest but not insignificant. Specifically, at low to medium levels of wind electricity penetration, the available literature (again, primarily from a subset of OECD countries) suggests that the additional costs of managing electric system variability and uncertainty, ensuring generation adequacy, and adding new transmission to accommodate wind energy will be system specific but generally in the range of US $cent_{2005}$ 0.7/kWh to US $cent_{2005}$ 3/kWh. The technical challenges and costs of integration are found to increase with wind electricity penetration. [7.5.4]

7.6 Environmental and social impacts

Wind energy has significant potential to reduce (and is already reducing) GHG emissions. Moreover, attempts to measure the relative impacts of various electricity supply technologies suggest that wind energy generally has a comparatively small environmental footprint. [9.3.4, 10.6] As with other industrial activities, however, wind energy has the potential to produce some detrimental impacts on the environment and on human activities and well being, and many local and national governments have established planning and siting requirements to reduce those impacts. As wind energy deployment increases and as larger wind power plants are considered, existing concerns may become more acute and new concerns may arise. [7.6]

Although the major environmental benefits of wind energy result from displacing electricity generated from fossil fuel-based power plants, estimating those benefits is somewhat complicated by the operational characteristics of the electric system and the investment decisions that are made about new power plants. In the short run, increased wind energy will typically displace the operations of existing fossil fuel-fired plants. In the longer term, however, new generating plants may be needed, and the presence of wind energy can influence what types of power plants are built. The impacts arising from the manufacture, transport, installation, operation and decommissioning of wind turbines should also be considered, but a comprehensive review of available studies demonstrates that the energy used and GHG emissions produced during these steps are small compared to the energy generated and emissions avoided over the lifetime of wind power plants. The GHG emissions intensity of wind energy is estimated to range from 8 to 20 g CO_2/kWh in most instances, whereas energy payback times are between 3.4 and 8.5 months. In addition, managing the variability of wind power output has not been found to significantly degrade the GHG emissions benefits of wind energy. [7.6.1]

Other studies have considered the local ecological impacts of wind energy development. The construction and operation of both on- and offshore wind power plants impacts wildlife through bird and bat collisions and through habitat and ecosystem modifications, with the nature and magnitude of those impacts being site- and species-specific. For offshore wind energy, implications for benthic resources, fisheries and marine life more generally must be considered. Research is also underway on the potential impact of wind power plants on the local climate. Bird and bat fatalities through collisions with wind turbines are among the most publicized environmental concerns. Though much remains unknown about the nature and population-level implications of these impacts, avian fatality rates have been reported at between 0.95 and 11.67 per MW per year. Raptor fatalities, though much lower in absolute number, have raised special concerns in some cases, and as offshore wind energy has increased, concerns have also been raised about seabirds. Bat fatalities have not been researched as extensively, but fatality rates ranging from 0.2 to 53.3 per MW per year have been reported; the impact of wind power plants on bat populations is of particular contemporary concern. The magnitude and population-level consequences of bird and bat collision fatalities can also be viewed in the context of other fatalities caused by human activities. The number of bird fatalities at existing wind power plants appears to be orders of magnitude lower than other anthropogenic causes of bird deaths, it has been suggested that onshore wind power plants are not currently causing meaningful declines in bird population levels, and other energy supply options also impact birds and bats through collisions, habitat modifications and contributions to global climate change. Improved methods to assess species-specific population-level impacts and their possible mitigation are needed, as are robust comparisons between the impacts of wind energy and of other electricity supply options. [7.6.2]

Wind power plants can also impact habitats and ecosystems through avoidance of or displacement from an area, habitat destruction and reduced reproduction. Additionally, the impacts of wind power plants on marine life have moved into focus as offshore development has increased. The impacts of offshore wind energy on marine life vary between the installation, operation and decommissioning phases, depend greatly on site-specific conditions, and may be negative or positive. Potential negative impacts include underwater sounds and vibrations, electromagnetic fields, physical disruption and the establishment of invasive species. The physical structures may, however, create new breeding grounds or shelters and act as artificial reefs or fish aggregation devices. Additional research is warranted on these impacts and their long-term and population-level consequences, but they do not appear to be disproportionately large compared to onshore wind energy. [7.6.2]

Surveys have consistently found wind energy to be widely accepted by the general public. Translating this support into increased deployment, however, often requires the support of local host communities and/or decision makers. To that end, in addition to ecological concerns, a number of concerns are often raised about the impacts of wind power plants on local communities. Perhaps most importantly, modern wind energy technology involves large structures, so wind turbines are unavoidably visible in the landscape. Other impacts of concern include land and marine usage (including possible radar interference), proximal impacts such as noise and flicker, and property value impacts. Regardless of the type and degree of social and environmental concerns, addressing them is an essential part of any successful wind power planning and plant siting process, and engaging local residents is often an integral aspect of that process. Though some of the concerns can be readily mitigated, others—such as visual impacts—are more difficult to address. Efforts to better understand the nature and magnitude of the remaining impacts, together with efforts to minimize and mitigate those impacts, will need to be pursued in concert with increasing wind energy deployment. In practice, planning and siting regulations vary dramatically by jurisdiction, and planning and siting processes have been obstacles to wind energy development in some countries and contexts. [7.6.3]

7.7 Prospects for technology improvement and innovation

Over the past three decades, innovation in wind turbine design has led to significant cost reductions. Public and private R&D programmes have played a major role in these technical advances, leading to system- and component-level technology improvements, as well as improvements in resource assessment, technical standards, electric system integration, wind energy forecasting and other areas. From 1974 to 2006, government R&D budgets for wind energy in IEA countries totalled USD_{2005} 3.8 billion, representing 1% of total energy R&D expenditure. In 2008, OECD research funding for wind energy totalled USD_{2005} 180 million. [7.7, 7.7.1]

Though onshore wind energy technology is already commercially manufactured and deployed at a large scale, continued incremental advances are expected to yield improved turbine design procedures, more efficient materials usage, increased reliability and energy capture, reduced O&M costs and longer component lifetimes. In addition, as offshore wind energy gains more attention, new technology challenges arise and more radical technology innovations are possible. Wind power plants and turbines are complex systems that require integrated design approaches to optimize cost and performance. At the plant level, considerations include the selection of a wind turbine for a given wind resource regime; wind turbine siting, spacing and installation procedures; O&M methodologies; and electric system integration. Studies have identified a number of areas where technology advances could result in changes in the investment cost, annual energy production, reliability, O&M cost and electric system integration of wind energy. [7.3.1, 7.7.1, 7.7.2]

At the component level, a range of opportunities are being pursued, including: advanced tower concepts that reduce the need for large cranes and minimize materials demands; advanced rotors and blades through better designs, coupled with better materials and advanced manufacturing methods; reduced energy losses and improved availability through advanced turbine control and condition monitoring; advanced drive trains, generators and power electronics; and manufacturing learning improvements. [7.7.3]

In addition, there are several areas of possible advancement that are more specific to offshore wind energy, including O&M procedures, installation and assembly schemes, support structure design, and the development of larger turbines, possibly including new turbine concepts. Foundation structure innovation, in particular, offers the potential to access deeper waters, thereby increasing the technical potential of wind energy. Offshore turbines have historically been installed primarily in relatively shallow water, up to 30 m deep, on a mono-pile structure that is essentially an extension of the tower, but gravity-based structures have become more common. These approaches, as well as other concepts that are more appropriate for deeper waters, including floating platforms, are depicted in Figure TS.7.4. Additionally, offshore turbine size is not restricted in the same way as onshore wind turbines, and the relatively higher cost of offshore foundations provides motivation for larger turbines. [7.7.3]

Wind turbines are designed to withstand a wide range of challenging conditions with minimal attention. Significant effort is therefore needed to enhance fundamental understanding of the operating environment in which turbines operate in order to facilitate a new generation of reliable, safe, cost-effective wind turbines, and to further optimize wind power plant siting and design. Research in the areas of aeroelastics, unsteady aerodynamics, aeroacoustics, advanced control systems, and atmospheric science, for example, is anticipated to lead to improved design tools, and thereby increase the reliability of the technology and encourage further design innovation. Fundamental research of this nature will help improve wind turbine design, wind power plant performance estimates, wind resource assessments, short-term wind energy forecasting, and estimates of the impact of large-scale wind energy deployment on the local climate, as well as the impact of potential climate change effects on wind resources. [7.7.4]

7.8 Cost trends

Though the cost of wind energy has declined significantly since the 1980s, policy measures are currently required to ensure rapid deployment in most regions of the world. In some areas with good wind resources, however, the cost of wind energy is competitive with current energy market prices, even without considering relative environmental impacts. Moreover, continued technology advancements are expected, supporting further cost reduction. [7.8]

The levelized cost of energy from on- and offshore wind power plants is affected by five primary factors: annual energy production; investment costs; O&M costs; financing costs; and the assumed economic life of

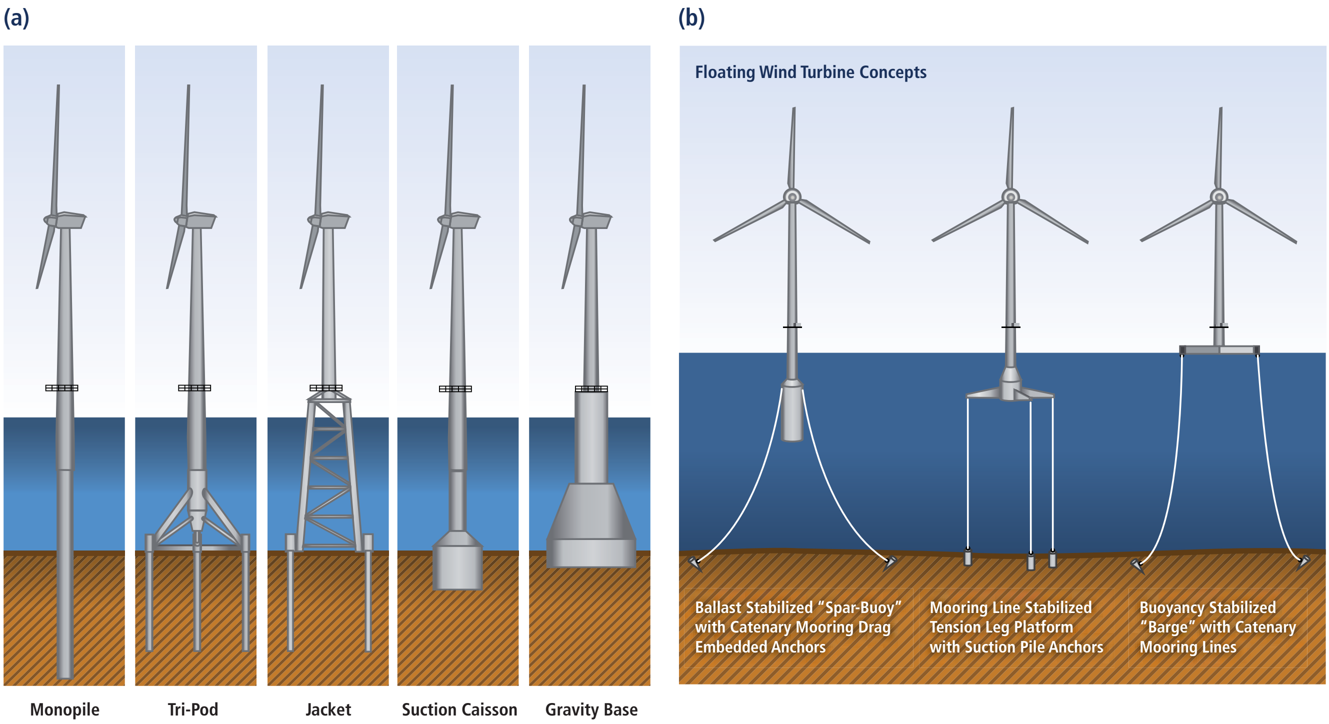


Figure TS.7.4 | Offshore wind turbine foundation designs: (a) near-term concepts and (b) floating offshore turbine concepts. [Figure 7.19] the power plant.[13] From the 1980s to roughly 2004, the investment cost of onshore wind power plants dropped. From 2004 to 2009, however, investment costs increased, the primary drivers of which were: escalation in the cost of labour and materials inputs; increasing profit margins among turbine manufacturers and their suppliers; the relative strength of the Euro currency; and the increased size of turbine rotors and hub heights. In 2009, the average investment cost for onshore wind power plants installed worldwide was approximately USD_{2005} 1,750/kW, with many plants falling in the range of USD_{2005} 1,400 to 2,100/kW; investment costs in China in 2008 and 2009 were around USD_{2005} 1,000 to 1,350/kW. There is far less experience with offshore wind power plants, and the investment costs of offshore plants are highly site-specific. Nonetheless, the investment costs of offshore plants have historically been 50 to more than 100% higher than for onshore plants; O&M costs are also greater for offshore plants. Offshore costs have also been influenced by some of the same factors that caused rising onshore costs from 2004 through 2009, as well as by several unique factors. The most recently installed or announced offshore plants have investment costs that are reported to range from roughly USD_{2005} 3,200/kW to USD_{2005} 5,000/kW. Notwithstanding the increased water depth of offshore plants over time, the majority of the operating plants have been built in relatively shallow water. The performance of wind power plants is highly site-specific, and is primarily governed by the characteristics of the local wind regime, but is also impacted by wind turbine design optimization, performance and availability, and by the effectiveness of O&M procedures. Performance therefore varies by location, but has also generally improved with time. Offshore wind power plants are often exposed to better wind resources. [7.8.1–7.8.3]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for on- and offshore wind power plants over a large set and range of input parameters has been calculated to range from US $cent_{2005}$ 3.5/kWh to US $cent_{2005}$ 17/kWh and from US $cent_{2005}$ 7.5/kWh to US $cent_{2005}$ 23/kWh, respectively. [1.3.2, 10.5.1, Annex II, Annex III]

Figure TS.7.5 presents the LCOE of on- and offshore wind energy over a somewhat different set and range of parameters, and shows that the LCOE varies substantially depending on assumed investment costs, energy production and discount rates. For onshore wind energy, estimates are provided for plants built in 2009; for offshore wind energy, estimates are provided for plants built from 2008 to 2009 as well as those plants that were planned for completion in the early 2010s. The LCOE for onshore wind energy in good to excellent wind resource regimes are estimated to average approximately US $cent_{2005}$ 5/kWh to US $cent_{2005}$ 10/kWh, and can reach more than US $cent_{2005}$ 15/kWh in lower-resource areas. Though

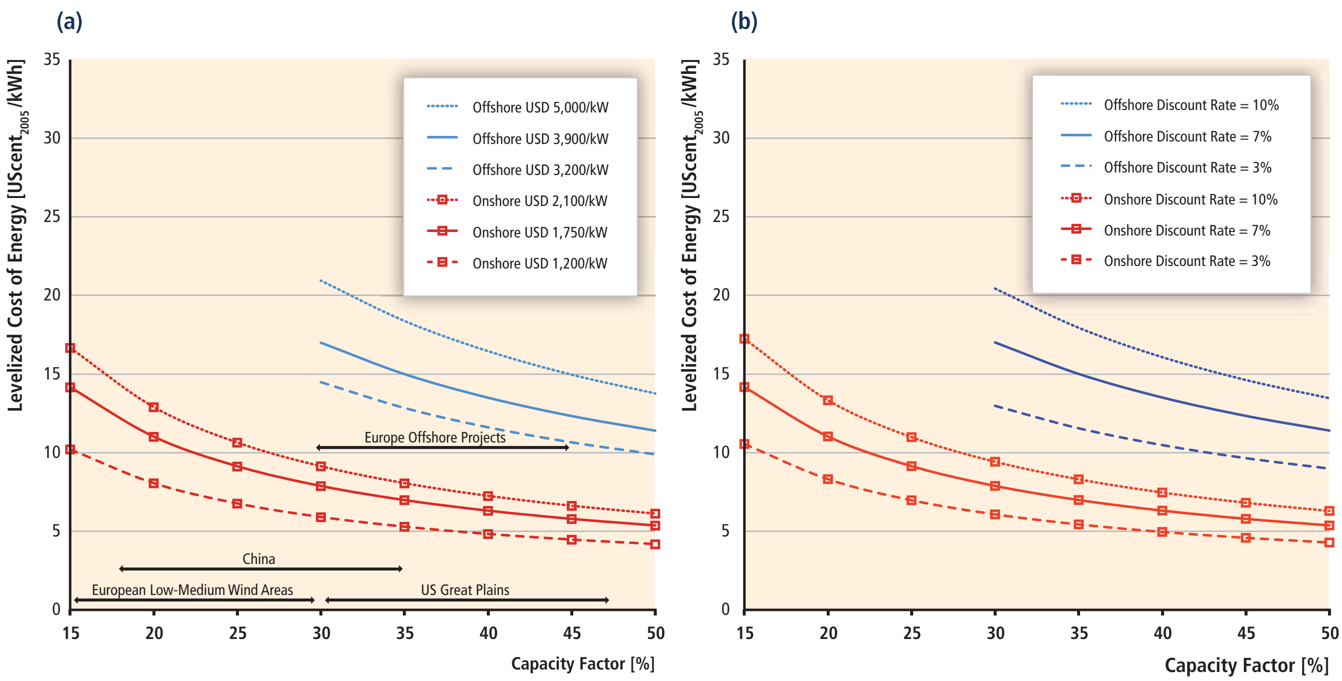


Figure TS.7.5 | Estimated levelized cost of on- and offshore wind energy, 2009: (a) as a function of capacity factor and investment cost* and (b) as a function of capacity factor and discount rate**. [Figure 7.23]

Notes: * Discount rate assumed to equal 7%. ** Onshore investment cost assumed at USD_{2005} 1,750/kW, and offshore at USD_{2005} 3,900/kW.

13 The economic competitiveness of wind energy in comparison to other energy sources, which necessarily must also include other factors such as subsidies and environmental externalities, is not covered in this section.

the offshore cost estimates are more uncertain, typical LCOE are estimated to range from US cent$_{2005}$ 10/kWh to more than US cent$_{2005}$ 20/kWh for recently built or planned plants located in relatively shallow water. Where the exploitable onshore wind resource is limited, offshore plants can sometimes compete with onshore plants. [7.8.3, Annex II, Annex III]

A number of studies have developed forecasted cost trajectories for on- and offshore wind energy based on differing combinations of learning curve estimates, engineering models and/or expert judgement. Among these studies, the starting year of the forecasts, the methodological approaches and the assumed wind energy deployment levels vary. Nonetheless, a review of this literature supports the idea that continued R&D, testing and experience could yield reductions in the levelized cost of onshore wind energy of 10 to 30% by 2020. Offshore wind energy is anticipated to experience somewhat deeper cost reductions of 10 to 40% by 2020, though some studies have identified scenarios in which market factors lead to cost increases in the near to medium term. [7.8.4]

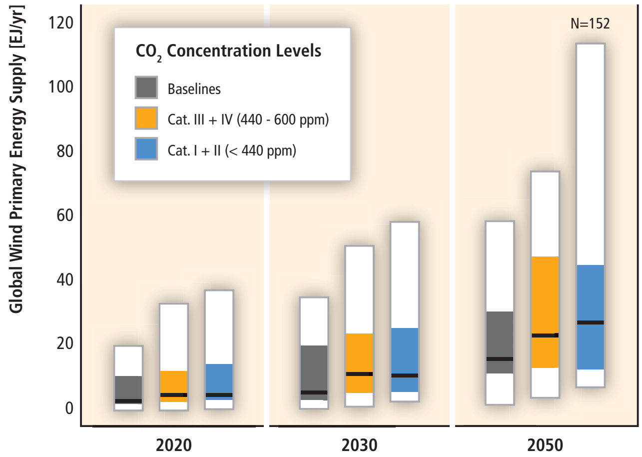


Figure TS.7.6 | Global primary energy supply of wind energy in long-term scenarios (median, 25th to 75th percentile range, and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration level in 2100; the specific number of scenarios underlying the figure is indicated in the right upper corner). [Figure 7.24]

7.9 Potential deployment

Given the commercial maturity and cost of onshore wind energy technology, increased utilization of wind energy offers the potential for significant near-term GHG emission reductions: this potential is not conditioned on technology breakthroughs, and no insurmountable technical barriers exist that preclude increased levels of wind energy penetration into electricity supply systems. As a result, in the near to medium term, the rapid increase in wind power capacity from 2000 to 2009 is expected by many studies to continue. [7.9, 7.9.1]

Moreover, a number of studies have assessed the longer-term potential of wind energy, often in the context of GHG concentration stabilization scenarios. [10.2, 10.3] Based on a review of this literature (including 164 different long-term scenarios), and as summarized in Figure TS.7.6, wind energy could play a significant long-term role in reducing global GHG emissions. By 2050, the median contribution of wind energy among the scenarios with GHG concentration stabilization ranges of 440 to 600 ppm CO_2 and <440 ppm CO_2 is 23 to 27 EJ/yr (6,500 to 7,600 TWh/yr), increasing to 45 to 47 EJ/yr at the 75th percentile of scenarios (12,400 to 12,900 TWh/yr), and to more than 100 EJ/yr in the highest study (31,500 TWh). Achieving this contribution would require wind energy to deliver around 13 to 14% of global electricity supply in the median scenario result by 2050, increasing to 21 to 25% at the 75th percentile of the reviewed scenarios. [7.9.2]

Achieving the higher end of this range of global wind energy utilization would likely require not only economic support policies of adequate size and predictability, but also an expansion of wind energy utilization regionally, increased reliance on offshore wind energy in some regions, technical and institutional solutions to transmission constraints and operational integration concerns, and proactive efforts to mitigate and manage social and environmental concerns. Additional R&D is expected to lead to incremental cost reductions for onshore wind energy, and enhanced R&D expenditures may be especially important for offshore wind energy technology. Finally, for those markets with good wind resource potential but that are new to wind energy deployment, both knowledge and technology transfer may help facilitate early wind power plant installations. [7.9.2]

8. Integration of Renewable Energy into Present and Future Energy Systems

8.1 Introduction

In many countries, energy supply systems have evolved over decades, enabling the efficient and cost-effective distribution of electricity, gas, heat and transport energy carriers to provide useful energy services to end users. The transition to a low-carbon future that employs high shares of RE may require considerable investment in new RE technologies and infrastructure, including more flexible electricity grids, expansion of district heating and cooling schemes, distribution systems for RE-derived gases and liquid fuels, energy storage systems, novel methods of transport, and innovative distributed energy and control systems in buildings. Enhanced RE integration can lead to the provision of the full range of energy services for large and small communities in both developed and developing countries. Regardless of the energy supply system presently in place, whether in energy-rich or energy-poor communities, over the long term, and through measured system planning and integration, there are few, if any, technical limits to increasing the shares of RE at the national, regional and local scales as well as for individual buildings, although other barriers may need to be overcome. [8.1, 8.2]

Energy supply systems are continuously evolving, with the aim of increasing conversion technology efficiencies, reducing losses and lowering the costs of providing energy services to end users. To provide a greater share of RE heating, cooling, transport fuels and electricity may require modification of current policies, markets and existing energy supply systems over time so that they can accommodate higher rates of deployment leading to greater supplies of RE. [8.1]

All countries have access to some RE resources and in many parts of the world these are abundant. The characteristics of many of these resources distinguish them from fossil fuels and nuclear systems. Some resources, such as solar and ocean energy, are widely distributed, whereas others, such as large-scale hydropower, are constrained by geographic location and hence integration options are more centralized. Some RE resources are variable and have limited predictability. Others have lower energy densities and their technical specifications differ from solid, liquid and gaseous fossil fuels. Such RE resource characteristics can constrain the ease of integration and invoke additional system costs, particularly when reaching higher shares of RE. [8.1, 8.2]

Following the structural outline of Chapter 8, RE resources can be used through integration into energy supply networks delivering energy to consumers using energy carriers with varying shares of RE embedded or by direct integration into the transport, buildings, industry and agriculture end-use sectors (Figure TS.8.1). [8.2, 8.3]

The general and specific requirements for enhanced integration of RE into energy supply systems are reasonably well understood. However, since integration issues tend to be site-specific, analyses of typical additional costs for RE integration options are limited and future research is required for use in scenario modelling. For example, it is not clear how the possible trend towards more decentralized energy supply systems might affect the future costs for developing further centralized heat and power supplies and the possible avoidance of constructing new infrastructure. [8.2]

Centralized energy systems, based mainly on fossil fuels, have evolved to provide reasonably cost-effective energy services to end users using

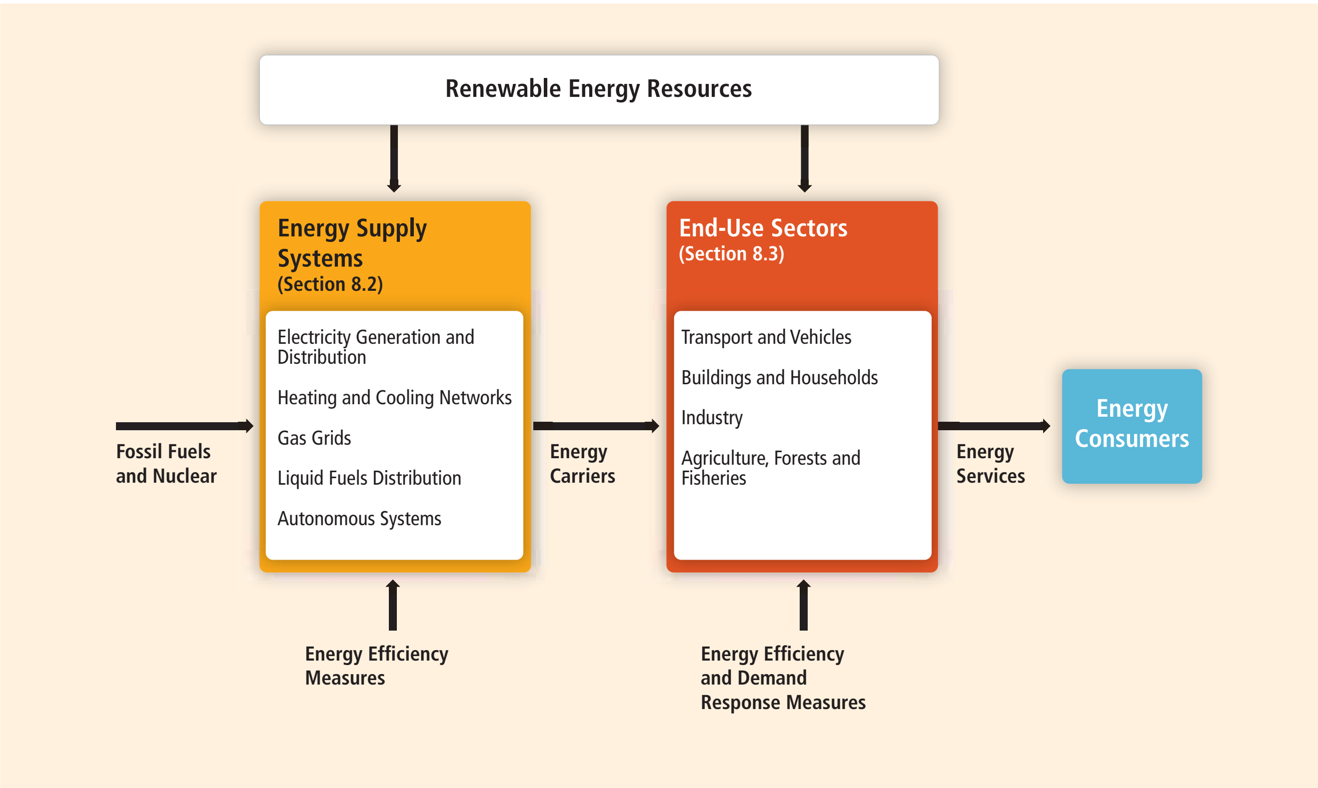


Figure TS.8.1 | Pathways for RE integration to provide energy services, either into energy supply systems or on-site for use by the end-use sectors. [Figure 8.1] a range of energy carriers including solid, liquid and gaseous fuels, electricity, and heat. Increasing the deployment of RE technologies requires their integration into these existing systems by overcoming the associated technical, economic, environmental and social barriers. The advent of decentralized energy systems could open up new deployment opportunities. [8.1, 8.2]

In some regions, RE electricity systems could become the dominant future energy supply, especially if heating and transport demands are also to be met by electricity. This could be driven by parallel developments in electric vehicles, increased heating and cooling using electricity (including heat pumps), flexible demand response services (including the use of smart meters), and other innovative technologies. [8.1, 8.2.1.2, 8.2.2, 8.3.1–8.3.3]

The various energy systems differ markedly between countries and regions around the world and each is complex. As a result, a range of approaches are needed to encourage RE integration, whether centralized or decentralized. Prior to making any significant change in an energy supply system that involves increasing the integration of RE, a careful assessment of the RE resource availability; the suitability of existing technologies; institutional, economic and social constraints; the potential risks; and the need for related capacity building and skills development should be undertaken. [8.1, 8.2]

The majority of scenarios that stabilize atmospheric GHG concentrations around 450 ppm CO_2eq show that RE will exceed a 50% share of low-carbon primary energy by 2050. This transition can be illustrated by many scenarios, the single example of increasing market shares shown in Figure TS.8.2 being based on the IEA's World Energy Outlook 2010 '450 Policy Scenario'. To achieve such increased shares of primary and consumer energy from RE by 2035 would require the annual average incremental growth in primary RE to more than treble from today's level to around 4.0 EJ/yr. [8.1, 10.2, 10.2.2.4]

In order to gain greater RE deployment in each of the transport, building, industry and agriculture sectors, strategic elements need to be better understood, as do the social issues. Transition pathways for increasing the shares of each RE technology through integration depend on the specific sector, technology and region. Facilitating a smoother integration with energy supply systems and providing multiple benefits for energy end users should be the ultimate aims. [8.2, 8.3]

Several mature RE technologies have already been successfully integrated into a wide range of energy supply systems, mostly at relatively low shares but with some examples (including small- and large-scale hydropower, wind power, geothermal heat and power, first-generation biofuels and solar water heating systems) exceeding 30%. This was due mainly to their improved cost-competitiveness, an increase in support policies and growing public support due to the threats of an insecure energy supply and climate change. Exceptional examples are large-scale hydropower in Norway and hydro and geothermal power in Iceland approaching 100% of RE electricity, as has also been achieved by several small islands and towns. [8.2.1.3, 8.2.5.5, 11.2, 11.5]

Other less mature technologies require continuing investment in research, development, and demonstration (RD&D), infrastructure, capacity building and other supporting measures over the longer term. Such technologies include advanced biofuels, fuel cells, solar fuels, distributed power generation control systems, electric vehicles, solar absorption cooling and enhanced geothermal systems. [11.5, 11.6]

The current status of RE use varies for each end-use sector. There are also major regional variations in future pathways to enhance further integration by removal of barriers. For example, in the building sector, integrating RE technologies is vastly different for commercial high-rise buildings and apartments in mega-cities than for integration into small, modest village dwellings in developing countries that currently have limited access to energy services. [8.3.2]

Most energy supply systems can accommodate a greater share of RE than at present, particularly if the RE share is at relatively low levels (usually assumed to be below a 20% share of electricity, heat, pipeline gas blend or biofuel blend). To accommodate higher RE shares in the future, most energy supply systems will need to evolve and be adapted. In all cases, the maximum practical RE share will depend on the technologies involved, the RE resources available and the type and age of the present energy system. Further integration and increased rates of deployment can be encouraged by local, national and regional initiatives. The overall aim of Chapter 8 is to present the current knowledge on opportunities and challenges relating to RE integration for governments wishing to develop a coherent framework in preparation for future higher levels of RE penetration. Existing power supply systems, natural gas grids, heating/cooling schemes, petroleum-based transport fuel supply distribution networks and vehicles can all be adapted to accommodate greater supplies of RE than at present. RE technologies range from mature to those at the early concept demonstration stage. New technologies could enable increased RE uptake and their integration will depend upon improved cost-effectiveness, social acceptance, reliability and political support at national and local government levels in order to gain greater market shares. [8.1.2, 11.5]

Taking a holistic approach to the whole energy system may be a prerequisite to ensure efficient and flexible RE integration. This would include achieving mutual support between the different energy sectors, an intelligent forecasting and control strategy and coherent long-term planning. Together, these would enable the provision of electricity, heating, cooling and mobility to be more closely inter-linked. The optimum combination of technologies and social mechanisms to enable RE integration to reach high shares varies with the limitations of specific site conditions, characteristics of the available RE resources, and local energy demands. Exactly how present energy supply and demand systems can be adapted and developed to accommodate higher shares of RE, and the additional costs involved for their integration, depend on the specific circumstances, so

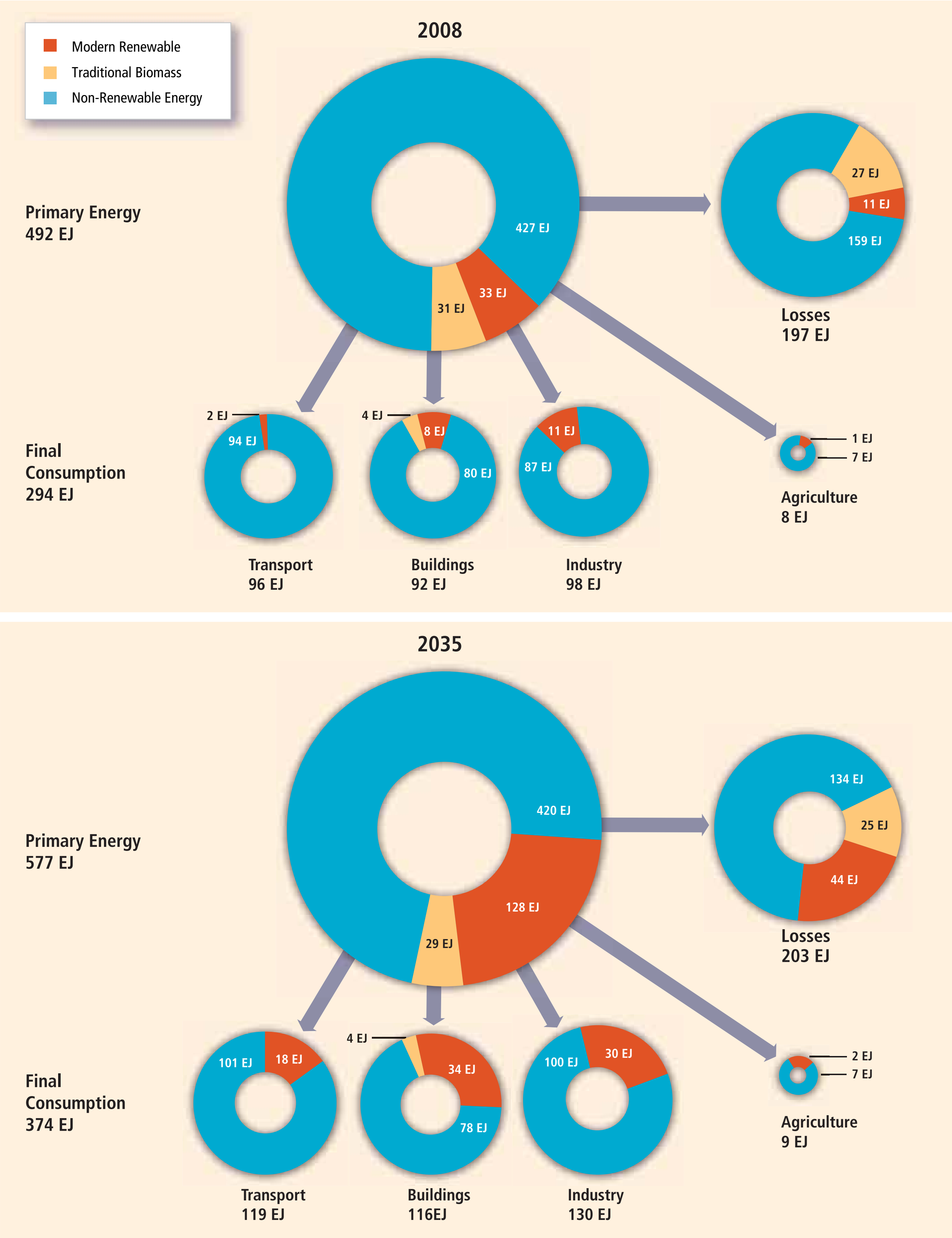

Modern Renewable
Traditional Biomass
Non-Renewable Energy
2008
Primary Energy
492 EJ
427 EJ
33 EJ
31 EJ
27 EJ
11 EJ
159 EJ
Losses
197 EJ
Final
Consumption
294 EJ
2 EJ
94 EJ
4 EJ
8 EJ
80 EJ
11 EJ
87 EJ
1 EJ
7 EJ
Agriculture
8 EJ
Transport
96 EJ
Buildings
92 EJ
Industry
98 EJ
2035
Primary Energy
577 EJ
420 EJ
128 EJ
29 EJ
134 EJ
25 EJ
44 EJ
Losses
203 EJ
Final
Consumption
374 EJ
101 EJ
18 EJ
4 EJ
34 EJ
78 EJ
100 EJ
30 EJ
2 EJ
7 EJ
Agriculture
9 EJ
Transport
119 EJ
Buildings
116EJ
Industry
130 EJ

Figure TS.8.2 | (Preceding page) RE shares (red) of primary and final consumption energy in the transport, buildings (including traditional biomass), industry and agriculture sectors in 2008 and an indication of the projected increased RE shares needed by 2035 in order to be consistent with a 450 ppm CO_2eq stabilization level. [Figure 8.2]

Notes: Area of circles are approximately to scale. Energy system losses occur during the conversion, refining and distribution of primary energy sources to produce energy services for final consumption. 'Non-renewable' energy (blue) includes coal, oil, natural gas (with and without CCS by 2035) and nuclear power. This scenario example is based on data taken from the IEA World Energy Outlook 2010 but converted to direct equivalents. [Annex II.4] Energy efficiency improvements above the baseline are included in the 2035 projection. RE in the buildings sector includes traditional solid biomass fuels (yellow) for cooking and heating for 2.7 billion people in developing countries [2.2] along with some coal. By 2035, some traditional biomass has been partly replaced by modern bioenergy conversion systems. Excluding traditional biomass, the overall RE system efficiency (when converting from primary to consumer energy) remains around 66%.

further studies will be required. This is particularly the case for the electricity sector due to the wide variety of existing power generation systems and scales that vary with country and region. [8.2.1, 8.2.2, 8.3]

8.2 Integration of renewable energy into electrical power systems

Electrical power systems have been evolving since the end of the 19th century. Today, electrical power systems vary in scale and technological sophistication from the synchronized Eastern Interconnection in North America to small individual diesel-powered autonomous systems, with some systems, as in China, undergoing rapid expansion and transformation. Within these differences, however, electrical power systems are operated and planned with a common purpose of providing a reliable and cost-effective supply of electricity. Looking forward, electric power systems are expected to continue to expand in importance given that they supply modern energy, enable the transport of energy over long distances, and provide a potential pathway for delivering low-carbon energy. [8.2.1]

Electric power systems have several important characteristics that affect the challenges of integrating RE. The majority of electric power systems operate using alternating current (AC) whereby the majority of generation is synchronized and operated at a frequency of approximately either 50 or 60 Hz, depending on the region. The demand for electricity varies throughout the day, week and season, depending on the needs of electricity users. The aggregate variation in demand is matched by variation in schedules and dispatch instructions for generation in order to continuously maintain a balance between supply and demand. Generators and other power system assets are used to provide active power control to maintain the system frequency and reactive power control to maintain voltage within specified limits. Minute-to-minute variations in supply and demand are managed with automatic control of generation through services called regulation and load following, while changes over longer time scales of hours to days are managed by dispatching and scheduling generation (including turning generation on or off, which is also known as unit commitment). This continuous balancing is required irrespective of the mechanism used to achieve it. Some regions choose organized electricity markets in order to determine which generation units should be committed and/or how they should be dispatched. Even autonomous systems must employ methods to maintain a balance between generation and demand (via controllable generators, controllable loads, or storage resources like batteries). [8.2.1.1]

In addition to maintaining a balance between supply and demand, electric power systems must also transfer electricity between generation and demand through transmission and distribution networks with limited capacity. Ensuring availability of adequate generation and network capacity requires planning over multiple years. Planning electrical power systems incorporates the knowledge that individual components of the system, including generation and network components, will periodically fail (a contingency). A target degree of reliability can be met, however, by building adequate resources. One important metric used to determine the contribution of generation—fossil-fuel based or renewable—to meeting demand with a target level of reliability is called the capacity credit. [8.2.1.1]

Based on the features of electrical power systems, several RE characteristics are important for integrating RE into power systems. In particular, variability and predictability (or uncertainty) of RE is relevant for scheduling and dispatch in the electrical power system, the location of RE resources is a relevant indicator for impact on needs for electrical networks, and capacity factor, capacity credit and power plant characteristics are indicators relevant for comparison, for example, with thermal generation. [8.2.1.2]

Some RE electricity resources (particularly ocean, solar PV, wind) are variable and only partially dispatchable: generation from these resources can be reduced if needed, but maximum generation depends on availability of the RE resource (e.g., tidal currents, sun or wind). The capacity credit can be low if the generation is not well correlated with times of high demand. In addition, the variability and partial predictability of some RE increases the burden on dispatchable generation or other resources to ensure balance between supply and demand given deviations in RE. In many cases variability and partial predictability are somewhat mitigated by geographic diversity—changes and forecast errors will not always occur at the same time in the same direction. A general challenge for most RE, however, is that renewable resources are location specific, therefore concentrated renewably generated electricity may need to be transported over considerable distances and require network expansion. Dispatchable renewable sources (including hydropower, bioenergy, geothermal energy, and CSP with thermal storage) can in many cases offer extra flexibility for the system to integrate other renewable sources and often have a higher capacity credit. [8.2.1.2]

A very brief summary of the particular characteristics for a selection of the technologies is given in Table TS.8.1. [8.2.1.3]

Table TS.8.1 | Summary of integration characteristics for a selection of RE technologies. [Table 8.1]

Technology		Plant size range (MW)	Variability: Characteristic time scales for power system operation (Time scale)	Dispatchability (See legend)	Geographical diversity potential (See legend)	Predictability (See legend)	Capacity factor range %	Capacity credit range %	Active power, frequency control (See legend)	Voltage, reactive power control (See legend)
Bioenergy		0.1–100	Seasons (depending on biomass availability)	+++	+	++	50–90	Similar to thermal and CHP	++	++
Direct solar energy	PV	0.004–100 modular	Minutes to years	+	++	+	12–27	<25–75	+	+
	CSP with thermal storage[1]	50–250	Hours to years	++	+[2]	++	35–42	90	++	++
Geothermal energy		2–100	Years	+++	N/A	++	60–90	Similar to thermal	++	++
Hydro power	Run of river	0.1–1,500	Hours to years	++	+	++	20–95	0–90	++	++
	Reservoir	1–20,000	Days to years	+++	+	++	30–60	Similar to thermal	++	++
Ocean Energy	Tidal range	0.1–300	Hours to days	+	+	++	22.5–28.5	<10%	++	++
	Tidal current	1–200	Hours to days	+	+	++	19–60	10–20	+	++
	Wave	1–200	Minutes to years	+	++	+	22–31	16	+	+
Wind energy		5–300	Minutes to years	+	++	+	20–40 onshore, 30–45 offshore	5–40	+	++

Notes: 1. Assuming a CSP system with six hours of thermal storage in US Southwest. 2. In areas with direct-normal irradiance (DNI) >2,000 $kWh/m^2/yr$ (7,200 $MJ/m^2/yr$).

Plant size: range of typical rated plant capacity.

Characteristic time scales: time scales where variability significant for power system integration occurs.

Dispatchability: degree of plant dispatchability: + low partial dispatchability, ++ partial dispatchability, +++ dispatchable.

Geographical diversity potential: degree to which siting of the technology may mitigate variability and improve predictability, without substantial need for additional network: +moderate potential, ++ high diversity potential.

Predictability: Accuracy to which plant output power can be predicted at relevant time scales to assist power system operation: + moderate prediction accuracy (typical <10% Root Mean Square (RMS) error of rated power day ahead), ++ high prediction accuracy.

Active power and frequency control: technology possibilities enabling plant to participate in active power control and frequency response during normal situations (steady state, dynamic) and during network fault situations (for example active power support during fault ride-through): + good possibilities, ++ full control possibilities.

Voltage and reactive power control: technology possibilities enabling plant to participate in voltage and reactive power control during normal situations (steady state, dynamic) and during network fault situations (for example reactive power support during fault ride-through): + good possibilities, ++ full control possibilities.

There is already significant experience with operating electrical power systems with a large share of renewable sources, in particular hydropower and geothermal power. Hydropower storage and strong interconnections help manage fluctuations in river flows. Balancing costs for variable generation are incurred when there are differences between the scheduled generation (according to forecasts) and the actual production. Variability and uncertainty increase balancing requirements. Overall, balancing is expected to become more difficult to achieve as partially dispatchable RE penetrations increase. Studies show clearly that combining different variable renewable sources, and resources from larger geographical areas, will be beneficial in smoothing the variability and decreasing overall uncertainty for the power systems. [8.2.1.3]

The key issue is the importance of *network infrastructure,* both to deliver power from the generation plant to the consumer as well as to enable larger regions to be balanced. Strengthening connections within an electrical power system and introducing additional interconnections to other systems can directly mitigate the impact of variable and uncertain RE sources. Network expansion is required for most RE, although the level is dependent on the resource and location relative to existing network infrastructure. Amongst other challenges will be expanding network infrastructure within the context of public opposition to overhead network infrastructure. In general, major changes will be required in the generation plant mix, the electrical power systems' infrastructure and operational procedures to make the transition to increased renewable generation while maintaining cost and environmental effectiveness. These changes will require major investments far enough in advance to maintain a reliable and secure electricity supply. [8.2.1.3]

In addition to improving network infrastructure, several other important integration options have been identified through operating experience or studies:

Increased generation flexibility: An increasing penetration of variable renewable sources implies a greater need to manage variability and uncertainty. Greater flexibility is required from the generation mix. Generation provides most of a power system's existing flexibility to cope with variability and uncertainty through ramping up or down and cycling as needed. Greater need for flexibility can imply either investment in new flexible generation or improvements to existing power plants to enable them to operate in a more flexible manner. [8.2.1.3]

Demand side measures: Although demand side measures have historically been implemented only to reduce average demand or demand during peak load periods, demand side measures may potentially contribute to meeting needs resulting from increased variable renewable generation. The development of advanced communications technology, with smart electricity meters linked to control centres, offers the potential to access much greater levels of flexibility from demand. Electricity users can be provided with incentives to modify and/or reduce their consumption by pricing electricity differently at different times, in particular with higher prices during higher demand periods. This reduction in demand during high demand periods can mitigate the impact of the low capacity credit of some types of variable generation. Furthermore, demand that can quickly be curtailed without notice during any time of the year can provide reserves rather than requiring generation resources to provide this reserve. Demand that can be scheduled to be met at anytime of the day or that responds to real-time electricity prices can participate in intra-day balancing thereby mitigating operational challenges that are expected to become increasingly difficult with variable generation. [8.2.1.3]

Electrical energy storage: By storing electrical energy when renewable output is high and the demand low, and generating when renewable output is low and the demand high, the curtailment of RE can be reduced, and the base-load units on the system will operate more efficiently. Storage can also reduce transmission congestion and may reduce the need for, or delay, transmission upgrades. Technologies such as batteries or flywheels that store smaller amounts of energy (minutes to hours) can in theory be used to provide power in the intra-hour timeframe to regulate the balance between supply and demand. [8.2.1.3]

Improved operational/market and planning methods: To help cope with the variability and uncertainty associated with variable generation sources, forecasts of their output can be combined with improved operational methods to determine both the required reserve to maintain the demand-generation balance, and also optimal generation scheduling. Making scheduling decisions closer to real time (i.e., shorter gate closure time in markets) and more frequently allows newer, more accurate information to be used in dispatching generating units. Moving to larger balancing areas, or shared balancing between areas, is also desirable with large amounts of variable generation, due to the aggregation benefits of multiple, dispersed renewable sources. [8.2.1.3]

In summary, RE can be integrated into all types of electrical power systems from large interconnected continental-scale systems to small autonomous systems. System characteristics including the network infrastructure, demand pattern and its geographic location, generation mix, control and communication capability combined with the location, geographical footprint, variability and predictability of the renewable resources determine the scale of the integration challenge. As the amounts of RE resources increase, additional electricity network infrastructure (transmission and/or distribution) will generally have to be constructed. Variable renewable sources, such as wind, can be more difficult to integrate than dispatchable renewable sources, such as bioenergy, and with increasing levels maintaining reliability becomes more challenging and costly. These challenges and costs can be minimized by deploying a portfolio of options including electrical network interconnection, the development of complementary flexible generation, larger balancing areas, sub-hourly markets, demand that can respond in relation to supply availability, storage technologies, and better forecasting, system operating and planning tools.

8.3 Integration of renewable energy into heating and cooling networks

A district heating (DH) or district cooling (DC) network allows multiple energy sources (Figure TS.8.3) to be connected to many energy consumers by pumping the energy carriers (hot or cold water and sometimes steam) through insulated underground pipelines. Centralized heat production can facilitate the use of low-cost and/or low-grade RE heat from geothermal or solar thermal sources or combustion of biomass (including refuse-derived fuels and waste by-products that are often unsuitable for use by individual heating systems). Waste heat from CHP generation and industrial processes can also be used. This flexibility produces competition among various heat sources, fuels and technologies. Centralized heat production can also facilitate the application of cost-effective measures that reduce local air pollution compared with having a multitude of small individual boilers. Being flexible in the sources of heat or cold utilized, district heating and cooling systems allow for the continuing uptake of several types of RE so that a gradual or rapid substitution of competing fossil fuels is usually feasible. [8.2.2]

Occupiers of buildings and industries connected to a network can benefit from a professionally managed central system, hence avoiding the need to operate and maintain individual heating/cooling equipment. Several high-latitude countries already have a district heating market penetration of 30 to 50%, with Iceland reaching 96% using its geothermal resources. World annual delivery of district heat has been estimated to be around 11 EJ though heat data are uncertain. [8.2.2.1]

DH schemes can provide electricity through CHP system designs and can also provide demand response options that can facilitate increased integration of RE, including by using RE electricity for heat pumps and electric boilers. Thermal storage systems can bridge the heat supply/demand gap resulting from variable, discontinuous or non-synchronized heating systems. For short-term storage (hours and days), the thermal capacity of the distribution network itself can be used. Thermal storage systems with storage periods up to several months at temperatures up to hundreds of degrees Celsius use a variety of materials and corresponding storage mechanisms that can have capacities up to several TJ. Combined production of heat, cold and electricity (tri-generation), as well as the possibility for diurnal and seasonal storage of heat and cold, mean that high overall system efficiency can be obtained and higher shares of RE achieved through increased integration. [8.2.2.2, 8.2.2.3]

Many commercial geothermal and biomass heat and CHP plants have been successfully integrated into DH systems without government support. Several large-scale solar thermal systems with collector areas

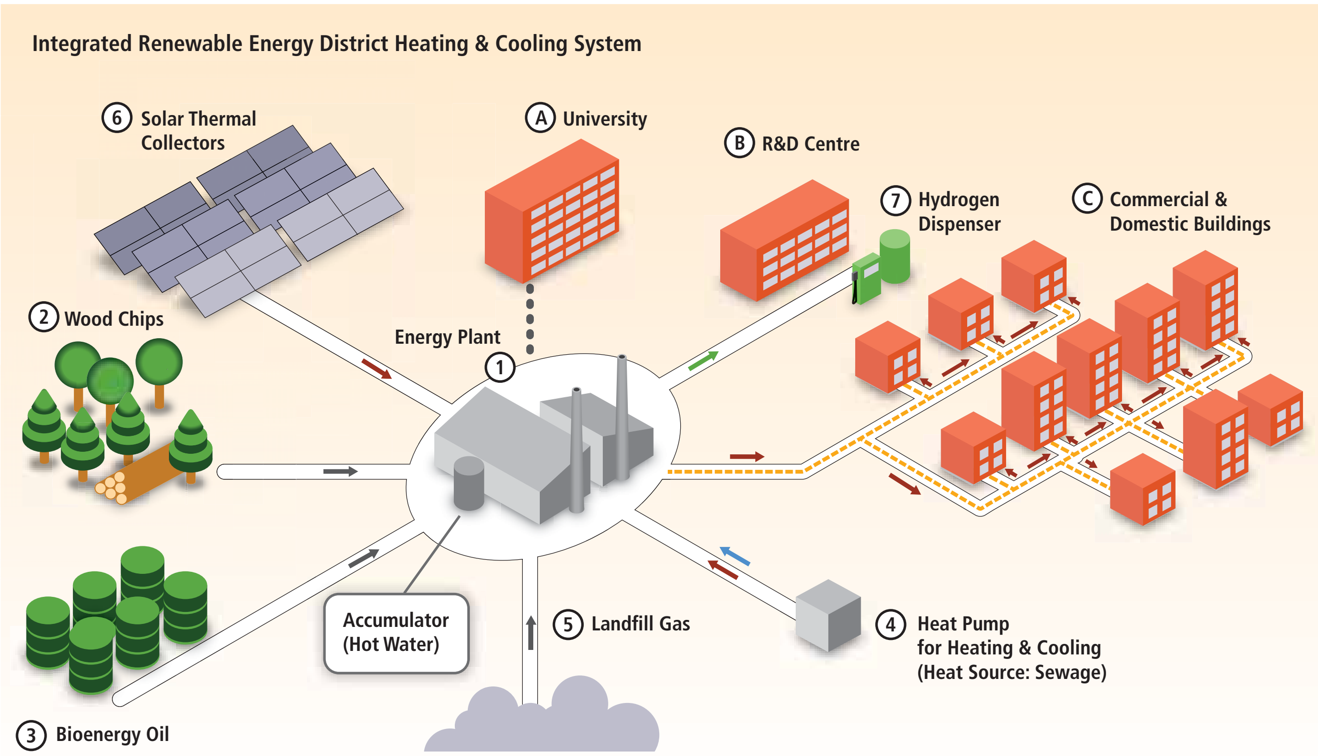


Figure TS.8.3 | An integrated RE-based energy plant in Lillestrøm, Norway, supplying the University, R&D Centre and a range of commercial and domestic buildings using a district heating and cooling system incorporating a range of RE heat sources, thermal storage and a hydrogen production and distribution system. (Total investment around USD_{2005} 25 million and due for completion in 2011.) 1) Central energy system with 1,200 m^3 accumulator hot water storage tank; (2) 20 MW_{th} wood burner system (with flue gas heat recovery); (3) 40 MW_{th} bio-oil burner; (4) 4.5 MW_{th} heat pump; (5) 1.5 MW_{th} landfill gas burner and a 5 km pipeline; (6) 10,000 m^2 solar thermal collector system; and (7) RE-based hydrogen production (using water electrolysis and sorption-enhanced steam methane reforming of landfill gas) and vehicle dispensing system. [Figure 8.3] of around 10,000 m² (Figure TS.8.3) have also been built in Denmark, Norway and elsewhere. The best mix of hot and cold sources, and heat transfer and storage technologies, depends strongly on local conditions, including user demand patterns. As a result, the heat energy supply mix varies widely between different systems. [3.5.3, 8.2.2]

Establishing or expanding a DH scheme involves high up-front capital costs for the piping network. Distribution costs alone can represent roughly half of the total cost but are subject to large variations depending on the heat demand density and the local conditions for building the insulated piping network. Increasing urbanization facilitates DH since network capital costs are lower for green-field sites and distribution losses per unit of heat delivered are lower in areas with higher heat demand densities. Heat distribution losses typically range from 5 to 30% but the extent to which high losses are considered a problem depends on the source and cost of the heat. [8.2.2.1, 8.2.2.3]

Expanding the use of deep geothermal and biomass CHP plants in DH systems can facilitate a higher share of RE sources, but to be economically viable this usually requires the overall system to have a large heat load. Some governments therefore support investments in DH networks as well as provide additional incentives for using RE in the system. [8.2.2.4]

Modern building designs and uses have tended to reduce their demand for additional heating whereas the global demand for cooling has tended to increase. The cooling demand to provide comfort has increased in some low-latitude regions where countries have become wealthier and in some higher latitudes where summers have become warmer. Cooling load reductions can be achieved by the use of passive cooling building design options or active RE solutions including solar absorption chillers. As for DH, the rate of uptake of energy efficiency to reduce cooling demand, deployment of new technologies, and the structure of the market, will determine the viability of developing a DC scheme. Modern DC systems, ranging from 5 to 300 MW_{th}, have been operating successfully for many years using natural aquifers, waterways, the sea or deep lakes as the sources of cold, classed as a form of RE. [8.2.2.4]

DH and DC schemes have typically been developed in situations where strong planning powers have existed, such as centrally planned economies, US university campuses, Western European countries with multi-utilities, and urban areas controlled by local municipalities.

8.4 Integration of renewable energy into gas grids

Over the past 50 years, large natural gas networks have been developed in several parts of the world. And more recently there has been increasing interest to 'green' them by integrating RE-based gases. Gaseous fuels from RE sources originate largely from biomass and can be produced either by anaerobic digestion to produce biogas (mainly methane and CO_2) or thermo-chemically to give synthesis (or producer) gas (mainly hydrogen and carbon monoxide). Biomethane, synthesis gas and, in the longer term, RE-based hydrogen can be injected into existing gas pipelines for distribution at the national, regional or local level. Differences in existing infrastructure, gas quality, and production and consumption levels can make planning difficult for increasing the RE share of gases by integration into an existing grid. [8.2.3, 8.2.3.1]

Biogas production is growing rapidly and several large gas companies are now making plans to upgrade large quantities for injection at the required quality into national or regional transmission gas pipelines. Most of the biomethane currently produced around the world is already distributed in local gas pipeline systems primarily dedicated for heating purposes. This can be a cheaper option per unit of energy delivered (Figure TS.8.4) than when transported by trucks (usually to filling stations for supplying gas-powered vehicles) depending on distance and the annual volume to be transported. [8.2.3.4]

Gas utilization can be highly efficient when combusted for heat; used to generate electricity by fuelling gas engines, gas boilers or gas turbines; or used in vehicles either compressed or converted to a range of liquid fuels using various processes. For example, biogas or landfill gas can be combusted onsite to produce heat and/or electricity; cleaned and upgraded to natural gas quality biomethane for injection into gas grids; or, after compressing or liquefying, distributed to vehicle filling stations for use in dedicated or dual gas-fuelled vehicles. [8.2.3.2–8.2.3.4]

Technical challenges relate to gas source, composition and quality. Only biogas and syngas of a specified quality can be injected into existing gas

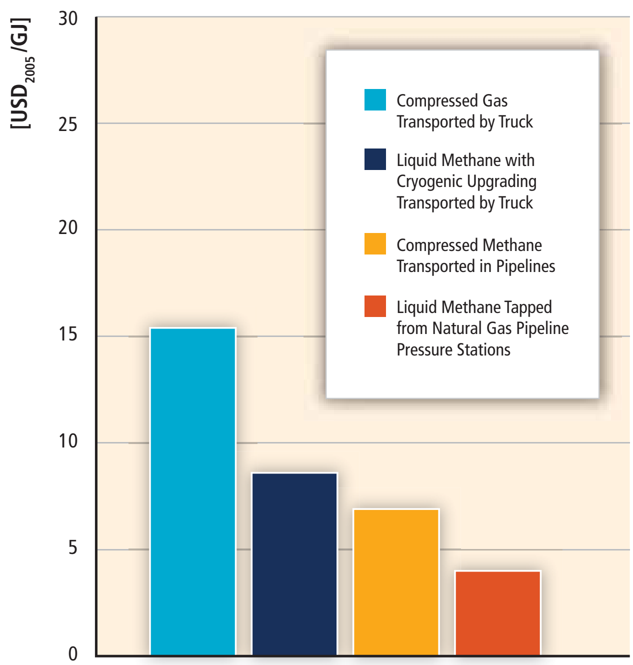


Figure TS.8.4 | Relative costs for distributing and dispensing biomethane (either compressed or liquefied) at the medium scale by truck or pipeline in Europe. [Figure 8.9] grids so clean-up is a critical step to remove water, CO_2 (thereby increasing the heating value) and additional by-products from the gas stream. The cost of upgrading varies according to the scale of the facility and the process, which can consume around 3 to 6% of the energy content of the gas. RE gas systems are likely to require significant storage capacity to account for variability and seasonality of supply. The size and shape of storage facilities and the required quality of the gas will depend on the primary energy source of production and its end use. [8.2.3]

Hydrogen gas can be produced from RE sources by several routes including biomass gasification, the reformation of biomethane, or electrolysis of water. The potential RE resource base for hydrogen is therefore greater than for biogas or syngas. Future production of hydrogen from variable RE resources, such as wind or solar power by electrolysis, will depend significantly on the interaction with existing electricity systems and the degree of surplus capacity. In the short term, blending of hydrogen with natural gas (up to 20% by volume) and transporting it long distances in existing gas grids could be an option. In the longer term, the construction of pipelines for carrying pure hydrogen is possible, constructed from special steels to avoid embrittlement. The rate-limiting factors for deploying hydrogen are likely to be the capital and time involved in building a new hydrogen infrastructure and any additional cost for storage in order to accommodate variable RE sources. [8.2.3.2, 8.2.3.4]

In order to blend a RE gas into a gas grid, the gas source needs to be located near to the existing system to avoid high costs of additional pipeline construction. In the case of remote plant locations due to resource availability, it may be better to use the gas onsite where feasible to avoid the need for transmission and upgrading. [8.2.3.5]

8.5 Integration of renewable energy into liquid fuels

Most of the projected demand for liquid biofuels is for transport purposes, though industrial demand could emerge for bio-lubricants and bio-chemicals such as methanol. In addition, large amounts of traditional solid biomass could eventually be replaced by more convenient, safer and healthier liquid fuels such as RE-derived dimethyl ether (DME) or ethanol gels. [8.2.4]

Producing bioethanol and biodiesel fuels from various crops, usually used for food, is well understood (Figure TS.8.5). The biofuels produced can take advantage of existing infrastructure components already used for petroleum-based fuels including storage, blending, distribution and dispensing. However, sharing petroleum-product infrastructure (storage tanks, pipelines, trucks) with ethanol or blends can lead to problems from water absorption and equipment corrosion, so may require investment in specialized pipeline materials or linings. Decentralized biomass production, seasonality and remote agricultural locations away from existing oil refineries or fuel distribution centres, can impact the supply chain logistics and storage of biofuels. Technologies continue to evolve to produce biofuels from non-food feedstocks and biofuels that are more compatible with existing petroleum fuels and infrastructure. Quality control procedures need to be implemented to ensure that such biofuels meet all applicable product specifications. [8.2.4.1, 8.2.4.3, 8.2.4.4]

The use of blended fuels produced by replacing a portion (typically 5 to 25% but can be up to 100% substitution) of gasoline with ethanol,

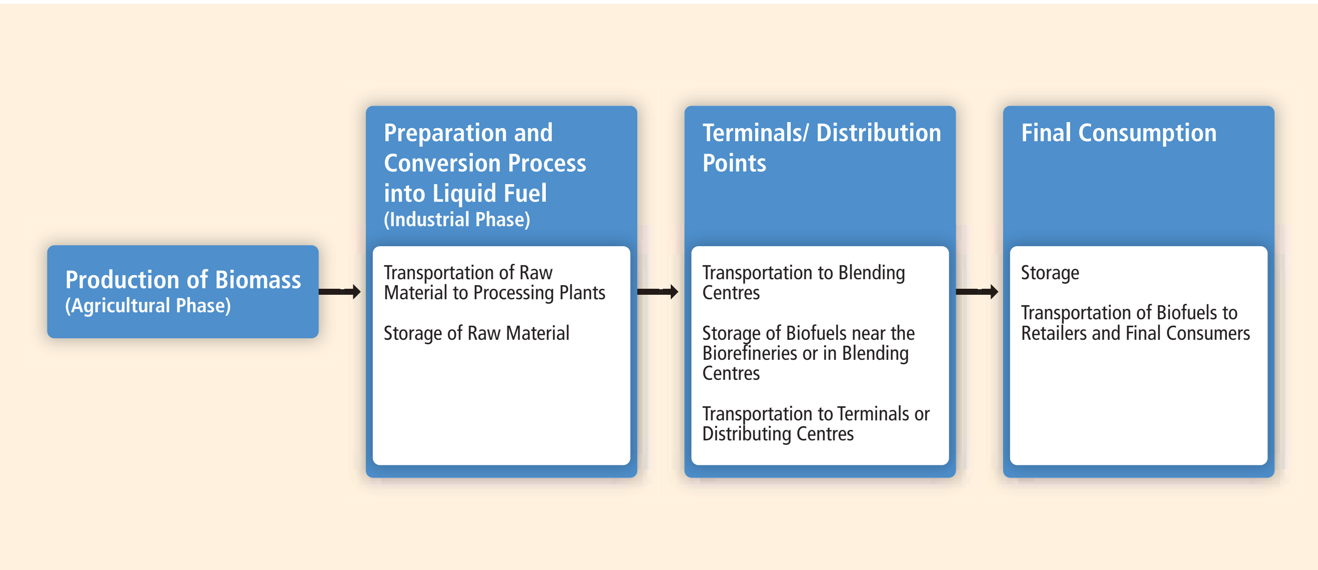


Figure TS.8.5 | The production, blending and distribution system for a range of liquid biofuels is similar regardless of the biomass feedstock. [Figure 8.11] or diesel with biodiesel, requires investment in infrastructure including additional tanks and pumps at vehicle service stations. Although the cost of biofuel delivery is a small fraction of the overall cost, the logistics and capital requirements for widespread integration and expansion could present major hurdles if not well planned. Since ethanol has only around two-thirds the energy density (by volume) of gasoline, larger storage systems, more rail cars or vessels, and larger capacity pipelines are needed to store and transport the same amount of energy. This increases the fuel storage and delivery costs. Although pipelines would, in theory, be the most economical method of delivery, and pipeline shipments of ethanol have been successfully achieved, a number of technical and logistical challenges remain. Typically, current volumes of ethanol produced in an agricultural region to meet local demand, or for export, are usually too low to justify the related investment costs and operational challenges of constructing a dedicated pipeline. [8.2.4.3]

8.6 Integration of renewable energy into autonomous systems

Autonomous energy supply systems are typically small scale and are often located in off-grid remote areas, on small islands, or in individual buildings where the provision of commercial energy is not readily available through grids and networks. Several types of autonomous systems exist and can make use of either single energy carriers, for example, electricity, heat, or liquid, gaseous or solid fuels, or a combination of carriers. [8.2.5, 8.2.5.1]

In principle, RE integration issues for autonomous systems are similar to centralized systems, for example, for supply/demand balancing of electricity supply systems, selection of heating and cooling options, production of RE gases and liquid biofuel production for local use. However, unlike larger centralized supply systems, smaller autonomous systems often have fewer RE supply options that are readily available at a local scale. Additionally, some of the technical and institutional options for managing integration within larger networks become more difficult or even implausible for smaller autonomous systems, such as RE supply forecasting, probabilistic unit commitment procedures, stringent fuel quality standards, and the smoothing effects of geographical and technical diversity. [8.2.1–8.2.5]

RE integration solutions typically become more restricted as supply systems become smaller. Therefore greater reliance must be placed on those solutions that are readily available. Focusing on variable RE resources, because of restricted options for interconnection and operating and planning procedures, autonomous systems will naturally have a tendency to focus on energy storage options, various types of demand response, and highly flexible fossil fuel generation to help match supply and demand. RE supply options that better match local load profiles, or that are dispatchable, may be chosen over other lower-cost options that do not have as strong a match with load patterns or are variable. Managing RE integration within autonomous systems will, all else being equal, be more costly than in larger integrated networks because of the restricted set of options, but in most instances, such as on islands or in remote rural areas, there is no choice for the energy users. One implication is that autonomous electricity system users and designers can face difficult trade-offs between a desire for reliable and continuous supply and minimizing overall supply costs. [8.2.5]

The integration of RE conversion technologies, balancing options and end-use technologies in an autonomous energy system depend on the site-specific availability of RE resources and the local energy demand. These can vary with local climate and lifestyles. The balance between cost and reliability is critical when designing and deploying autonomous power systems, particularly for rural areas of developing economies because the additional cost of providing continuous and reliable supply may become higher for smaller autonomous systems. [8.2.5.2]

8.7 End-use sectors: Strategic elements for transition pathways

RE technology developments have continued to evolve, resulting in increased deployment in the transport, building, industry, and agriculture, forestry and fishery sectors. In order to achieve greater RE deployment in all sectors, both technical and non-technical issues should be addressed. Regional variations exist for each sector due to the current status of RE uptake, the wide range of energy system types, the related infrastructure currently in place, the different possible pathways to enhance increased RE integration, the transition issues yet to be overcome, and the future trends affected by variations in national and local ambitions and cultures. [8.3, 8.3.1]

8.7.1 Transport

Recent trends and projections show strong growth in transport demand, including the rapidly increasing number of vehicles worldwide. Meeting this demand, whilst achieving a low-carbon, secure energy supply, will require strong policy initiatives, rapid technological change, monetary incentives and/or the willingness of customers to pay additional costs. [8.3.1]

In 2008, the combustion of fossil fuels for transport consumed around 19% of global primary energy use, equivalent to 30% of total consumer energy and producing around 22% of GHG emissions, plus a significant share of local air-polluting emissions. Light duty vehicles (LDVs) accounted for over half of transport fuel consumption worldwide, with heavy duty vehicles (HDVs) accounting for 24%, aviation 11%, shipping 10% and rail 3%. Demand for mobility is growing rapidly with the number of motorized vehicles projected to triple by 2050 and with a similar growth in air travel. Maintaining a secure supply of energy is therefore a serious concern for the transport sector with about 94% of transport fuels presently coming from oil products that, for most countries, are imported. [8.3.1]

There are a number of possible fuel/vehicle pathways from the conversion of the primary energy source to an energy carrier (or fuel) through to the end use, whether in advanced internal combustion engine vehicles (ICEVs), electric battery vehicles (EVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) or hydrogen fuel cell vehicles (HFCVs) (Figure TS.8.6). [8.3.1.2]

Improving the efficiency of the transport sector, and decarbonizing it, have been identified as being critically important to achieving long-term, deep reductions in global GHG emissions. The approaches to reducing transport-related emissions include a reduction in travel demand, increased vehicle efficiency, shifting to more efficient modes of transport, and replacing petroleum-based fuels with alternative low- or near-zero-carbon fuels (including biofuels, electricity or hydrogen produced from low-carbon primary energy sources). Scenario studies strongly suggest that a combination of technologies will be needed to accomplish 50 to 80% reductions (compared to current rates) in GHG emissions by 2050 whilst meeting the growing transport energy demand (Figure TS.8.7). [8.3.1.1]

The current use of RE for transport is only a few percent of the total energy demand, mainly through electric rail and the blending of liquid biofuels with petroleum products. Millions of LDVs capable of running on high-biofuel blends are already in the world fleet and biofuel technology is commercially mature, as is the use of compressed biomethane in vehicles suitable for running on compressed natural gas. [8.2.3]

However, making a transition to new fuels and engine types is a complex process involving technology development, cost, infrastructure, consumer acceptance, and environmental and resource impacts. Transition issues vary for biofuels, hydrogen, and electric vehicles (Table TS.8.2) with no one option seen to be a clear 'winner' and all needing several decades to be deployed at a large scale. Biofuels are well proven, contributing around 2% of road transport fuels in 2008, but there are issues of sustainability. [2.5] Many hydrogen fuel cell vehicles have been demonstrated, but these are unlikely to be commercialized until at least 2015 to 2020 due to the barriers of fuel cell durability, cost, onboard hydrogen storage issues and hydrogen infrastructure availability. For EVs and PHEVs, the cost and relatively short life of present

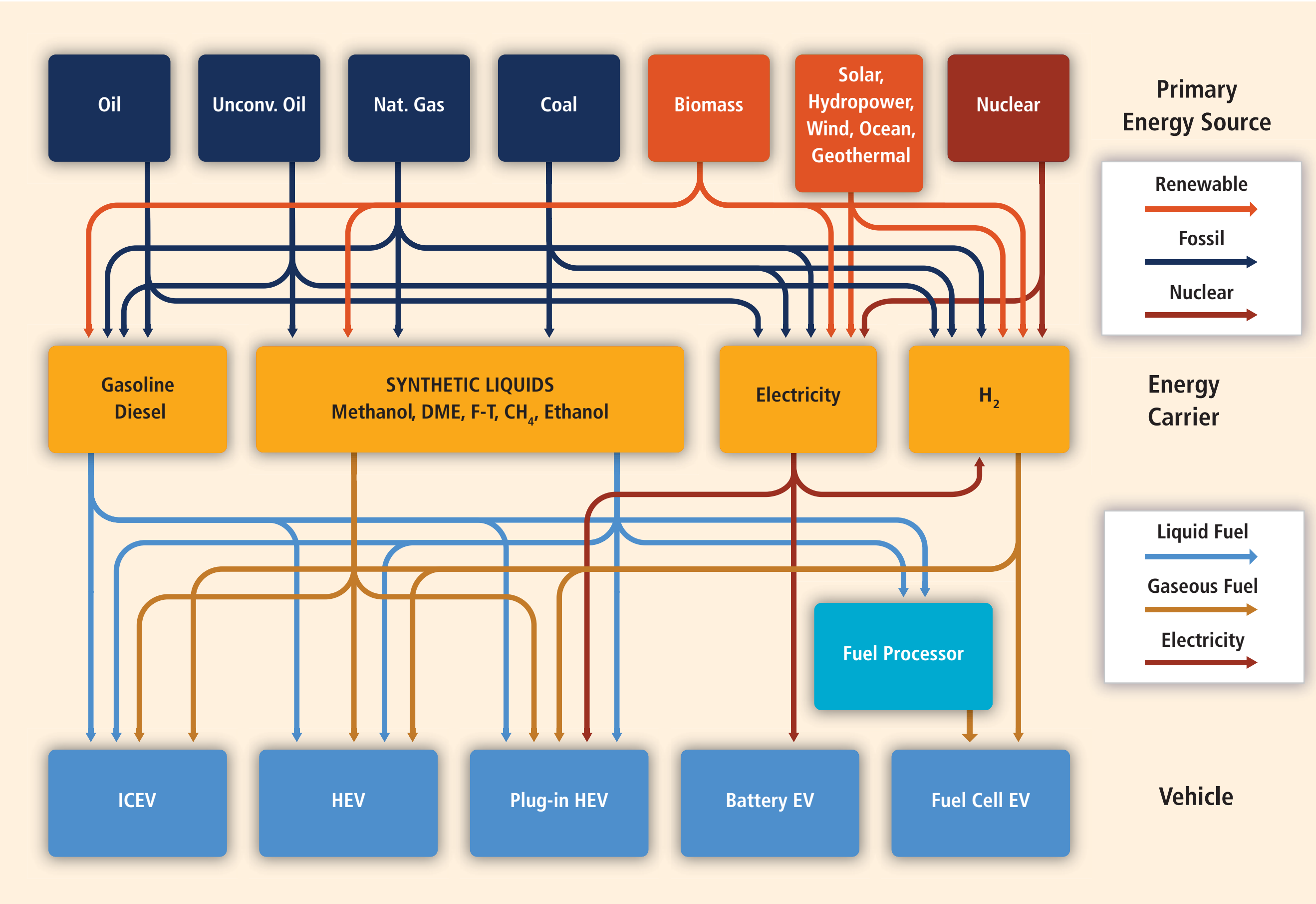


Figure TS.8.6 | A range of possible light duty vehicle fuel pathways, from primary energy sources (top), through energy carriers, to end-use vehicle drive train options (bottom) (with RE resources highlighted in green). [Figure 8.13]

Notes: F-T= Fischer-Tropsch process; DME = dimethyl ether; ICE = internal combustion engine; HEV = hybrid electric vehicle; EV = electric vehicle; 'unconventional oil' refers to oil sands, oil shale and other heavy crudes.

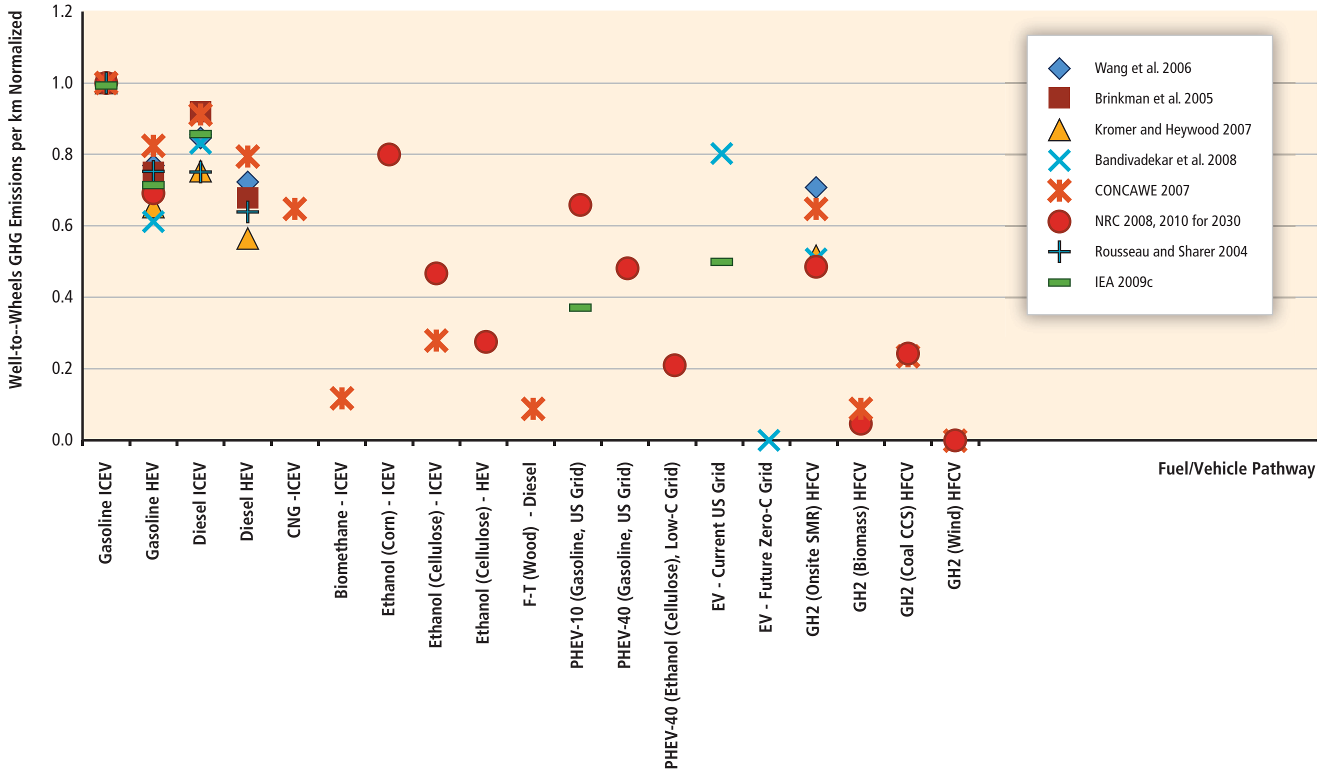


Figure TS.8.7 | Well-to-wheels (WTW) GHG emission reductions per kilometre travelled, with ranges shown taken from selected studies of alternative light duty fuel/vehicle pathways, normalized to the GHG emissions of a gasoline, internal combustion engine, light-duty vehicle. [Figure 8.17]

Notes: To allow for easier comparison among studies, WTW GHG emissions per km were normalized to emissions from a gasoline ICEV (such that 'Gasoline ICEV' = 1) taken from each study and ranging from 170 to 394 g CO_2/km. For all hydrogen pathways, hydrogen is stored onboard the vehicle as a compressed gas (GH2). CNG = compressed natural gas; SMR = steam methane reformer.

battery technologies, the limited vehicle range between recharging, and the time for recharging, can be barriers to consumer acceptance. EV and PHEV designs are undergoing rapid development, spurred by recent policy initiatives worldwide, and several companies have announced plans to commercialize them. One strategy could be to introduce PHEVs initially while developing and scaling up battery technologies. For hydrogen and electric vehicles, it may take several decades to implement a practical transport system by developing the necessary infrastructure at the large scale.

An advantage of *biofuels* is their relative compatibility with the existing liquid fuel infrastructure. They can be blended with petroleum products and most ICE vehicles can be run on blends, some even on up to 100% biofuel. They are similar to gasoline or diesel in terms of vehicle performance[14] and refuelling times, though some have limits on the concentrations that can be blended and they typically cannot be easily distributed using existing fuel pipelines without modifications. The sustainability of the available biomass resource is a serious issue for some biofuels. [2.5, 8.2.4, 8.3.1.2]

14 Performance in this instance excludes energy content. The energy content of biofuels is generally lower than their equivalent petroleum product.

Hydrogen has the potential to tap vast new energy resources to provide transport with zero or near-zero emissions. The technology for hydrogen from biomass gasification is being developed, and could become competitive beyond 2025. Hydrogen derived from RE sources by electrolysis has cost barriers rather than issues of technical feasibility or resource availability. Initially RE and other low-carbon technologies will likely be used to generate electricity, a development that could help enable near-zero-carbon hydrogen to be co-produced with electricity or heat in future energy complexes. Hydrogen is not yet widely distributed compared to electricity, natural gas, gasoline, diesel or biofuels but could be preferred in the future for large HDVs that have a long range and need relatively fast refuelling times. Bringing hydrogen to large numbers of vehicles would require building a new refuelling infrastructure that could take several decades to construct. The first steps to provide hydrogen to test fleets and demonstrate refuelling technologies in mini-networks have begun in several countries. [2.6.3.2, 8.3.1, 8.3.1.2]

For RE *electricity* to supply high numbers of EVs and PHEVs in future markets, several innovations must occur such as development of batteries and low-cost electricity supply available for recharging when the EVs need it. If using night-time, off-peak recharging, new capacity is less likely to be needed and in some locations there may be a good temporal match with

Table TS.8.2 | Transition issues for the use of biofuels, hydrogen and electricity as transport fuels for light duty vehicles. [Summarized from 8.3.1]

Technology Status	Biofuels	Hydrogen	Electricity
Existing and potential primary resources	Sugar, starch, oil crops; cellulosic crops; forest, agricultural and solid wastes; algae and other biological oils.	Fossil fuels; nuclear; all RE. Potential RE resource base is large but inefficiencies and costs of converting to H_2 can be an issue.	Fossil fuels, nuclear, all RE. Potential RE resource base is large.
Fuel production	First generation: ethanol from sugar and starch crops, biomethane, biodiesel. Advanced second-generation biofuels, e.g., from cellulosic biomass, bio-wastes, bio-oils, and algae after at least 2015.	Fossil H_2 commercial for large-scale industrial applications, but not competitive as transport fuel. Renewable H_2 generally more costly.	Commercial power readily available. RE electricity can be more costly, but preferred for transport due to low GHG emissions on a lifecycle basis.
Vehicles	Millions of flexi-fuel vehicles exist that use high shares of ethanol. Conventional ICEVs limited to low concentration blends of ethanol (<25%). Some commercial agricultural tractors and machinery can run on 100% biodiesel.	Demonstration HFCVs. Commercial HFCVs not until 2015 to 2020.	Demonstration PHEVs, Commercial PHEVs not until 2012 to 2015. Limited current use of EVs. Commercial EVs not until 2015 to 2020.
Costs[1] compared with gasoline ICE vehicles			
Incremental vehicle price compared to future gasoline ICEV (USD_{2005})	Similar price.	HFCV experience (by 2035) price increment >USD 5,300	Experience (by 2035) price increment: PHEVs >USD 5,900; EVs >USD 14,000
Fuel cost (USD_{2005}/km)	Fuel cost per km varies with biofuel type and level of agricultural subsidy. Biofuel can compete if price per unit of energy equates to gasoline/diesel price per unit of energy. Ethanol in Brazil competes without subsidies.	Target fuel cost at USD 3 to 4/kg for mature H_2 infrastructure—may prove optimistic. When used in HFCVs, competes with gasoline in HCEVs at USD 0.40 to 0.53/l. Assumes HFCV has twice fuel economy of gasoline ICEV. RE-derived H_2 around 1.5 to 3 times more expensive than other from sources.	Electricity cost per km, when the power is purchased at USD 0.10 to 0.30/kWh, competes with gasoline when purchased at USD 0.3 to 0.9/l (assuming the EV has fuel economy 3 times that of the gasoline ICEV).
Compatibility with existing infrastructure	Partly compatible with existing petroleum distribution system. Separate distribution and storage infrastructure may be needed for ethanol.	New H_2 infrastructure needed, as well as renewable H_2 production sources. Infrastructure deployment must be coordinated with vehicle market growth.	Widespread electric infrastructure in place. Need to add in-home and public recharger costs, RE generation sources, and upgrading of transmission and distribution (especially for fast chargers).
Consumer acceptance	Depends upon comparative fuel costs. Alcohol vehicles can have shorter range than gasoline. Potential cost impact on food crops. Land use and water issues can be factors.	Depends upon comparative vehicle and fuel costs. Public perception of safety. Poor public refuelling station availability in early markets.	High initial vehicle cost. High electricity cost of charging on-peak. Limited range unless PHEV. Modest to long recharging time, but home recharging possible. Significantly degraded performance in extreme cold winters or hot summers. Poor public refuelling station availability in early markets
GHG emissions	Depends on feedstock, pathway and land use issue[2]. Low for fuels from biomass residues including sugarcane. Near-term can be high for corn ethanol. Advanced second-generation biofuels likely to be lower.	Depends on H_2 production mix. Compared to future hybrid gasoline ICEVs, WTW GHG emissions for HFCVs using H_2 from natural gas can be slightly more or less depending on assumptions. WTW GHG emissions can approach zero for RE or nuclear pathways.	Depends on grid mix. Using coal-dominated grid mix, EVs and PHEVs have WTW GHG emissions similar or higher than gasoline HEV. With larger fraction of RE and low-carbon electricity, WTW emissions are lower.
Petroleum consumption	Low for blends	Very low	Very low
Environmental and sustainability issues			
Air pollution	Similar to gasoline. Additional issues for ethanol due to permeation of volatile organic compounds through fuel tank seals. Aldehyde emissions.	Zero emission vehicle	Zero emission vehicle.
Water use	More than gasoline depending on feedstock and crop irrigation needs.	Potentially low but depends on pathway as electrolysis and steam reformation depend on water.	Potentially very low but depends on pathway used for power generation.
Land use	Might compete with food and fibre production on cropland.	Depends on pathway.	Depends on pathway.
Materials use		Platinum in fuel cells. Neodymium and other rare earths in electric motors. Material recycling.	Lithium in batteries. Neodymium and other rare earths in electric motors. Material recycling.

Notes: 1. Costs quoted do not always include payback of incremental first vehicle costs. 2. Indirect land use-related GHG emissions linked to biofuels is not included.

wind or hydropower resources. Grid flexibility and/or energy storage may also be needed to balance vehicle recharging electricity demand with RE source availability. [8.2.1]

Other than LDVs, it is possible to introduce RE options and lower GHG emissions in the other transport sectors: HDVs, aviation, maritime and rail. The use of biofuels is key for increasing the share of RE in these sub-sectors but current designs of ICEs would probably need to be modified to operate on high-biofuel blends (above 80%). Aviation has perhaps less potential for fuel switching than the other sub-sectors due to safety needs and to minimize fuel weight and volume. However, various airlines and aircraft manufacturers have flown demonstration test flights using various biofuel blends, but significantly more processing is needed than for road fuels to ensure that stringent aviation fuel specifications are met, particularly at cold temperatures. For rail transport, as around 90% of the industry is powered by diesel fuel, greater electrification and the increased use of biodiesel are the two primary options for introducing RE. [8.3.1.5]

Given all these uncertainties and cost reduction challenges, it is important to maintain a portfolio approach over a long time line that includes behavioural changes (for example to reduce annual vehicle kilometres travelled or kilometres flown), more energy efficient vehicles, and a variety of low-carbon fuels. [8.3.1.5]

8.7.2 Buildings and households

The building sector provides shelter and a variety of energy services to support the livelihoods and well-being of people living in both developed and developing countries. In 2008, it accounted for approximately 120 EJ (about 37%) of total global final energy use (including between 30 and 45 EJ of primary energy from traditional biomass used for cooking and heating). The high share of total building energy demand for heating and cooling is usually met by fossil fuels (oil burners, gas heaters) and electricity (fans and air-conditioners). In many regions, these can be replaced economically by district heating and cooling (DHC) schemes or by the direct use of RE systems in buildings, such as modern biomass pellets and enclosed stoves, heat pumps (including ground source), solar thermal water and space heating, and solar sorption cooling systems. [2.2, 8.2.2, 8.3.2]

RE electricity generation technologies integrated into buildings (such as solar PV panels) provide the potential for buildings to become energy suppliers rather than energy consumers. Integration of RE into existing urban environments, combined with energy efficient appliances and 'green building' designs, are key to further deployment. For both household and commercial building sub-sectors, energy vectors and energy service delivery systems vary depending on the local characteristics and RE resources of a region, its wealth, and the average age of the current buildings and infrastructure impacting stock turnover. [8.3.2]

The features and conditions of energy demands in an existing or new building, and the prospects for RE integration, differ with location and between one building design and another. In both urban and rural settlements in developed countries, most buildings are connected to electricity, water and sewage distribution schemes. With a low building stock turnover rate of only around 1% per year in developed countries, future retrofitting of existing buildings will need to play a significant role in RE integration as well as energy efficiency improvements. Examples include installation of solar water heaters and ground source heat pumps and development or extensions of DHC systems that, being flexible on sources of heat or cold, allow for a transition to a greater share of RE over time. These can involve relatively high up-front investment costs and long payback periods, but these can possibly be offset by amended planning consents and regulations so they become more enabling, improved energy efficient designs, and the provision of economic incentives and financial arrangements. [8.2.2, 8.3.2.1]

Grid electricity supply is available in most urban areas of developing countries, although often the supply system has limited capacity and is unreliable. Increased integration of RE technologies using local RE resources could help ensure a secure energy supply and also improve energy access. In urban and rural settlements in developing countries, energy consumption patterns often include the unsustainable use of biomass and charcoal. The challenge is to reverse the increasing traditional biomass consumption patterns by providing improved access to modern energy carriers and services and increasing the share of RE through integration measures. The distributed nature of solar and other RE resources is beneficial for their integration into new and existing buildings however modest they might be, including dwellings in rural areas not connected to energy supply grids. [8.2.2.2, 8.2.5]

8.7.3 Industry

Manufacturing industries account for about 30% of global final energy use, although the share differs markedly between countries. The sector is highly diverse, but around 85% of industrial energy use is by the more energy-intensive 'heavy' industries including iron and steel, non-ferrous metals, chemicals and fertilizers, petroleum refining, mineral mining, and pulp and paper. [8.3.3.1]

There are no severe technical limits to increasing the direct and indirect use of RE in industry in the future. However, integration in the short term may be limited by factors such as land and space constraints or demands for high reliability and continuous operation. In addition to the integration of higher shares of RE, key measures to reduce industrial energy demands and/or GHG emissions include energy efficiency, recycling of materials, CCS for CO_2-emitting industries such as cement manufacturing, and the substitution of fossil fuel feedstocks. In addition, industry can provide demand-response facilities that are likely to achieve greater prominence in future electricity systems that have a higher penetration of variable RE sources. [8.3.3.1]

The main opportunities for RE integration in industry include:

- Direct use of biomass-derived fuels and process residues for onsite production, and use of biofuels, heat and CHP; [2.4.3]
- Indirect use through increased use of RE-based electricity, including electro-thermal processes; [8.3.3]
- Indirect use through other purchased RE-based energy carriers including heat, liquid fuels, biogas, and, possibly to a greater degree in the future, hydrogen; [8.2.2–8.2.4]
- Direct use of solar thermal energy for process heat and steam demands although few examples exist to date; [3.3.2] and
- Direct use of geothermal resources for process heat and steam demands. [4.3.5]

Industry is not only a potential user of RE but also a potential supplier of bioenergy as a co-product. The current direct use of RE in industry is dominated by biomass produced in the pulp and paper, sugar and ethanol industries as process by-products and used for cogenerated heat and electricity, mainly onsite for the process but also sold off-site. Biomass is also an important fuel for many small and medium enterprises such as brick making, notably as charcoal in developing countries. [8.3.3.1]

Possible pathways for increased use of RE in energy-intensive industries vary between the different industrial sub-sectors. Biomass, for example, is technically able to replace fossil fuels in boilers, kilns and furnaces or to replace petrochemicals with bio-based chemicals and materials. However, due to the scale of many industrial operations, access to sufficient volumes of local biomass may be a constraint. Use of solar technologies can be constrained in some locations with low annual sunshine hours. The direct supply of hydropower to aluminium smelters is not unusual but, for many energy-intensive processes, the main option is indirect integration of RE through switching to RE electricity from the grid, or, in the future, to hydrogen. The broad range of options for producing low-carbon electricity, and its versatility of use, implies that electro-thermal processes could become more important in the future for replacing fossil fuels in a range of industrial processes. [8.3.3.2]

Less energy-intensive 'light' industries, including food processing, textiles, light manufacturing of appliances and electronics, automotive assembly plants, and saw-milling, although numerous, account for a smaller share of total energy use than do the heavy industries. Much of the energy demand by these 'light' industries reflects the energy use in commercial buildings for lighting, space heating, cooling, ventilation and office equipment. In general, light industries are more flexible and offer more readily accessible opportunities for the integration of RE than do energy-intensive industries. [8.3.3.3]

RE integration for process heat is practical at temperatures below around 400°C using the combustion of biomass (including charcoal) as well as solar thermal or direct geothermal energy. To meet process heat demand above 400°C, RE resources, with the exception of high-temperature solar, are less suitable (Figure TS.8.8). [8.3.3.3]

The potentials and costs for increasing the use of RE in industry are poorly understood due to the complexity and diversity of industry and the various geographical and local climatic conditions. Near-term opportunities for achieving higher RE shares could result from the increased utilization of process residues, CHP in biomass-based industries, and substitution of fossil fuels used for heating. Solar thermal technologies are promising with further development of collectors, thermal storage, back-up systems, process adaptation and integration under evaluation. RE integration using electricity generated from RE sources for electro-technologies may have the largest impact both in the near and long term. [8.3.3.2, 8.3.3.3]

Use of RE in industry has had difficulty in competing in the past in many regions due to relatively low fossil fuel prices together with low, or

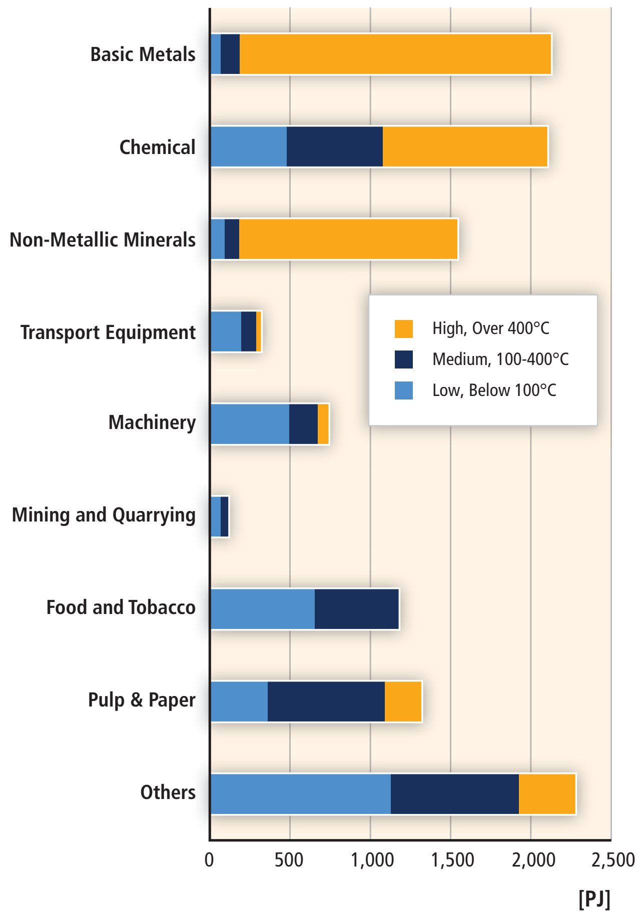


Figure TS.8.8 | Industrial heat demands for various temperature quality ranges by the heavy industrial and light manufacturing sub-sectors, based on an assessment within 32 European countries. [Figure 8.23] non-existent, energy and carbon taxes. RE support policies in different countries tend to focus more on the transport and building sectors than on industry and consequently the potential for RE integration is relatively uncertain. Where support policies have been applied, successful RE deployment has resulted. [8.3.3.3]

8.7.4 Agriculture, forestry and fishing

Agriculture is a relatively low energy-consuming sector, utilizing only around 3% of total global consumer energy. The sector includes large corporate-owned farms and forests as well as subsistence farmers and fisher-folk in developing countries. The relatively high indirect energy use for the manufacture of fertilizers and machinery is included in the industry sector. Pumping water for irrigation usually accounts for the highest on-farm energy demand, along with diesel use for machinery and electricity for milking, refrigeration and fixed equipment. [8.3.4.1]

In many regions, land under cultivation could simultaneously be used for RE production. Multi-use of land for agriculture and energy purposes is becoming common, such as wind turbines constructed on grazing land; biogas plants used for treating animal manure with the nutrients recycled to the land; waterways used for small- and micro-hydropower systems; crop residues collected and combusted for heat and power; and energy crops grown and managed specifically to provide a biomass feedstock for liquid biofuels, heat and power generation (with co-products possibly used for feed and fibre). [2.6, 8.3.4.2, 8.3.4.3]

Since RE resources including wind, solar, crop residues and animal wastes are often abundant in rural areas, their capture and integration can enable the landowner or farm manager to utilize them locally for the farming operations. They can also earn additional revenue when energy carriers such as RE electricity or biogas are exported off the farm. [8.3.4]

Despite barriers to greater RE technology deployment including high capital costs, lack of available financing and remoteness from energy demand, it is likely that RE will be used to a greater degree by the global agricultural sector in the future to meet energy demands for primary production and post-harvest operations at both large and small scales. [8.3.4.1–8.3.4.2]

Integration strategies that could increase the deployment of RE in the primary sector will partly depend upon the local and regional RE resources, on-farm energy demand patterns, project financing opportunities and existing energy markets. [8.3.4.3]

9. Renewable Energy in the Context of Sustainable Development

9.1 Introduction

Sustainable development (SD) addresses concerns about relationships between human society and nature. Traditionally, SD has been framed in the three-pillar model—Economy, Ecology, and Society—allowing a schematic categorization of development goals, with the three pillars being interdependent and mutually reinforcing. Within another conceptual framework, SD can be oriented along a continuum between the two paradigms of weak sustainability and strong sustainability. The two paradigms differ in assumptions about the substitutability of natural and human-made capital. RE can contribute to the development goals of the three-pillar model and can be assessed in terms of both weak and strong SD, since RE utilization is defined as sustaining natural capital as long as the resource use does not reduce the potential for future harvest. [9.1]

9.2 Interactions between sustainable development and renewable energy

The relationship between RE and SD can be viewed as a hierarchy of goals and constraints that involve both global and regional or local considerations. Though the exact contribution of RE to SD has to be evaluated in a country-specific context, RE offers the opportunity to contribute to a number of important SD goals: (1) social and economic development; (2) energy access; (3) energy security; and (4) climate change mitigation and the reduction of environmental and health impacts. The mitigation of dangerous anthropogenic climate change is seen as one strong driving force behind the increased use of RE worldwide. [9.2, 9.2.1]

These goals can be linked to both the three-pillar model and the weak and strong SD paradigms. SD concepts provide useful frameworks for policymakers to assess the contribution of RE to SD and to formulate appropriate economic, social and environmental measures. [9.2.1]

The use of indicators can assist countries in monitoring progress made in energy subsystems consistent with sustainability principles, although there are many different ways to classify indicators of SD. The assessments carried out for the report and Chapter 9 are based on different methodological tools, including bottom-up indicators derived from attributional lifecycle assessments (LCA) or energy statistics, dynamic integrated modelling approaches, and qualitative analyses. [9.2.2]

Conventional economic growth metrics (GDP) as well as the conceptually broader Human Development Index (HDI) are analyzed to evaluate the contribution of RE to social and economic development. Potential employment opportunities, which serve as a motivation for some countries to support RE deployment, as well as critical financing questions for developing countries are also addressed. [9.2.2]

Access to modern energy services, whether from renewable or non-renewable sources, is closely correlated with measures of development, particularly for those countries at earlier development stages. Providing access to modern energy for the poorest members of society is crucial for the achievement of any single of the eight Millennium Development Goals. Concrete indicators used include per capita final energy consumption related to income, as well as breakdowns of electricity access (divided into rural and urban areas), and numbers for those parts of the population using coal or traditional biomass for cooking. [9.2.2]

Despite the lack of a commonly accepted definition, the term 'energy security' can best be understood as robustness against (sudden) disruptions of energy supply. Two broad themes can be identified that are relevant to energy security, whether for current systems or for the planning of future RE systems: availability and distribution of resources; and variability and reliability of energy supply. The indicators used to provide information about the energy security criterion of SD are the magnitude of reserves, the reserves-to-production ratio, the share of imports in total primary energy consumption, the share of energy imports in total imports, as well as the share of variable and unpredictable RE sources. [9.2.2]

To evaluate the overall burden from the energy system on the environment, and to identify potential trade-offs, a range of impacts and categories have to be taken into account. These include mass emissions to air (in particular GHGs) and water, and usage of water, energy and land per unit of energy generated and these must be evaluated across technologies. While recognizing that LCAs do not give the only possible answer as to the sustainability of a given technology, they are a particularly useful methodology for determining total system impacts of a given technology, which can serve as a basis for comparison. [9.2.2]

Scenario analyses provide insights into what extent integrated models take account of the four SD goals in different RE deployment pathways. Pathways are primarily understood as scenario results that attempt to address the complex interrelations among the different energy technologies at a global scale. Therefore, Chapter 9 mainly refers to global scenarios derived from integrated models that are also at the core of the analysis in Chapter 10. [9.2.2]

9.3 Social, environmental and economic impacts: Global and regional assessment

Countries at different levels of development have different incentives to advance RE. For developing countries, the most likely reasons to adopt RE technologies are providing access to energy, creating employment opportunities in the formal (i.e., legally regulated and taxable) economy, and reducing the costs of energy imports (or, in the case of fossil energy exporters, prolonging the lifetime of their natural resource base). For industrialized countries, the primary reasons to encourage RE include reducing carbon emissions to mitigate climate change, enhancing energy security, and actively promoting structural change in the economy, such that job losses in declining manufacturing sectors are softened by new employment opportunities related to RE. [9.3]

9.3.1 Social and economic development

Globally, per capita incomes are positively correlated with per capita energy use and economic growth can be identified as the most relevant factor behind increasing energy consumption in the last decades. However, there is no agreement on the direction of the causal relationship between energy use and increased macroeconomic output. [9.3.1.1]

As economic activity expands and diversifies, demands for more sophisticated and flexible energy sources arise: from a sectoral perspective, countries at an early stage of development consume the largest part of total primary energy in the residential (and to a lesser extent agricultural) sector; in emerging economies the manufacturing sector dominates, while in fully industrialized countries services and transport account for steadily increasing shares (see Figure TS.9.1). [9.3.1.1]

Despite the close correlation between GDP and energy use, a wide variety of energy use patterns across countries prevails: some have achieved high levels of per capita incomes with relatively low energy consumption. Others remain rather poor despite elevated levels of energy use, in particular countries abundantly endowed with fossil fuel resources, in which energy is often heavily subsidized. One hypothesis suggests that economic growth can largely be decoupled from energy use by steady declines in energy intensity. Further, it is often asserted that developing economies and economies in transition can 'leapfrog', that is, limit their energy use by adopting modern, highly efficient energy technologies. [9.3.1.1, Box 9.5]

Access to clean and reliable energy constitutes an important prerequisite for fundamental determinants of human development, such as health, education, gender equality and environmental safety. Using the HDI as a proxy indicator of development, countries that have achieved high HDI levels in general consume relatively large amounts of energy per capita and no country has achieved a high or even a medium HDI without significant access to non-traditional energy supplies. A certain minimum amount of energy is required to guarantee an acceptable standard of living (e.g., 42 GJ per capita), after which raising energy consumption yields only marginal improvements in the quality of life. [9.3.1.2]

Estimates of current net employment effects of RE differ due to disagreements regarding the use of the appropriate methodology. Still, there seems to be agreement about the positive long-term effects of RE

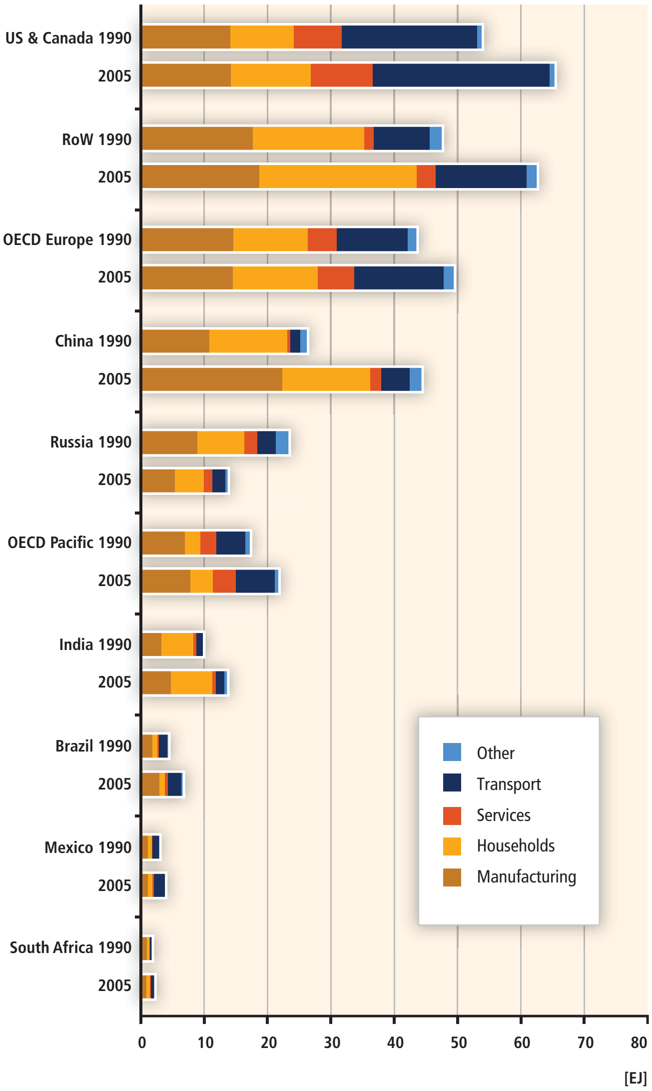


Figure TS.9.1 | Energy use (EJ) by economic sector. Note that the underlying data are calculated using the IEA physical content method, not the direct equivalent method.[1]

Notes: RoW = Rest of World. [Figure 9. 2] 1. Historical energy data have only been available for energy use by economic sector. For a conversion of the data using the direct equivalent method, the different energy carriers used by each economic sector would need to be known.

as an important contribution to job creation, which has been stressed in many national green-growth strategies. [9.3.1.3]

In general, the purely economic costs of RE exceed those of fossil fuel-based energy production in most instances. Especially for developing countries, the associated costs are a major factor determining the desirability of RE to meet increasing energy demand, and concerns have been voiced that increased energy prices might endanger industrializing countries' development prospects. Overall, cost considerations cannot be discussed independently of the burden-sharing regime adopted, that is, without specifying who assumes the costs for the benefits brought about from reduced GHG emissions, which can be characterized as a global public good. [9.3.1.4]

9.3.2 Energy access

Significant parts of the global population today have no or limited access to modern and clean energy services. From a sustainable development perspective, sustainable energy expansion needs to increase the availability of energy services to groups that currently have no or limited access to them: the poor (measured by wealth, income or more integrative indicators), those in rural areas and those without connections to the grid. [9.3.2]

Acknowledging the existing constraints regarding data availability and quality, 2009 estimates of the number of people without access to electricity are around 1.4 billion. The number of people relying on traditional biomass for cooking is around 2.7 billion, which causes significant health problems (notably indoor air pollution) and other social burdens (e.g., time spent gathering fuel) in the developing world. Given the strong correlation between household income and use of low quality fuels (Figure TS.9.2), a major challenge is to reverse the pattern of inefficient biomass consumption by changing the present, often unsustainable, use to more sustainable and efficient alternatives. [9.3.2]

By defining energy access as 'access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses', the incremental process of climbing the steps of the energy ladder is illustrated; even basic levels of access to modern energy services can provide substantial benefits to a community or household. [9.3.2]

In developing countries, decentralized grids based on RE have expanded and improved energy access; they are generally more competitive in rural areas with significant distances to the national grid and the low levels of rural electrification offer significant opportunities for RE-based mini-grid systems. In addition, non-electrical RE technologies offer opportunities for direct modernization of energy services, for example, using solar energy for water heating and crop drying, biofuels for transportation, biogas and modern biomass for heating, cooling, cooking and lighting, and wind for water pumping. While the specific role of RE in providing energy access in a more sustainable manner than other energy sources is not well understood, some of these technologies allow local communities to widen their energy choices; they stimulate economies, provide incentives for local entrepreneurial efforts and meet basic needs and services related to lighting and cooking, thus providing ancillary health and education benefits. [9.3.2]

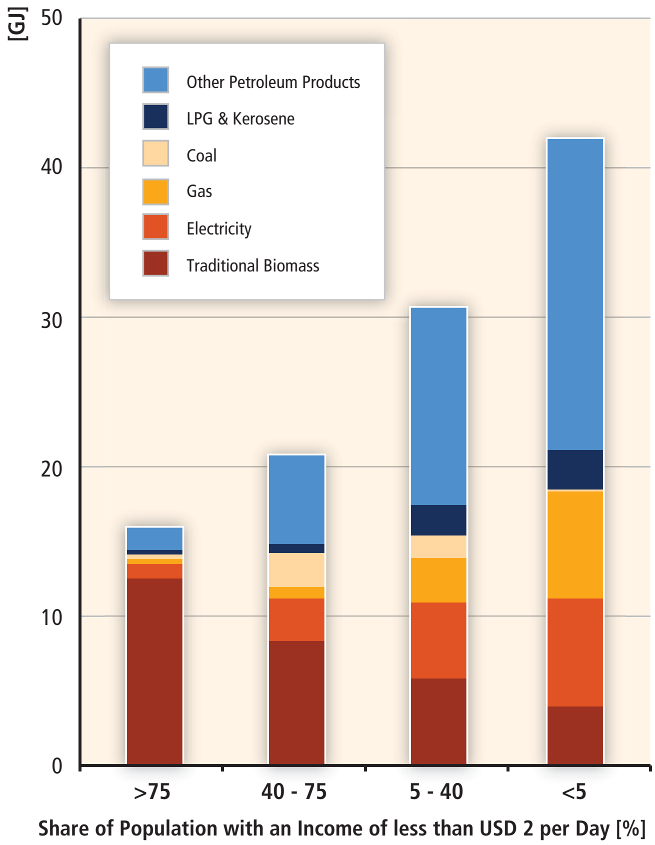


Figure TS.9.2 | The relationship between per capita final energy consumption and income in developing countries. Data refer to the most recent year available during the period 2000 to 2008. [Figure 9.5]

Note: LPG = liquid petroleum gas.

9.3.3 Energy security

The use of RE permits substitution away from increasingly scarce fossil fuel supplies; current estimates of the ratio of proven reserves to current production show that globally oil and natural gas would be exhausted in about four and six decades, respectively. [9.3.3.1]

As many renewable sources are localized and not internationally tradable, increasing their share in a country's energy portfolio diminishes the dependence on imports of fossil fuels, whose spatial distribution of reserves, production and exports is very uneven and highly concentrated in a few regions (Figure TS.9.3). As long as RE markets are not characterized by such geographically concentrated supply, this helps to diversify the portfolio of energy sources and to reduce the economy's vulnerability to price volatility. For oil-importing developing countries, increased uptake of RE technologies could be an avenue to redirect foreign exchange flows away from energy imports towards imports of goods that cannot be produced locally, such as high-tech capital goods. For example, Kenya and Senegal spend more than half of their export earnings for importing energy, while India spends over 45%. [9.3.3.1]

However, import dependencies can also occur in relation to the technologies needed for implementation of RE, with the secure access to required scarce inorganic mineral raw materials at reasonable prices constituting an upcoming challenge for all industries. [9.3.3.1]

The variable output profiles of some RE technologies often necessitate technical and institutional measures appropriate to local conditions to assure a constant and reliable energy supply. Reliable energy access is a particular challenge in developing countries and indicators for the reliability of infrastructure services show that in sub-Saharan Africa, almost 50% of firms maintain their own generation equipment. Many developing countries therefore specifically link energy access and security issues by broadening the definition of energy security to include stability and reliability of local supply. [9.3.3.2]

9.3.4 Climate change mitigation and reduction of environmental and health impacts

Sustainable development must ensure environmental quality and prevent undue environmental harm. No large-scale technology deployment comes without environmental trade-offs and a large body of literature is available that assesses various environmental impacts of the broad range of energy technologies (RE, fossil and nuclear) from a bottom-up perspective. [9.3.4]

Impacts on the climate through GHG emissions are generally well covered, and LCAs [Box 9.2] facilitate a quantitative comparison of 'cradle to grave' emissions across technologies. While a significant number of studies report on air pollutant emissions and operational water use, evidence is scarce for lifecycle emissions to water, land use, and health impacts other than those linked to air pollution. The assessment concentrates on those sectors which are best covered by the literature, such as electricity generation and transport fuels for GHG emissions. Heating and household energy are discussed only briefly, in particular with regards to air pollution and health. Impacts on biodiversity and ecosystems are mostly site-specific, difficult to quantify and are presented in a more qualitative manner. To account for burdens associated with accidents as opposed to normal operation, an overview of risks associated with energy technologies is provided. [9.3.4]

LCAs for electricity generation indicate that *GHG emissions from RE technologies* are, in general, considerably lower than those associated with fossil fuel options, and in a range of conditions, less than fossil fuels employing CCS. The maximum estimate for CSP, geothermal, hydropower, ocean and wind energy is less than or equal to 100 g CO_2eq/kWh, and median values for all RE range from 4 to 46 g CO_2eq/kWh. The upper quartile of the distribution of estimates for PV and biopower extend two to three times above the maximum for other RE technologies. However, GHG balances of bioenergy production have more uncertainties: excluding LUC, biopower could reduce GHG emissions compared to fossil fuelled systems and can lead to avoided GHG emissions from residues and wastes in landfill disposals and co-products; the combination of

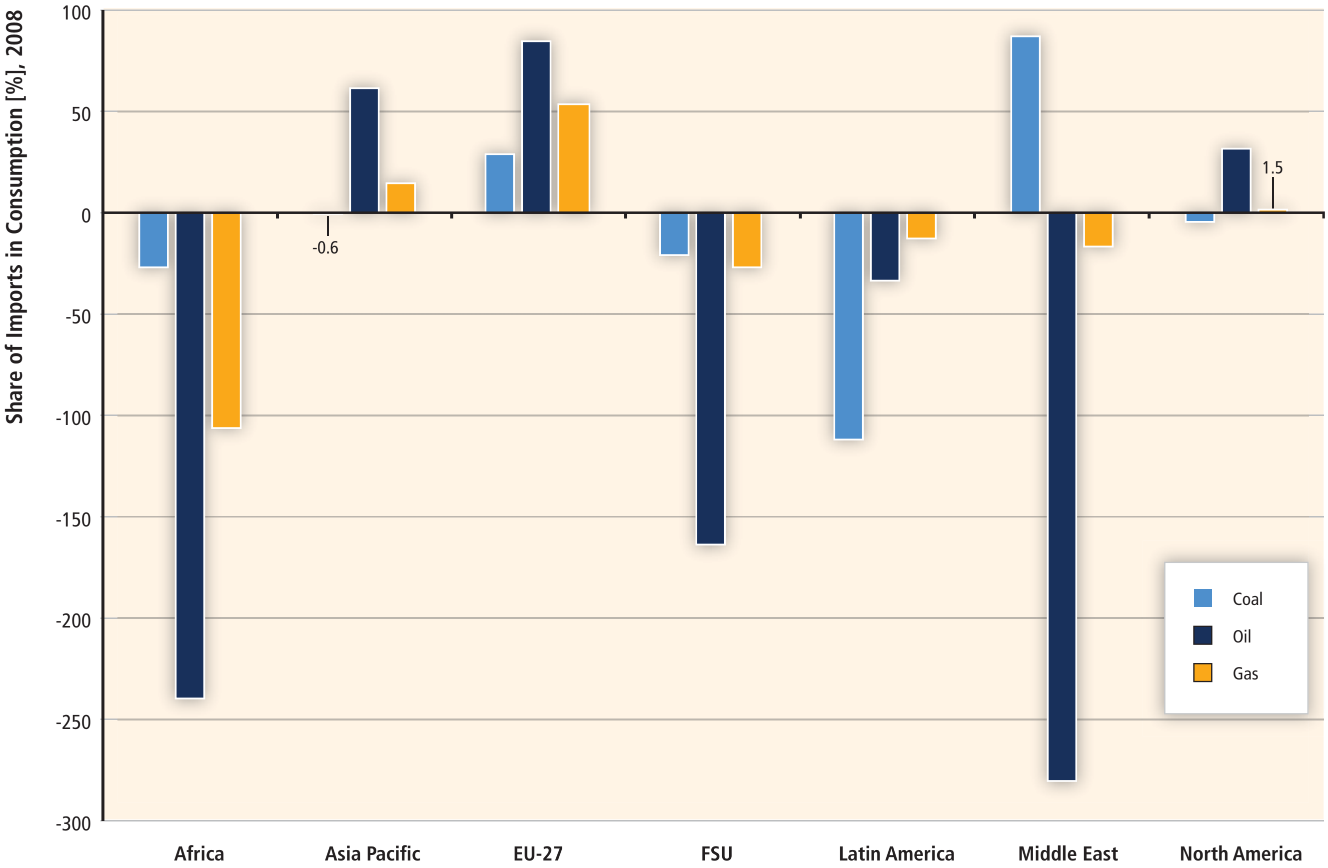


Figure TS.9.3 | Energy imports as the share of total primary energy consumption (%) for coal (hard coal and lignite), crude oil and natural gas for selected world regions in 2008. Negative values denote net exporters of energy carriers. [Figure 9.6]

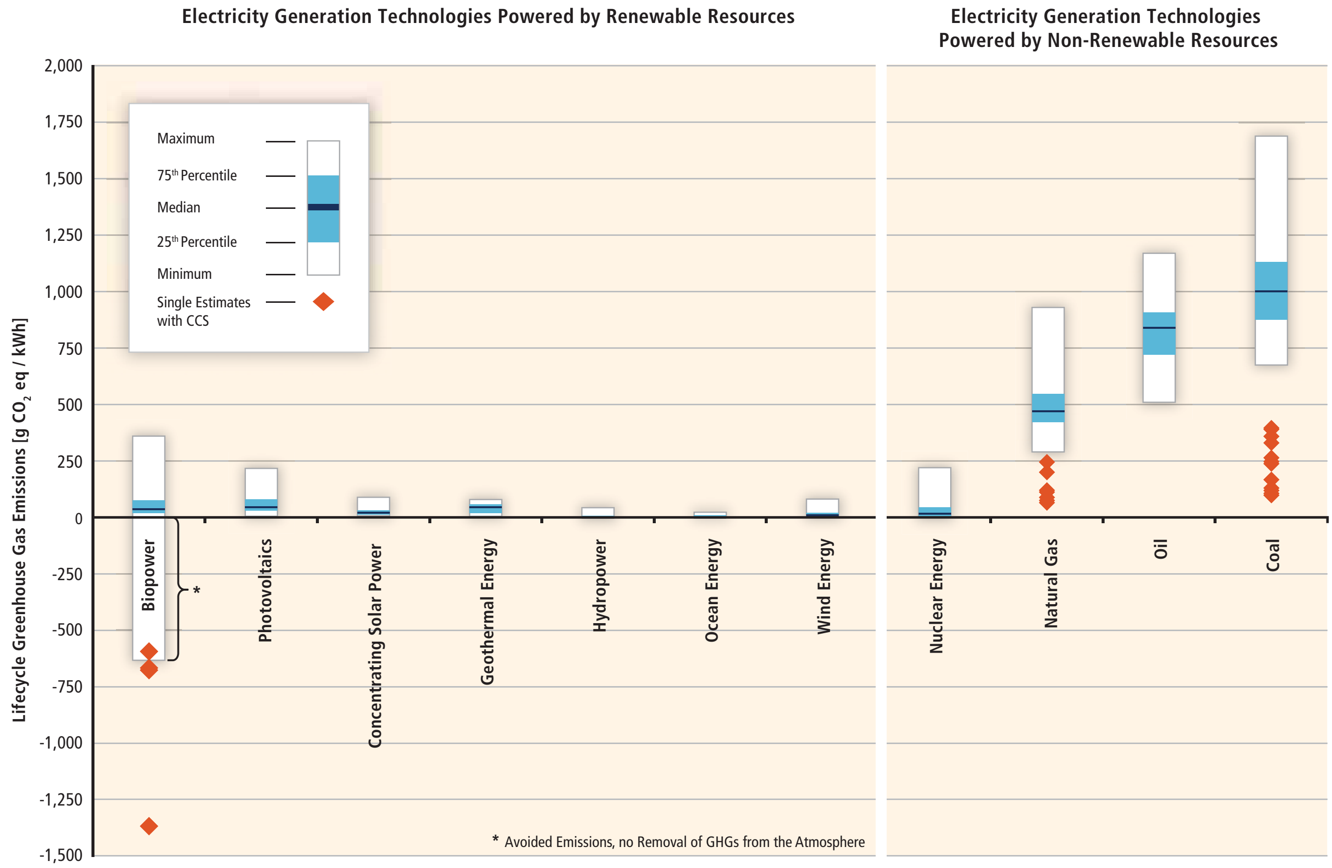
bioenergy with CCS may provide for further reductions (Figure TS.9.4). [9.3.4.1]

Accounting for differences in the quality of power produced, potential impacts to grid operation related to the addition of variable generation sources, and for direct or indirect LUC could reduce the GHG emissions benefit from switching to renewable electricity generation, but is not likely to negate the benefit. [9.3.4.1]

Measures such as the energy payback time, describing the energetic efficiency of technologies or fuels, have been declining rapidly for some RE technologies over recent years (e.g., wind and PV) due to technological advances and economies of scale. Fossil and nuclear power technologies are characterized by the continuous energy requirements for fuel extraction and processing, which might become increasingly important as qualities of conventional fuel supply decline and shares of unconventional fuels rise. [9.3.4.1]

For the assessment of *GHG emissions from transportation fuels*, selected petroleum fuels, first-generation biofuels (i.e., sugar- and starch-based ethanol, oilseed-based biodiesel and renewable diesel), and selected next-generation biofuels derived from lignocellulosic biomass (i.e., ethanol and Fischer-Tropsch diesel) are compared on a well-to-wheel basis. In this comparison, GHG emissions from LUC (direct and indirect) and other indirect effects (e.g., petroleum consumption rebound) have been excluded, but are separately considered below. Substituting biofuels for petroleum-based fuels has the potential to reduce lifecycle GHG emissions directly associated with the fuel supply chain. While first-generation biofuels result in relatively modest GHG mitigation potential (-19 to 77 g CO_2eq/MJ for first-generation biofuels versus 85 to 109 g CO_2eq/MJ for petroleum fuels), most next-generation biofuels (with lifecycle GHG emissions between -10 and 38 g CO_2eq/MJ) could provide greater climate benefits. Estimates of lifecycle GHG emissions are variable and uncertain for both biofuels and petroleum fuels, primarily due to assumptions about biophysical parameters, methodological issues and where and how the feedstocks are produced. [9.3.4.1]

Lifecycle *GHG emissions from LUC* are difficult to quantify, with land and biomass resource management practices strongly influencing any GHG emission reduction benefits and as such the sustainability of bioenergy. Changes to land use or management, brought about directly or indirectly by biomass production for use as fuels, power or heat, can lead to changes in terrestrial carbon stocks. Depending on the converted land's prior condition, this can either cause significant upfront emissions, requiring a time



Count of Estimates	222(+4)	124	42	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	13	6	11	5	49	32	36(+4)	10	50(+10)

Figure TS.9.4 | Estimates of lifecycle GHG emissions (g CO_2eq/kWh) for broad categories of electricity generation technologies, plus some technologies integrated with CCS. Land-use related net changes in carbon stocks (mainly applicable to biopower and hydropower from reservoirs) and land management impacts are excluded; negative estimates[1] for biopower are based on assumptions about avoided emissions from residues and wastes in landfill disposals and co-products. References and methods for the review are reported in Annex II. The number of estimates is greater than the number of references because many studies considered multiple scenarios. Numbers reported in parentheses pertain to additional references and estimates that evaluated technologies with CCS. Distributional information relates to estimates currently available in LCA literature, not necessarily to underlying theoretical or practical extrema, or the true central tendency when considering all deployment conditions. [Figure 9.8]

Note: 1. 'Negative estimates' within the terminology of lifecycle assessments presented in this report refer to avoided emissions. Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHGs from the atmosphere.

lag of decades to centuries before net savings are achieved, or improve the net uptake of carbon into soils and aboveground biomass. Assessments of the net GHG effects of bioenergy are made difficult by challenges in observation, measurement, and attribution of indirect LUC, which depends on the environmental, economic, social and policy context and is neither directly observable nor easily attributable to a single cause. Illustrative estimates of direct and indirect LUC-related GHG emissions induced by several first-generation biofuel pathways provide central tendencies (based on different reporting methods) for a 30-year timeframe: for ethanol (EU wheat, US maize, Brazilian sugarcane) 5 to 82 g CO_2eq/MJ and for diesel (soy and rapeseed) 35 to 63 g CO_2eq/MJ. [9.3.4.1]

Impacts from *local and regional air pollution* constitute another important assessment category, with air pollutants (including particulate matter (PM), nitrous oxides (NO_x), sulphur dioxide (SO_2) and non-methane volatile organic compounds (NMVOC)) having effects at the global [Box 9.4], regional and local scale. Compared to fossil-based power generation, non-combustion-based RE power generation technologies have the potential to significantly reduce regional and local air pollution and associated health impacts (see this section below). For transportation fuels, however, the effect of switching to biofuels on tailpipe emissions is not yet clear. [9.3.4.2]

Local air pollutant emissions from fossil fuels and biomass combustion constitute the most important energy related impacts on *human health*. Ambient air pollution, as well as exposure to indoor air pollution from the combustion of coal and traditional biomass, has major health impacts and is recognized as one of the most important causes of morbidity and mortality worldwide, particularly for women and children in developing countries. In 2000, for example, comparative quantifications of health risks showed that more than 1.6 million deaths and over 38.5 million of disability-adjusted life-years (DALYs) were attributable to indoor smoke from solid fuels. Besides a fuel switch, mitigation options include improved cookstoves, ventilation and building design and behavioural changes. [9.3.4.3]

Impacts on *water* relate to operational and upstream water consumption of energy technologies and to water quality. These impacts are site specific and need to be considered with respect to local resources and needs. RE technologies like hydropower and some bioenergy systems, for example, are dependent on water availability and can either increase competition or mitigate water scarcity. In water-scarce areas, non-thermal RE technologies (e.g., wind and PV) can provide clean electricity without putting additional stress on water resources. Conventionally cooled thermal RE technologies (e.g., CSP, geothermal, biopower) can use more water during operation than non-RE technologies, yet dry cooling configurations can reduce this impact (Figure TS.9.5). Water use in upstream processes can be high for some energy technologies, particularly for fuel extraction and biomass feedstock production; including the latter, the current water footprint for electricity generation from biomass can be up to several hundred times greater than operational water consumption requirements for thermal power plants. Feedstock production, mining operations and fuel processing can also affect water quality. [9.3.4.4]

Most energy technologies have substantial *land requirements* when the whole supply chain is included. While the literature on lifecycle estimates for land use by energy technologies is scarce, the available evidence suggests that lifecycle land use by fossil energy chains can be comparable to or higher than land use by RE sources. For most RE sources, land use requirements are largest during the operational stage. An exception is the land intensity of bioenergy from dedicated feedstocks, which is significantly higher than for any other energy technology and shows substantial variations in energy yields per hectare for different feedstocks and climatic zones. A number of RE technologies (wind, wave and ocean) occupy large areas, but allow secondary uses such as farming, fishing and recreational activities. [9.3.4.5] Connected to land use are (site-specific) impacts on *ecosystems and biodiversity*. Occurring through various pathways, the most evident ones are through large-scale direct physical alteration of habitats and, more indirectly, habitat deterioration. [9.3.4.6]

The comparative assessment of *accident risks* is a pivotal aspect in a comprehensive evaluation of energy security aspects and sustainability performance associated with current and future energy systems. Risks of various energy technologies to society and the environment occur not only during the actual energy generation, but at all stages of energy chains. Accident risks of RE technologies are not negligible, but the technologies' often decentralized structure strongly limits the potential for disastrous consequences in terms of fatalities. While RE technologies overall exhibit low fatality rates, dams associated with some hydropower projects may create a specific risk depending on site-specific factors. [9.3.4.7]

9.4 Implication of sustainable development pathways for renewable energy

Following the more static analysis of the impacts of current and emerging RE systems on the four SD goals, the SD implications of possible future RE deployment pathways are assessed in a more dynamic manner and thus incorporate the intertemporal component of SD. Since the interaction of future RE and SD pathways cannot be anticipated by relying on a partial analysis of individual energy technologies, the discussion is based on results from the scenario literature that typically treats the portfolio of technological alternatives in the framework of a global or regional energy system. [9.4]

The vast majority of models used to generate the scenarios reviewed (see Chapter 10, Section 10.2) capture the interactions between different options for supplying, transforming and using energy. The models range from regional, energy-economic models to integrated assessment models (IAMs) and are here referred to as integrated models. Historically, these models have focused much more on the technological and macroeconomic aspects of energy transitions, and in the process have produced largely aggregated measures of technological penetration or energy generated by particular sources of supply. The value of these models in generating long-term scenarios and their potential to help understand the interrelation between SD and RE rests on their ability to consider interactions across a broad set of human activities over different regional and time scales. Integrated models continually undergo developments, some of which will be crucial for the representation of sustainability concerns in the future, for example, increasing their temporal and spatial resolution, allowing for a better representation of the distribution of wealth across the population and incorporating greater detail in human and physical Earth system characterization. [9.4]

The assessment focuses on what model-based analyses currently have to say with respect to SD pathways and the role of RE and evaluates how model-based analyses can be improved to provide a better understanding of sustainability issues in the future. [9.4]

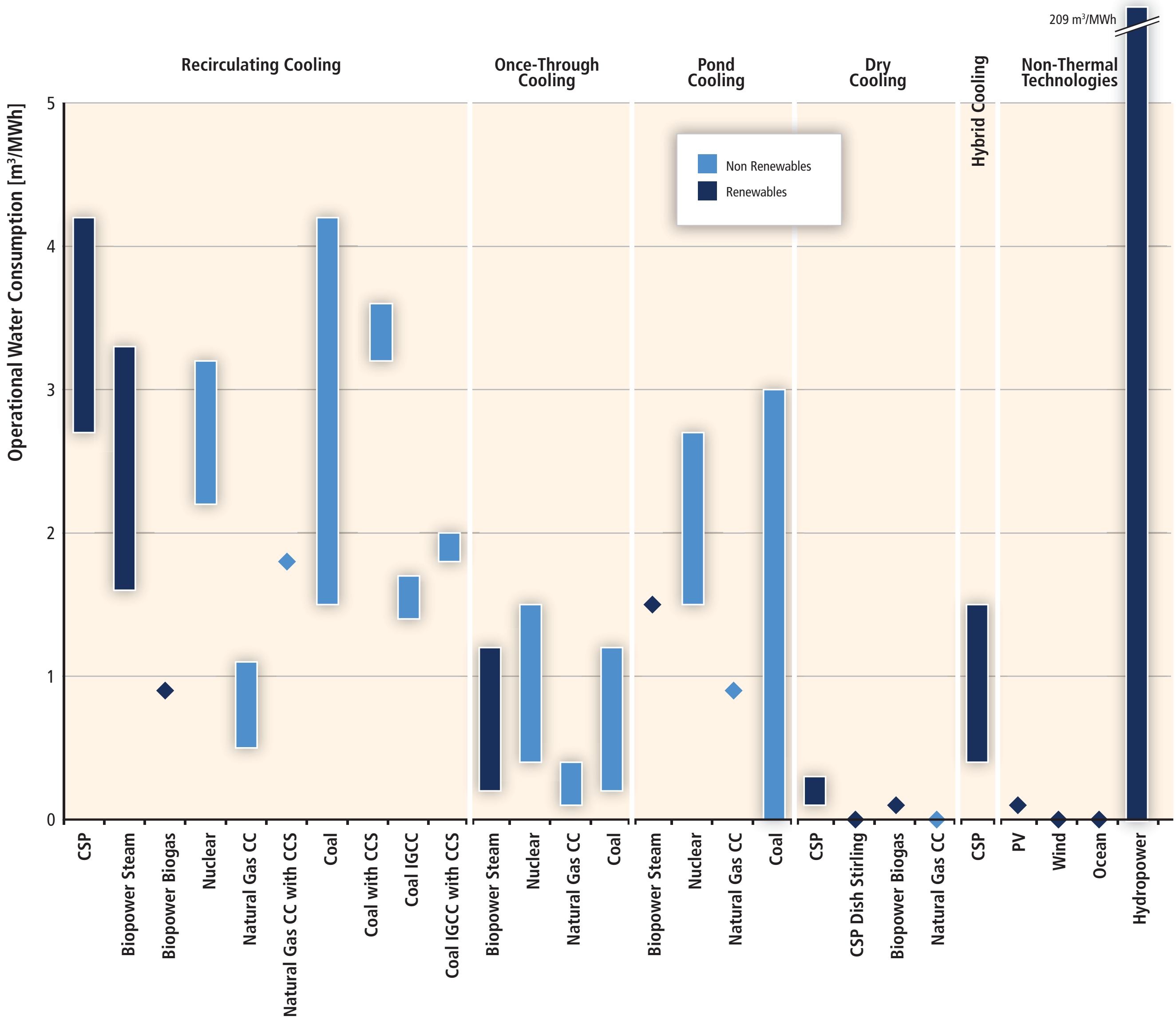


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Figure TS.9.5 | Ranges of rates of operational water consumption by thermal and non-thermal electricity-generating technologies based on a review of available literature (m^3/MWh). Bars represent absolute ranges from available literature, diamonds single estimates; n represents the number of estimates reported in the sources. Methods and references used in this literature review are reported in Annex II. Note that upper values for hydropower result from a few studies measuring gross evaporation values, and may not be representative (see Box 5.2). [Figure 9.14]

Notes: CSP: concentrated solar power; CCS: carbon capture and storage; IGCC: integrated gasification combined cycle; CC: combined cycle; PV: photovoltaic.

9.4.1 Social and economic development

Integrated models usually have a strong macro-perspective and do not consider advanced welfare measures. [9.2.2, 9.3.1] Instead, they focus on economic growth, which in itself is an insufficient measure of sustainability, but can be used as an indicative welfare measure in the context of different stabilization pathways. Mitigation scenarios usually include a tentative strong sustainability constraint by putting an upper limit on future GHG emissions. This results in welfare losses (usually measured as GDP or consumption foregone) based on assumptions about the availability and costs of mitigation technologies. Limiting the availability of technological alternatives for constraining GHGs further increases welfare losses. Studies that specifically assess the implications of constraining RE for different GHG concentration stabilization levels show that the wide availability of all RE technologies is essential in order to reach low stabilization levels and that the full availability of low-carbon technologies, including RE, is crucial for keeping mitigation costs at relatively low levels, even for less strict stabilization levels. [9.4.1]

With respect to regional effects, scenario analyses show that developing countries are likely to see most of the expansion in RE production. With the challenge to overcome high LCOEs of RE technologies still to be met, these results hint at the potential of developing countries to leapfrog the emission-intensive developing paths that developed countries have taken so far. Regional mitigation opportunities will, however, vary, depending on many factors including technology availability, but also population and economic growth. Costs will also depend on the allocation of tradable emission permits, both initially and over time, under a global climate mitigation regime. [9.4.1]

In general, scenario analyses point to the same links between RE, mitigation and economic growth in developed and developing countries, only the forces are generally larger in non-Annex I countries than in Annex I countries due to more rapid assumed economic growth and the consequently increasing mitigation burden over time. However, the modelling structures used to generate long-term global scenarios generally assume perfectly functioning economic markets and institutional infrastructures across all regions of the globe. They also discount the special circumstances that prevail in all countries, particularly in developing countries where these assumptions are particularly tenuous. These sorts of differences and the influence they might have on social and economic development among countries should be an area of active future research. [9.4.1]

9.4.2 Energy access

Integrated models thus far have often been based on developed country information and experience and assumed energy systems in other parts of the world and at different stages of development to behave likewise. Usually, models do not capture important and determinative dynamics in developing countries, such as fuel choices, behavioural heterogeneity and informal economies. This impedes an assessment of the interaction between RE and the future availability of energy services for different populations, including basic household level tasks, transportation, and energy for commerce, manufacturing and agriculture. However, some models have started to integrate factors such as potential supply shortages, informal economies and diverse income groups, and to increase the distributional resolution. [9.4.2]

Available scenario analyses are still characterized by large uncertainties. For India, results suggested that income distribution in a society is as important for increasing energy access as income growth. Also, increasing energy access is not necessarily beneficial for all aspects of SD, as a shift to modern energy away from, for example, traditional biomass could simply be a shift to fossil fuels. In general, available scenario analyses highlight the role of policies and finance for increased energy access, even though forced shifts to RE that would provide access to modern energy services could negatively affect household budgets. [9.4.2]

Further improvements in the distribution resolution and structural rigidity (inability of many models to capture social phenomena and structural changes that underlie peoples' utilization of energy technologies) are particularly challenging. An explicit representation of the energy consequences for the poorest, women, specific ethnic groups within countries, or those in specific geographical areas, tends to be outside the range of current global model output. In order to provide a more comprehensive view of the possible range of energy access options, future energy models should aim for a more explicit representation of relevant determinants (such as traditional fuels, modes of electrification, and income distribution) and link these to representations of alternative development pathways. [9.4.2]

9.4.3 Energy security

RE can influence energy security by mitigating concerns with respect to both availability and distribution of resources, as well as to the variability of energy sources. [9.2.2, 9.3.1] To the extent that RE deployment in mitigation scenarios reduces the overall risk of disruption by diversifying the energy portfolio, the energy system is less susceptible to (sudden) energy supply disruption. In scenarios, this role of RE will vary with the energy form. Solar, wind and ocean energy, which are closely associated with electricity production, have the potential to replace concentrated and increasingly scarce fossil fuels in the buildings and the industry sector. With appropriate carbon mitigation policies in place, electricity generation can be relatively easily decarbonized. In contrast, the demand for liquid fuels in the transport sector remains inelastic if no technological breakthrough can be achieved. While bioenergy could play an important role, this will depend on the availability of CCS that could divert its use to power generation with CCS—resulting in negative net carbon emissions for the system and smoothing the overall mitigation efforts significantly. [9.4.1, 9.4.3]

Against this background, energy security concerns raised in the past that related to oil supply disruptions are likely to remain relevant in the future. For developing countries the issue will become even more important, as their share in global total oil consumption increases in all assessed scenarios (Figure TS.9.6b). As long as technological alternatives for oil, for example, biofuels and/or the electrification of the transportation sector, do not play a dominant role in scenario analyses,

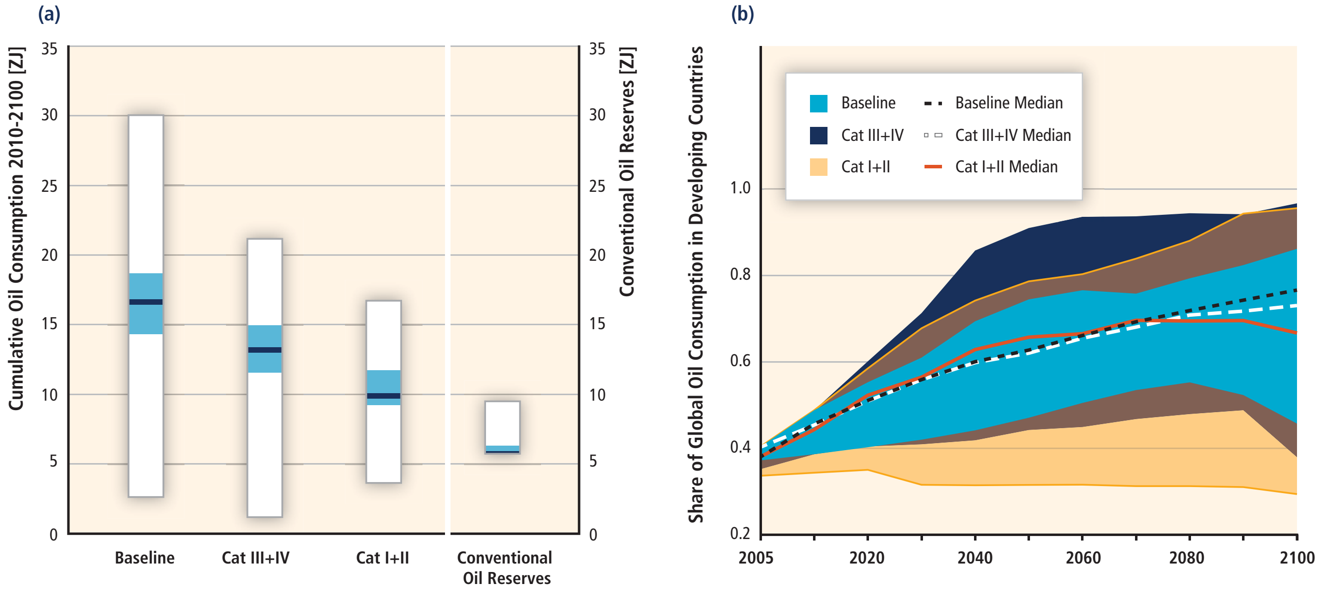


Figure TS.9.6 | (a) Conventional oil reserves compared to projected cumulative oil consumption (ZJ) from 2010 to 2100 in scenarios assessed in Chapter 10 for different scenario categories: baseline scenarios, Category III and IV scenarios and low stabilization (Category I+II) scenarios. The thick dark blue line corresponds to the median, the light blue bar corresponds to the inter-quartile range (25th to 75th percentile) and the white surrounding bar corresponds to the total range across all reviewed scenarios. The last column shows the range of proven recoverable conventional oil reserves (light blue bar) and estimated additional reserves (white surrounding bar). (b) Range of share of global oil consumed in non-Annex I countries for different scenario categories over time, based on scenarios assessed in Chapter 10. [Figure 9.18]

most mitigation scenarios do not see dramatic differences between the baseline and policy scenarios with respect to cumulative oil consumption (Figure TS.9.6a). [9.4.3]

An increased market for bioenergy could raise additional energy security concerns in the future if it was characterized by a small number of sellers and thus showed parallels to today's oil market. In such an environment, the risk that food prices could be linked to volatile bioenergy markets would have to be mitigated to impede severe impacts on SD as high and volatile food prices would clearly hurt the poor. [9.4.3]

The introduction of variable RE technologies also adds new concerns, such as vulnerability to extreme natural events or international price fluctuations, which are not yet satisfactorily addressed by large integrated models. Additional efforts to increase system reliability are likely to add costs and involve balancing needs (such as holding stocks of energy), the development of complementary flexible generation, strengthening network infrastructure and interconnections, energy storage technologies and modified institutional arrangements including regulatory and market mechanisms [7.5, 8.2.1, 9.4.3]

Energy security considerations today usually focus on the most prominent energy security issues in recent memory. However, energy security aspects of the future might go well beyond these issues, for example, in relation to critical material inputs for RE technologies. These broader concerns as well as options for addressing them, for example, recycling, are largely absent from future scenarios of mitigation and RE. [9.4.3]

9.4.4 Climate change mitigation and environmental and health impacts in scenarios of the future

Replacing fossil fuels with RE or other low-carbon technologies can significantly contribute to the reduction of NO_x and SO_2 emissions. Several models have included explicit representation of factors, such as sulphate pollution, that are linked to environmental or health impacts. Some scenario results show that climate policy can help drive improvements in local air pollution (i.e., PM), but air pollution reduction policies alone do not necessarily drive reductions in GHG emissions. Another implication of some potential energy trajectories is the possible diversion of land to support biofuel production. Scenario results have pointed at the possibility that, if not accompanied by other policy measures, climate policy could drive widespread deforestation, with land use being shifted to bioenergy crops with possibly adverse SD implications, including GHG emissions. [9.4.4]

Unfortunately, existing scenario literature does not explicitly treat the many non-emissions related elements of sustainable energy development, such as water use, the impacts of energy choices on household-level services, or indoor air quality. This can be partly explained by models being designed to look at fairly large world regions without income or geographic distributional detail. For a broad assessment of environmental impacts at the regional and local level, models would need to look at smaller scales of geographical impacts, which is currently a matter of ongoing research. Finally, many models do not explicitly allow for incorporation of LCA results of the technological alternatives. What these impacts are, whether and how to compare them across categories, and whether they might be incorporated into future scenarios would constitute useful areas for future research. [9.4.4]

9.5 Barriers and opportunities for renewable energy in the context of sustainable development

Pursuing a renewable energy deployment strategy in the context of SD implies that most environmental, social and economic effects are taken explicitly into account. Integrated planning, policy and implementation processes can support this by anticipating and overcoming potential barriers to and exploiting opportunities of RE deployment. [9.5]

Barriers that are particularly pertinent in a sustainable development context and that may either impede RE deployment or result in trade-offs with SD criteria relate to socio-cultural, information and awareness, market-related and economic barriers. [9.5.1]

Socio-cultural barriers or concerns have different origins and are intrinsically linked to societal and personal values and norms. Such values and norms affect the perception and acceptance of RE technologies and the potential impacts of their deployment by individuals, groups and societies. From a sustainable development perspective, barriers may arise from inadequate attention to such socio-cultural concerns, which include barriers related to behaviour; natural habitats and natural and human heritage sites, including impacts on biodiversity and ecosystems; landscape aesthetics; and water/land use and water/land use rights, as well as their availability for competing uses. [9.5.1.1]

Public awareness and acceptance is an important element in the need to rapidly and significantly scale up RE deployment to help meet climate change mitigation goals. Large-scale implementation can only be undertaken successfully with the understanding and support of the public. This may require dedicated communication efforts related to the achievements and the opportunities associated with wider-scale applications. At the same time, however, public participation in planning decisions as well as fairness and equity considerations in the distribution of the benefits and costs of RE deployment play an equally important role and cannot be side-stepped. [9.5.1.1]

In developing countries, limited technical and business skills and the absence of technical support systems are particularly apparent in the energy sector, where awareness of and information dissemination regarding available and appropriate RE options among potential consumers is a key determinant of uptake and market creation. This gap in awareness is often perceived as the single most important factor affecting the deployment of RE and development of small and medium enterprises that contribute to economic growth. Also, there is a need to focus on the capacity of private actors to develop, implement and deploy RE technologies, which includes increasing technical and business capability at the micro or firm level. [9.5.1.2]

Attitudes towards RE in addition to rationality are driven by emotions and psychological issues. To be successful, RE deployment and information and awareness efforts and strategies need to take this explicitly into account. [9.5.1.2]

To assess the economics of RE in the context of SD, social costs and benefits need to be explicitly considered. RE should be assessed against quantifiable criteria targeted at cost effectiveness, regional appropriateness, and environmental and distributional consequences. Grid size and technologies are key determinants of the *economic viability* of RE and of the competitiveness of RE compared to non-renewable energy. Appropriate RE technologies that are economically viable are often found to be available for expanding rural off-grid energy access, in particular smaller off-grid and mini-grid applications. [9.5.1.3]

In cases where deployment of RE is viable from an economic perspective, other economic and financial barriers may affect its deployment. High upfront costs of investments, including high installation and grid connection costs, are examples of frequently identified barriers to RE deployment. In developing countries, policy and entrepreneurial support systems are needed along with RE deployment to stimulate economic growth and SD and catalyze rural and peri-urban cash economies. Lack of adequate resource potential data directly affects uncertainty regarding resource availability, which may translate into higher risk premiums for investors and project developers. The internalization of environmental and social externalities frequently results in changes in the ranking of various energy sources and technologies, with important lessons for SD objectives and strategies. [9.5.1.3]

Strategies for SD at international, national and local levels as well as in private and nongovernmental spheres of society can help overcome barriers and create opportunities for RE deployment by integrating RE and SD policies and practices. [9.5.2]

Integrating RE policy into national and local SD strategies (explicitly recognized at the 2002 World Summit on Sustainable Development) provides a framework for countries to select effective SD and RE strategies and to align those with international policy measures. To that end, national strategies should include the removal of existing financial mechanisms that work against SD. For example, the removal of fossil fuel subsidies may have the potential to open up opportunities for more extensive use or even market entry of RE, but any subsidy reform towards the use of RE technologies needs to address the specific needs of the poor and demands a case-specific analysis. [9.5.2.1]

The CDM established under the Kyoto Protocol is a practical example of a mechanism for SD that internalizes environmental and social externalities. However, there are no international standards for sustainability assessments (including comparable SD indicators) to counter weaknesses in the existing system regarding sustainability approval. As input to the negotiations for a post-2012 climate regime, many suggestions have been made about how to reform the CDM to better achieve new and improved mechanisms for SD. [9.5.2.1]

Opportunities for RE to play a role in national strategies for SD can be approached by integrating SD and RE goals into development policies and by development of sectoral strategies for RE that contribute to goals for green growth and low-carbon and sustainable development including leapfrogging. [9.5.2.1]

At the local level, SD initiatives by cities, local governments, and private and nongovernmental organizations can be drivers of change and contribute to overcome local resistance to RE installations. [9.5.2.2]

9.6 Synthesis, knowledge gaps and future research needs

RE can contribute to SD and the four goals assessed to varying degrees. While benefits with respect to reduced environmental and health impacts may appear more clear-cut, the exact contribution to, for example, social and economic development is more ambiguous. Also, countries may prioritize the four SD goals according to their level of development. To some extent, however, these SD goals are also strongly interlinked. Climate change mitigation constitutes in itself a necessary prerequisite for successful social and economic development in many developing countries. [9.6.6]

Following this logic, climate change mitigation can be assessed under the strong SD paradigm, if mitigation goals are imposed as constraints on future development pathways. If climate change mitigation is balanced against economic growth or other socioeconomic criteria, the problem is framed within the paradigm of weak SD allowing for trade-offs between these goals and using cost-benefit type analyses to provide guidance in their prioritization. [9.6.6]

However, the existence of uncertainty and ignorance as inherent components of any development pathway, as well as the existence of associated and possibly 'unacceptably high' opportunity costs, will make continued adjustments crucial. In the future, integrated models may be in a favourable position to better link the weak and strong SD paradigms for decision-making processes. Within well-defined guardrails, integrated models could explore scenarios for different mitigation pathways, taking account of the remaining SD goals by including important and relevant bottom-up indicators. According to model type, these alternative development pathways might be optimized for socially beneficial outcomes. Equally, however, the incorporation of GHG emission-related LCA data will be crucial for a clear definition of appropriate GHG concentration stabilization levels in the first place. [9.6.6]

In order to improve the knowledge regarding the interrelations between SD and RE and to find answers to the question of effective, economically efficient and socially acceptable transformations of the energy system, it is necessary to develop a closer integration of insights from social, natural and economic sciences (e.g., through risk analysis approaches), reflecting the different dimensions of sustainability (especially intertemporal, spatial, and intergenerational). So far, the knowledge base is often limited to very narrow views from specific branches of research, which do not fully account for the complexity of the issue. [9.7]

10. Mitigation Potential and Costs

10.1 Introduction

Future GHG emission estimates are highly dependent on the evolution of many variables, including, among others, economic growth, population growth, energy demand, energy resources and the future costs and performance of energy supply and end-use technologies. Mitigation and other non-mitigation policy structures in the future will also influence deployment of mitigation technologies and therefore GHG emissions and the ability to meet climate goals. Not only must all these different forces be considered simultaneously when exploring the role of RE in climate mitigation [see Figure 1.14], it is not possible to know today with any certainty how these different key forces might evolve decades into the future. [10.1]

Questions about the role that RE sources are likely to play in the future, and how they might contribute to GHG mitigation pathways, need to be explored within this broader context. Chapter 10 provides such an exploration through the review of 164 existing medium- to long-term scenarios from large-scale, integrated models. The comprehensive review explores the range of global RE deployment levels emerging in recent published scenarios and identifies many of the key forces that drive the variation among scenarios (note that the chapter relies exclusively on existing published scenarios and does not create any new scenarios). It does so both at the scale of RE as a whole and also in the context of individual RE technologies. The review highlights the importance of interactions and competition with other technologies as well as the evolution of energy demand more generally. [10.2]

This large-scale review is complemented with a more detailed discussion of future RE deployment, using 4 of the 164 scenarios as illustrative examples. The chosen scenarios span a range of different future expectations about RE characteristics, are based on different methodologies and cover different GHG concentration stabilization levels. This approach provides a next level of detail for exploring the role of RE in climate change mitigation, distinguishing between different applications (electricity generation, heating and cooling, transport) and regions. [10.3]

As the resulting role of RE is significantly determined by cost factors, a more general discussion about cost curves and cost aspects is then provided. This discussion starts with an assessment of the strengths and shortcomings of supply curves for RE and GHG mitigation, and then reviews the existing literature on regional RE supply curves, as well as abatement cost curves, as they pertain to mitigation using RE sources. [10.4]

Costs of RE commercialization and deployment are then addressed. The chapter reviews present RE technology costs, as well as expectations about how these costs might evolve into the future. To allow an assessment of future market volumes and investment needs, based on the results of the four illustrative scenarios investments in RE are discussed in particular with respect to what might be required if ambitious climate protection goals are to be achieved. [10.5]

Standard economic measures do not cover the full set of costs. Therefore, social and environmental costs and benefits of increased deployment of RE in relation to climate change mitigation and SD are synthesized and discussed. [10.6]

10.2 Synthesis of mitigation scenarios for different renewable energy strategies

An increasing number of integrated scenario analyses that are able to provide relevant insights into the potential contribution of RE to future energy supplies and climate change mitigation has become available. To provide a broad context for understanding the role of RE in mitigation and the influence of RE on the costs of mitigation, 164 recent medium- to long-term scenarios from 16 global energy-economic and integrated assessment models were reviewed. The scenarios were collected through an open call. The scenarios cover a large range of CO_2 concentrations (350 to 1,050 ppm atmospheric CO_2 concentration by 2100), representing both mitigation and baseline scenarios. [10.2.2.1]

Although these scenarios represent some of the most recent and sophisticated thinking regarding climate mitigation and the role of RE in climate mitigation in the medium- to long-term, they, as with any analysis looking decades into the future, must be interpreted carefully. All of the scenarios were developed using quantitative modelling, but there is enormous variation in the detail and structure of the models used to construct the scenarios. In addition, the scenarios do not represent a random sample of possible scenarios that could be used for formal uncertainty analysis. Some modelling groups provided more scenarios than others. In scenario ensemble analyses based on collecting scenarios from different studies, such as the review here, there is an inevitable tension between the fact that the scenarios are not truly a random sample and the sense that the variation in the scenarios does still provide real and often clear insights into our knowledge about the future, or lack thereof. [10.2.1.2, 10.2.2.1]

A fundamental question relating to the role of RE in climate mitigation is how closely RE deployment levels are correlated with long-term atmospheric CO_2 concentration or related climate goals. The scenarios indicate that although there is a strong correlation between fossil and industrial CO_2 emissions pathways and long-term CO_2 concentration goals across the scenarios, the relationship between RE deployment and CO_2 concentration goals is far less robust (Figure TS.10.1). RE deployment generally increases with the stringency of the CO_2 concentration goal, but there is enormous variation among RE deployment levels for any given CO_2 concentration goal. For example, in scenarios that stabilize the atmospheric CO_2 concentration at a level of less than 440 ppm (Categories I and II), the median RE deployment levels are 139 EJ/yr in 2030 and 248 EJ/yr in 2050, with the highest levels reaching 252 EJ/yr in 2030 and up to 428 EJ/yr in 2050. These levels are considerably higher than the corresponding RE deployment levels in baseline scenarios, although it has to be acknowledged that the range of RE deployment in each of the CO_2 stabilization categories is wide. [10.2.2.2]

At the same time, it is also important to note that despite the variation, the absolute magnitudes of RE deployment are dramatically higher than those of today in the vast majority of the scenarios. In 2008, global renewable primary energy supply in direct equivalent stood at roughly 64 EJ/yr. The majority of this, about 30 EJ/yr, was traditional biomass. In contrast, by 2030, many scenarios indicate a doubling of RE deployment or more compared to today, and this is accompanied in most scenarios by a reduction in traditional biomass, implying substantial growth in non-traditional RE sources. By 2050, RE deployment levels in most scenarios are higher than 100 EJ/yr (median at 173 EJ/yr), reach 200 EJ/yr in many of the scenarios and more than 400 EJ/yr in some cases. Given that traditional biomass use decreases in most scenarios, the scenarios represent an increase in RE production (excluding traditional biomass) of anywhere from roughly three- to more than ten-fold. More than half of the scenarios show a contribution of RE in excess of a 17% share of primary energy supply in 2030, rising to more than 27% in 2050. The scenarios with the highest RE shares reach approximately 43% in 2030 and 77% in 2050. Deployments after 2050 are even larger. This is an extraordinary expansion in energy production from RE. [10.2.2.2]

Indeed, RE deployment is quite large in many of the baseline scenarios with no assumed GHG concentration stabilization level. By 2030, RE deployment levels of up to about 120 EJ/yr are projected, with many baseline scenarios reaching more than 100 EJ/yr in 2050 and in some cases up to 250 EJ/yr. These large RE baseline deployments result from a range of underlying scenario assumptions, for example, the assumption that energy consumption will continue to grow substantially throughout the century, assumptions about the ability of RE to contribute to increased energy access, assumptions about the availability of fossil resources, and other assumptions (e.g., improved costs and performance of RE technologies) that would render RE technologies economically increasingly competitive in many applications even absent climate policy. [10.2.2.2]

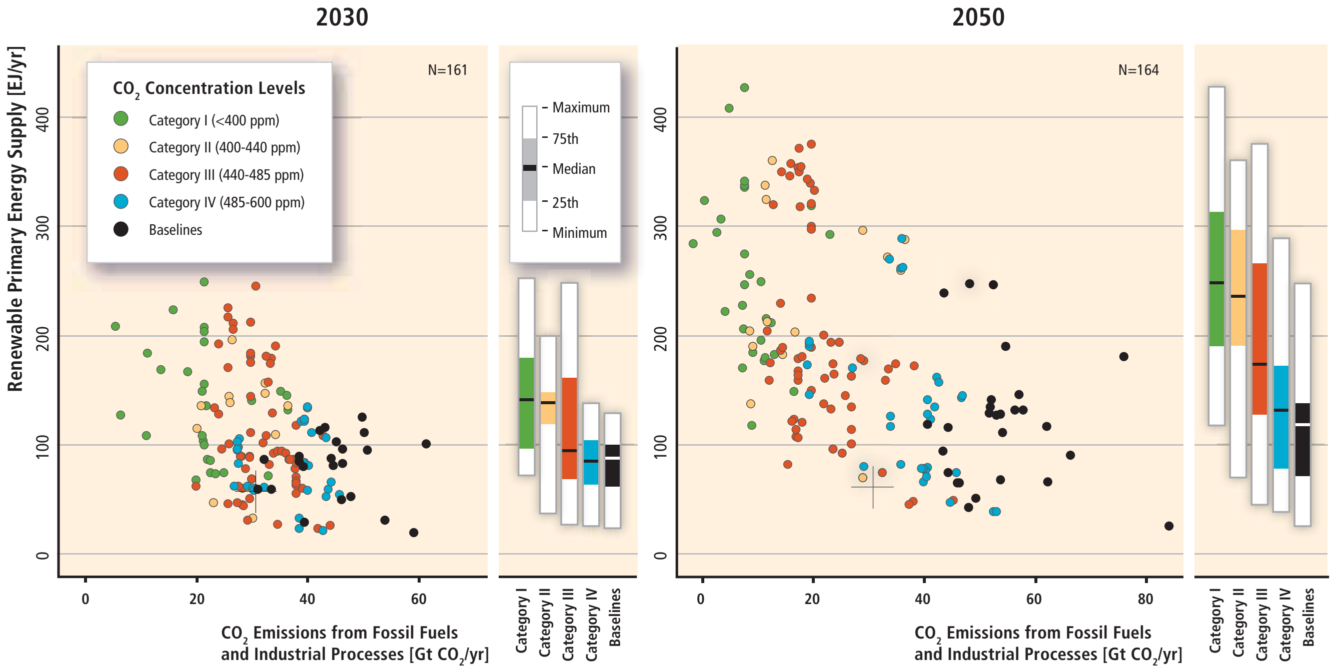


Figure TS.10.1 | Global RE primary energy supply (direct equivalent) from 164 long-term scenarios as a function of fossil and industrial CO_2 emissions in 2030 and 2050. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100. The panels to the right of the scatterplots show the deployment levels of RE in each of the atmospheric CO_2 concentration categories. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. The blue crossed-lines show the relationship in 2007. Pearson's correlation coefficients for the two data sets are -0.40 (2030) and -0.55 (2050). For data reporting reasons, only 161 scenarios are included in the 2030 results shown here, as opposed to the full set of 164 scenarios. RE deployment levels below those of today are a result both of model output as well as differences in the reporting of traditional biomass. [Figure 10.2]

The uncertainty in RE's role in climate mitigation results from uncertainty regarding a number of important forces that influence the deployment of RE. Two important factors are energy demand growth and the competition with other options to reduce CO_2 emissions (primarily nuclear energy and fossil energy with CCS). Meeting long-term climate goals requires a reduction in the CO_2 emissions from energy and other anthropogenic sources. For any given climate goal, this reduction is relatively well defined; there is a tight relationship between fossil and industrial CO_2 emissions and the deployment of freely emitting fossil energy across the scenarios (Figure TS.10.2). The demand for low-carbon energy (including RE, nuclear energy and fossil energy with CCS) is simply the difference between total primary energy demand and the production of freely-emitting fossil energy; that is, whatever energy cannot be supplied by freely-emitting fossil energy because of climate constraints must be supplied either by low-carbon energy or by measures that reduce energy consumption. However, scenarios indicate enormous uncertainty about energy demand growth, particularly many decades into the future. This variation is generally much larger than the effect of mitigation on energy consumption. Hence, there is substantial variability in low-carbon energy for any given CO_2 concentration goal due to variability in energy demand (Figure TS.10.2). [10.2.2.3]

The competition between RE, nuclear energy, and fossil energy with CCS then adds another layer of variability in the relationship between RE deployment and the CO_2 concentration goal. The cost, performance and availability of the competing supply side options—nuclear energy and fossil energy with CCS—is also uncertain. If the option to deploy these other supply-side mitigation technologies is constrained—because of cost and performance, but also potentially due to environmental, social or national security barriers—then, all things being equal, RE deployment levels will be higher (Figure TS.10.3). [10.2.2.4]

There is also great variation in the deployment characteristics of individual RE technologies. The absolute scales of deployments vary considerably among technologies and also deployment magnitudes are characterized by greater variation for some technologies relative to others (Figures TS.10.4 and TS.10.5). Further, the time scale of deployment varies across different RE sources, in large part representing differences in deployment levels today and (often) associated assumptions about relative technological maturity. [10.2.2.5]

The scenarios generally indicate that RE deployment is larger in non-Annex I countries over time than in the Annex I countries. Virtually all scenarios include the assumption that economic and energy demand growth will be larger at some point in the future in the non-Annex I countries than in the Annex I countries. The result is that the non-Annex I countries account for an increasingly large proportion of CO_2 emissions in baseline, or no-policy, cases and must therefore make larger emissions reductions over time (Figure TS.10.4). [10.2.2.5]

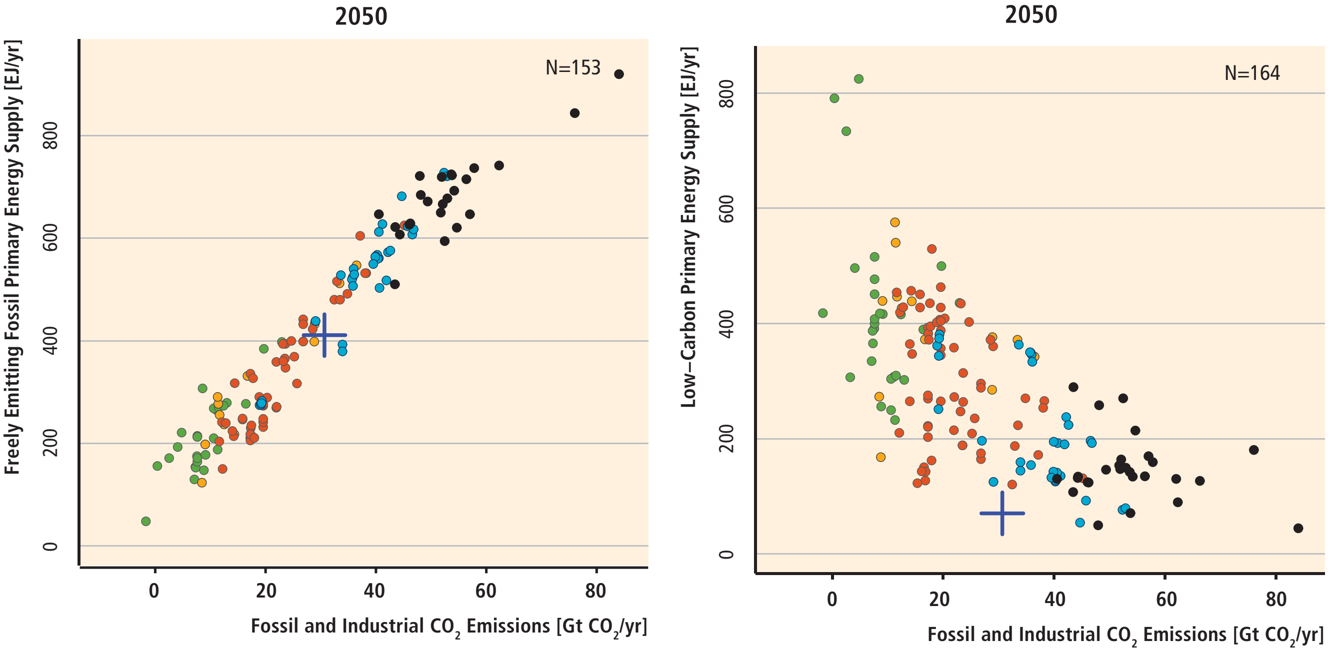


Figure TS.10.2 | Global freely emitting fossil fuel (left panel; direct equivalent) and low-carbon primary energy supply (right panel; direct equivalent) in 164 long-term scenarios in 2050 as a function of fossil and industrial CO_2 emissions. Low-carbon energy refers to energy from RE, fossil energy with CCS, and nuclear energy. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100. The blue crossed lines show the relationship in 2007. Pearson's correlation coefficients for the two data sets are 0.97 (freely emitting fossil) and -0.68 (low-carbon energy). For data reporting reasons, only 153 scenarios and 161 scenarios are included in the freely-emitting fossil and low-carbon primary energy results shown here, respectively, as opposed to the full set of 164 scenarios. [Figure 10.4, right panel, Figure 10.5, right panel]

Another fundamental question regarding RE and mitigation is the relationship between RE and mitigation costs. A number of studies have pursued scenario sensitivities that assume constraints on the deployment of individual mitigation options, including RE as well as nuclear energy and fossil energy with CCS (Figures TS.10.6 and TS.10.7). These studies indicate that mitigation costs are higher when options, including RE, are not available. Indeed, the cost penalty for limits on RE is often at least of the same order of magnitude as the cost penalty for limits on nuclear energy and fossil energy with CCS. The studies also indicate that more aggressive concentration goals may not be possible when RE options, or other low-carbon options, are not available. At the same time, when taking into account the wide range of assumptions across the full range of scenarios explored in this assessment, the scenarios demonstrate no meaningful link between measures of cost (e.g., carbon prices) and absolute RE deployment levels. This variation is a reflection of the fact that large-scale integrated models used to generate scenarios are characterized by a wide range of carbon prices and mitigation costs based on both parameter assumptions and model structure. To summarize, while there is an agreement in the literature that mitigation costs will increase if the deployment of RE technologies is constrained and that more ambitious concentration stabilization levels may not be reachable, there is little agreement on the precise magnitude of the cost increase. [10.2.2.6]

10.3 Assessment of representative mitigation scenarios for different renewable energy strategies

An in-depth analysis of 4 selected illustrative scenarios from the larger set of 164 scenarios allowed a more detailed look at the possible contribution of specific RE technologies in different regions and sectors. The IEA's World Energy Outlook (IEA WEO 2009) was selected as an example of a baseline scenario, while the other scenarios set clear GHG concentration stabilization levels. The chosen mitigation scenarios are ReMIND-RECIPE from the Potsdam Institute, MiniCAM EMF 22 from the Energy Modelling Forum Study 22 and the Energy [R] evolution scenario from the German Aerospace Centre, Greenpeace International and EREC (ER 2010). The scenarios work as illustrative examples, but they are not representative in a strict sense. However they represent four different future paths based on different methodologies and a wide range of underlying assumptions. Particularly, they stand for different RE deployment paths reaching from a typical

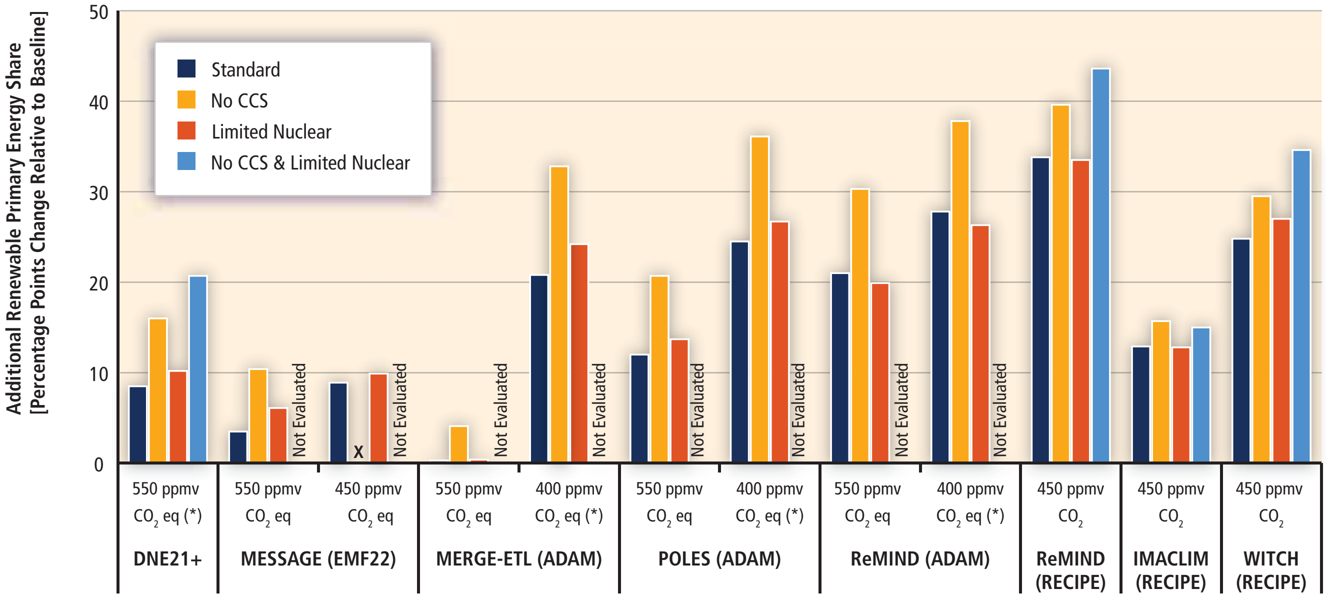


Figure TS.10.3 | Increase in global renewable primary energy share (direct equivalent) in 2050 in selected constrained technology scenarios compared to the respective baseline scenarios. The 'X' indicates that the respective concentration level for the scenario was not achieved. The definition of 'lim Nuclear' and 'no CCS' cases varies across models. The DNE21+, MERGE-ETL and POLES scenarios represent nuclear phase-outs at different speeds; the MESSAGE scenarios limit the deployment to 2010; and the ReMIND, IMACLIM and WITCH scenarios limit nuclear energy to the contribution in the respective baseline scenarios, which can still imply a significant expansion compared to current deployment levels. The REMIND (ADAM) 400 ppmv no CCS scenario refers to a scenario in which cumulative CO_2 storage is constrained to 120 Gt CO_2. The MERGE-ETL 400 ppmv no CCS case allows cumulative CO_2 storage of about 720 Gt CO_2. The POLES 400 ppmv CO_2eq no CCS scenario was infeasible and therefore the respective concentration level of the scenario shown here was relaxed by approximately 50 ppm CO_2. The DNE21+ scenario is approximated at 550 ppmv CO_2eq based on the emissions pathway through 2050. [Figure 10.6]

baseline perspective to a scenario that follows an optimistic application path for RE assuming that amongst others driven by specific policies the current high dynamic (increase rates) in the sector can be maintained. [10.3.1]

Figure TS.10.8 provides an overview of the resulting primary energy production by source for the four selected scenarios for 2020, 2030 and 2050 and compares the numbers with the range of the global primary energy supply. Using the direct equivalent methodology as done here, in 2050 bioenergy has the highest market share in all selected scenarios, followed by solar energy. The total RE share in the primary energy mix by 2050 has a substantial variation across all four scenarios. With 15% by 2050—more or less about today's level (12.9% in 2008)—the IEA WEO 2009 projects the lowest primary RE share, while the ER 2010 with 77% marks the upper level. The MiniCam EMF 22 expects that 31% and ReMIND-RECIPE that 48% of the world's primary energy demand will be provided by RE in 2050. The wide ranges of RE shares are a function of different assumptions for technology cost and performance data, availability of other mitigation technologies (e.g., CCS, nuclear power), infrastructure or integration constraints, non-economic barriers (e.g., sustainability aspects), specific policies and future energy demand projections. [10.3.1.4]

In addition, although deployment of the different technologies significantly increases over time, the resulting contribution of RE in the scenarios for most technologies in the different regions of the world is much lower than their corresponding technical potentials (Figure TS.10.9). The overall total global RE deployment by 2050 in all analyzed scenarios represents less than 3% of the available technical RE potential. On a regional level, the maximum deployment share out of the overall technical potential for RE in 2050 was found for China, with a total of 18% (ER 2010), followed by OECD Europe with 15% (ER 2010) and India with 13% (MiniCam EMF 22). Two regions have deployment rates of around 6% of the regional available technical RE potential by 2050: 7% in Developing Asia (MiniCam EMF 22) and 6% in OECD North America (ER 2010). The remaining five regions use less than 5% of the available technical potential for RE. [10.3.2.1]

Based on the resulting RE deployment for the selected four illustrative scenarios, the corresponding GHG mitigation potential has been calculated. For each sector, emission factors have been specified, addressing the kind of electricity generation or heat supply that RE displaces. As the substituted energy form depends on the overall system behaviour, this cannot be done exactly without conducting new and consistent scenario analysis or complex power plant dispatching analysis. Therefore, the calculation is necessarily based on simplified assumptions and can only be seen as indicative. Generally, attribution of precise mitigation potentials to RE should be viewed with caution. [10.3.3]

Very often RE applications are supposed to fully substitute for the existing mix of fossil fuel use, but in reality that may not be true as RE can compete, for instance, with nuclear energy or within the RE portfolio itself. To cover the uncertainties even partly for the specification of the emission factor, three different cases have been distinguished

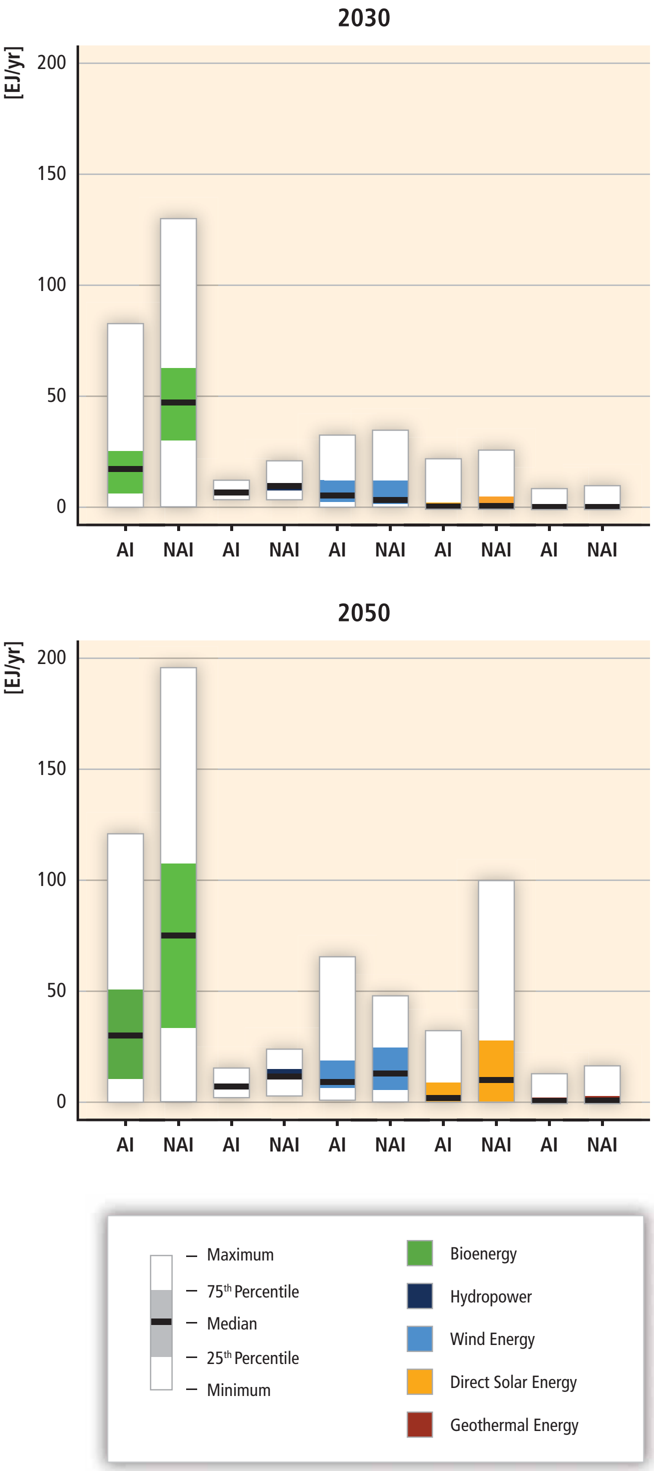


Figure TS.10.4 | Global RE primary energy supply (direct equivalent) by source in Annex I (AI) and Non-Annex I (NAI) countries in 164 long-term scenarios by 2030 and 2050. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. Depending on the source, the number of scenarios underlying these figures varies between 122 and 164. Although instructive for interpreting the information, it is important to note that the 164 scenarios are not explicitly a random sample meant for formal statistical analysis. (One reason that bioenergy supply appears larger than supplies from other sources is that the direct equivalent method is used to represent primary energy in this figure. Bioenergy is accounted for prior to conversion to fuels such as ethanol or electricity. The other technologies produce primarily (but not entirely) electricity, and they are accounted for based on the electricity produced. If primary equivalents were used, based on the substitution method, rather than direct equivalents, then energy production from non-biomass RE would be of the order of three times larger than shown here.) Ocean energy is not presented here as only very few scenarios consider this RE technology. [Figure 10.8]

(upper case: specific average CO_2 emissions of the fossil generation mix under the baseline scenario; medium case: specific average CO_2 emissions of the overall generation mix under the baseline scenario; and lower case: specific average CO_2 emissions of the generation mix of the particular analyzed scenario). Biofuels and other RE options for transport are excluded from the calculation due to limited data availability.

Additionally, to reflect the embedded GHG emissions from bioenergy used for direct heating, only half of the theoretical CO_2 savings have been considered in the calculation. Given the high uncertainties and variability of embedded GHG emissions, this is necessarily once more a simplified assumption. [10.3.3]

Figure TS.10.10 shows cumulative CO_2 reduction potentials from RE sources up to 2020, 2030 and 2050 resulting from the four scenarios reviewed here in detail. The analyzed scenarios outline a cumulative reduction potential (2010 to 2050) in the medium-case approach of between 244 Gt CO_2 (IEA WEO 2009) under the baseline conditions, 297 Gt CO_2 (MiniCam EMF 22), 482 Gt CO_2 (ER 2010) and 490 Gt CO_2 (ReMIND-RECIPE scenario). The full range across all calculated cases and scenarios is cumulative CO_2 savings of 218 Gt CO_2 (IEA WEO 2009) to 561 Gt CO_2 (ReMIND-RECIPE) compared to about 1,530 Gt CO_2 cumulative fossil and industrial CO_2 emissions in the WEO 2009 Reference scenario during the same period. However, these numbers exclude CO_2 savings for RE use in the transport sector (including biofuels and electric vehicles). The overall CO_2 mitigation potential can therefore be higher. [10.3.3]

10.4 Regional cost curves for mitigation with renewable energy sources

The concept of supply curves of carbon abatement, energy, or conserved energy all rest on the same foundation. They are curves consisting typically of discrete steps, each step relating the marginal cost of the abatement measure/energy generation technology or measure to conserve energy to its potential; these steps are ranked according to their cost. Graphically, the steps start at the lowest cost on the left with the next highest cost added to the right and so on, making an upward sloping left-to-right marginal cost curve. As a result, a curve is obtained that can be interpreted similarly to the concept of supply curves in traditional economics. [10.4.2.1]

The concept of energy conservation supply curves is often used, but it has common and specific limitations. The most often cited limitations in

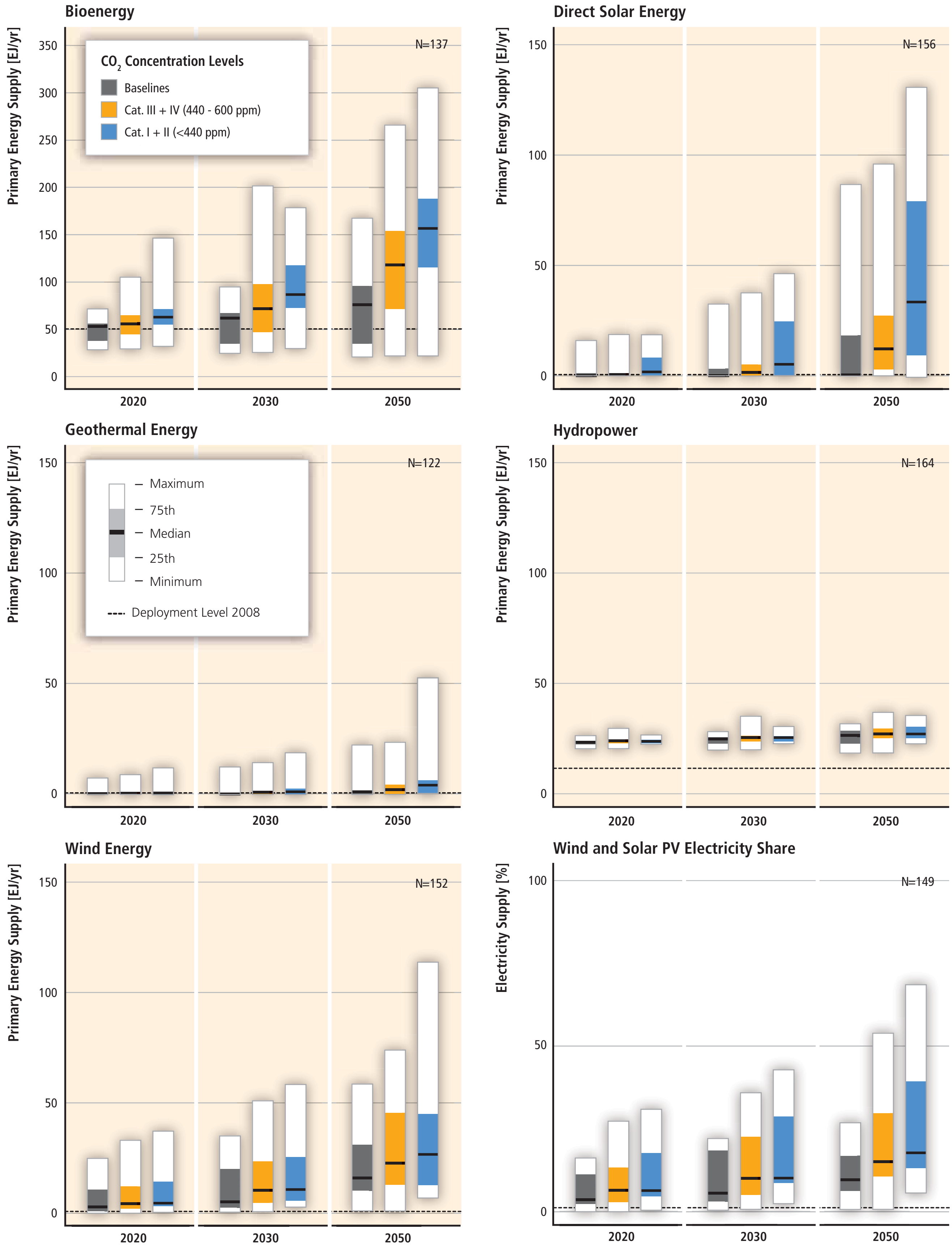

Bioenergy
Primary Energy Supply [EJ/yr]
0
50
100
150
200
250
300
350
CO_2 Concentration Levels
Baselines
Cat. III + IV (440 - 600 ppm)
Cat. I + II (<440 ppm)
N=137
2020
2030
2050
Direct Solar Energy
Primary Energy Supply [EJ/yr]
0
50
100
150
N=156
2020
2030
2050
Geothermal Energy
Primary Energy Supply [EJ/yr]
0
50
100
150
Maximum
75th
Median
25th
Minimum
Deployment Level 2008
N=122
2020
2030
2050
Hydropower
Primary Energy Supply [EJ/yr]
0
50
100
150
N=164
2020
2030
2050
Wind Energy
Primary Energy Supply [EJ/yr]
0
50
100
150
N=152
2020
2030
2050
Wind and Solar PV Electricity Share
Electricity Supply [%]
0
50
100
N=149
2020
2030
2050

Figure TS.10.5 | (Preceding page) Global primary energy supply (direct equivalent) of biomass, wind, solar, hydro, and geothermal energy in 164 long-term scenarios in 2020, 2030 and 2050, and grouped by different categories of atmospheric CO_2 concentration level in 2100. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. [Figure 10.9]

Notes: For data reporting reasons, the number of scenarios included in each of the panels shown here varies considerably. The number of scenarios underlying the individual panels, as opposed to the full set of 164 scenarios, is indicated in the right upper corner of each panel. One reason that bioenergy supply appears larger than supplies from other sources is that the direct equivalent method is used to represent primary energy in this figure. Bioenergy is accounted for prior to conversion to fuels such as biofuels, electricity and heat. The other technologies produce primarily (but not entirely) electricity and heat, and they are accounted for based on this secondary energy produced. If primary equivalents based on the substitution method were used rather than direct equivalent accounting, then energy production from non-biomass RE would be of the order of two to three times larger than shown here. Ocean energy is not presented here as scenarios so far seldom consider this RE technology. Finally, categories V and above are not included and Category IV is extended to 600 ppm from 570 ppm, because all stabilization scenarios lie below 600 ppm CO_2 in 2100, and because the lowest baselines scenarios reach concentration levels of slightly more than 600 ppm by 2100.

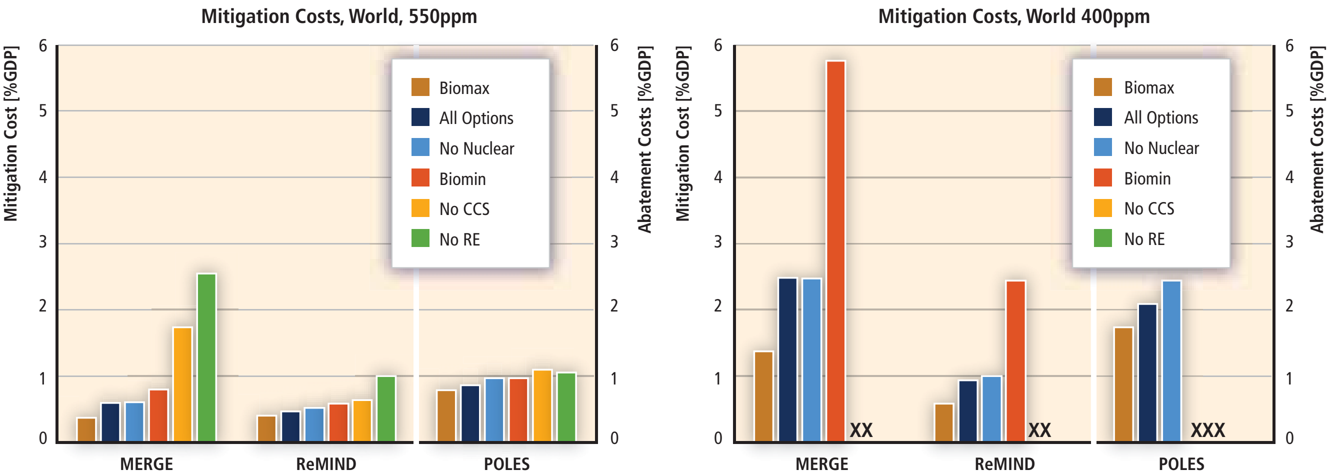


Figure TS.10.6 | Global mitigation costs (measured in terms of consumption loss) from the ADAM project under varying assumptions regarding technology availability for long-term stabilization levels of 550 and 400 ppmv CO_2eq. 'All options' refers to the standard technology portfolio assumptions in the different models, while 'biomax' and 'biomin' assume double and half the standard biomass potential of 200 EJ respectively. 'noccs' excludes CCS from the mitigation portfolio and 'nonuke' and 'norenew' constrain the deployment levels of nuclear and RE to the baseline level, which still potentially means a considerable expansion compared to today. The 'X' in the right panel indicates non-attainability of the 400 ppmv CO_2eq level in the case of limited technology options. [Figure 10.11]

this context are: controversy among scientists about potentials at negative costs; simplification of reality as actors also base their decisions on other criteria than those reflected in the curves; economic and technological uncertainty inherent to predicting the future, including energy price developments and discount rates; further uncertainty due to strong aggregation; high sensitivity relative to baseline assumptions and the entire future generation and transmission portfolio; consideration of individual measures separately, ignoring interdependencies between measures applied together or in different order; and, for carbon abatement curves, high sensitivity to (uncertain) emission factor assumptions. [10.4.2.1]

Having these criticisms in mind, it is also worth noting that it is very difficult to compare data and findings from RE abatement cost and supply curves, as very few studies have used a comprehensive and consistent approach that details their methodologies. Many of the regional and country studies provide less than 10% abatement of the baseline CO_2 emissions over the medium term at abatement costs under approximately USD_{2005} 100/t CO_2. The resulting low-cost abatement potentials are quite low compared to the reported mitigation potentials of many of the scenarios reviewed here. [10.4.3.2]

10.5 Cost of commercialization and deployment

Some RE technologies are broadly competitive with current market energy prices. Many of the other RE technologies can provide competitive energy services in certain circumstances, for example, in regions with favourable resource conditions or that lack the infrastructure for other low-cost energy supplies. In most regions of the world, however, policy measures are still required to ensure rapid deployment of many RE sources. [2.7, 3.8, 4.6, 5.8, 6.7, 7.8, 10.5.1, Figure TS.1.9]

Figures TS.10.11 and TS.10.12 provide additional data on levelized costs of energy (LCOE), also called levelized unit costs or levelized generation costs, for selected renewable power technologies and for renewable heating technologies, respectively. Figure TS.10.13 shows the levelized

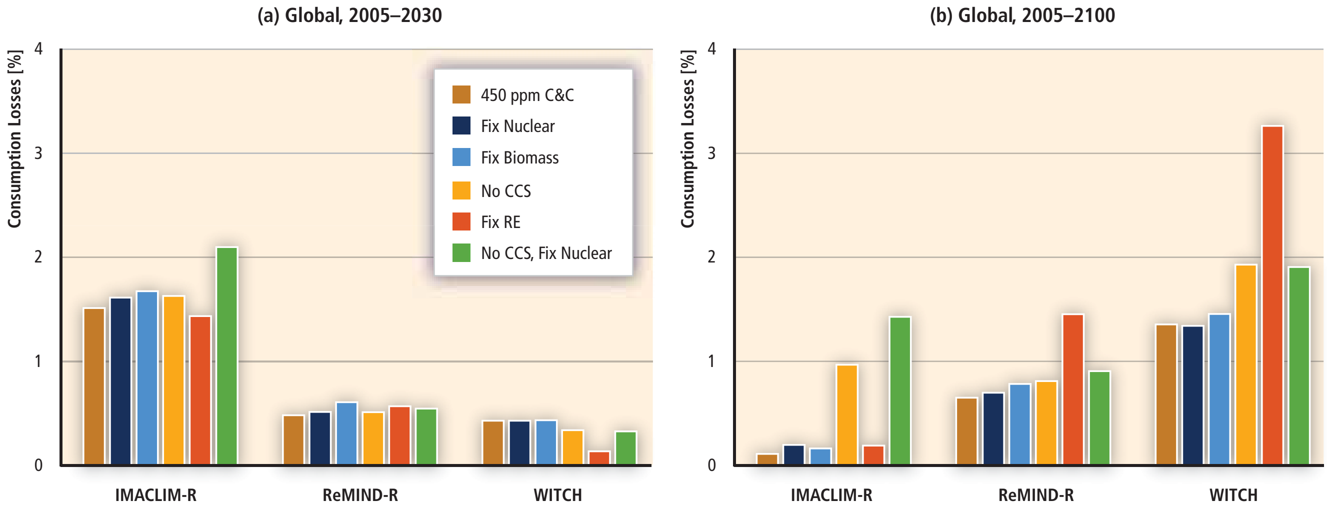


Figure TS.10.7 | Mitigation costs from the RECIPE project under varying assumptions regarding technology availability for a long-term stabilization level of 450 ppmv CO_2. Option values of technologies in terms of consumption losses for scenarios in which the option indicated is foregone (CCS) or limited to baseline levels (all other technologies) for the periods a) 2005 to 2030 and b) 2005 to 2100. Option values are calculated as differences in consumption losses for a scenario in which the use of certain technologies is limited with respect to the baseline scenario. Note that for WITCH, the generic backstop technology was assumed to be unavailable in the 'fix RE' scenario. [Figure 10.12]

cost of transport fuels (LCOF). LCOEs capture the full costs (i.e., investment costs, O&M costs, fuel costs and decommissioning costs) of an energy conversion installation and allocate these costs over the energy output during its lifetime, although not taking into account subsidies or policy incentives. As some RE technologies (e.g., PV, CSP and wind energy) are characterized by high shares of investment costs relative to variable costs, the applied discount rate has a prominent influence on the LCOE of these technologies (see Figures TS.10.11, TS.10.12 and TS.10.13). [10.5.1] The LCOEs are based on literature reviews and represent the most current cost data available. The respective ranges are rather broad as the levelized cost of identical technologies can vary across the globe depending on the RE resource base and local costs of investment, financing and O&M. Comparison between different technologies should not be based solely on the cost data provided in Figures TS 1.9,

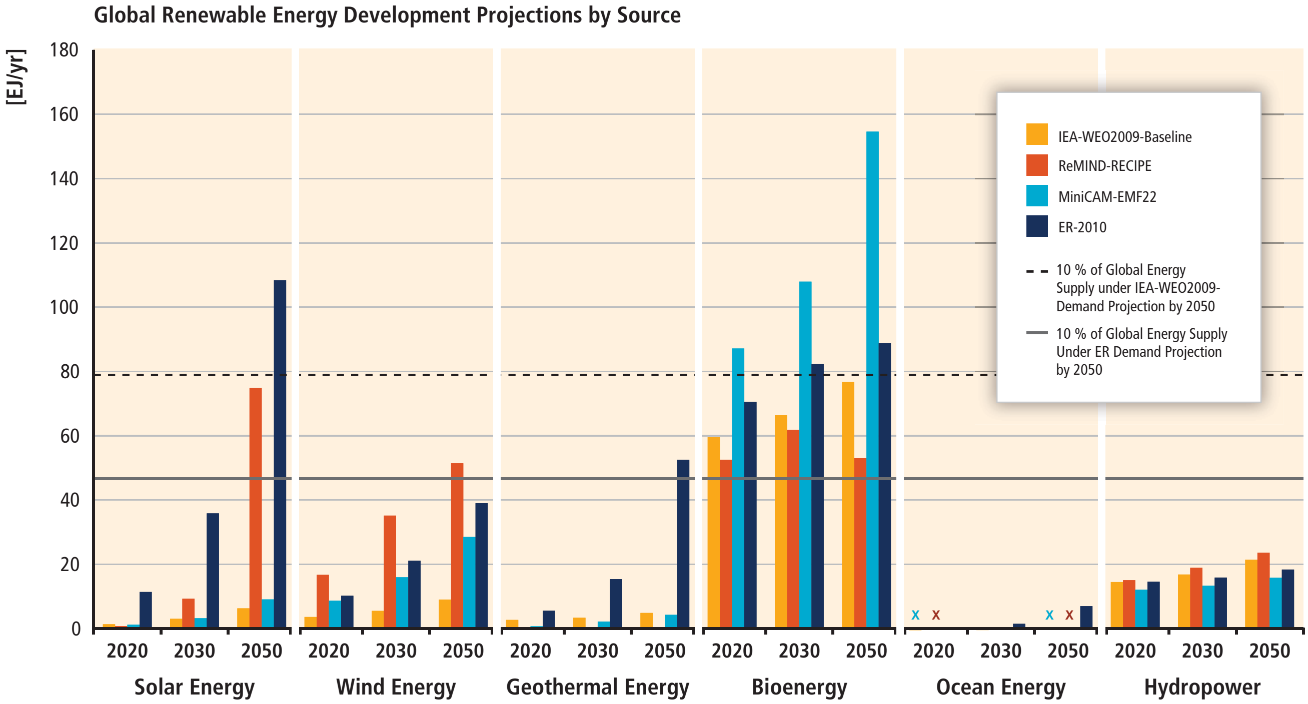
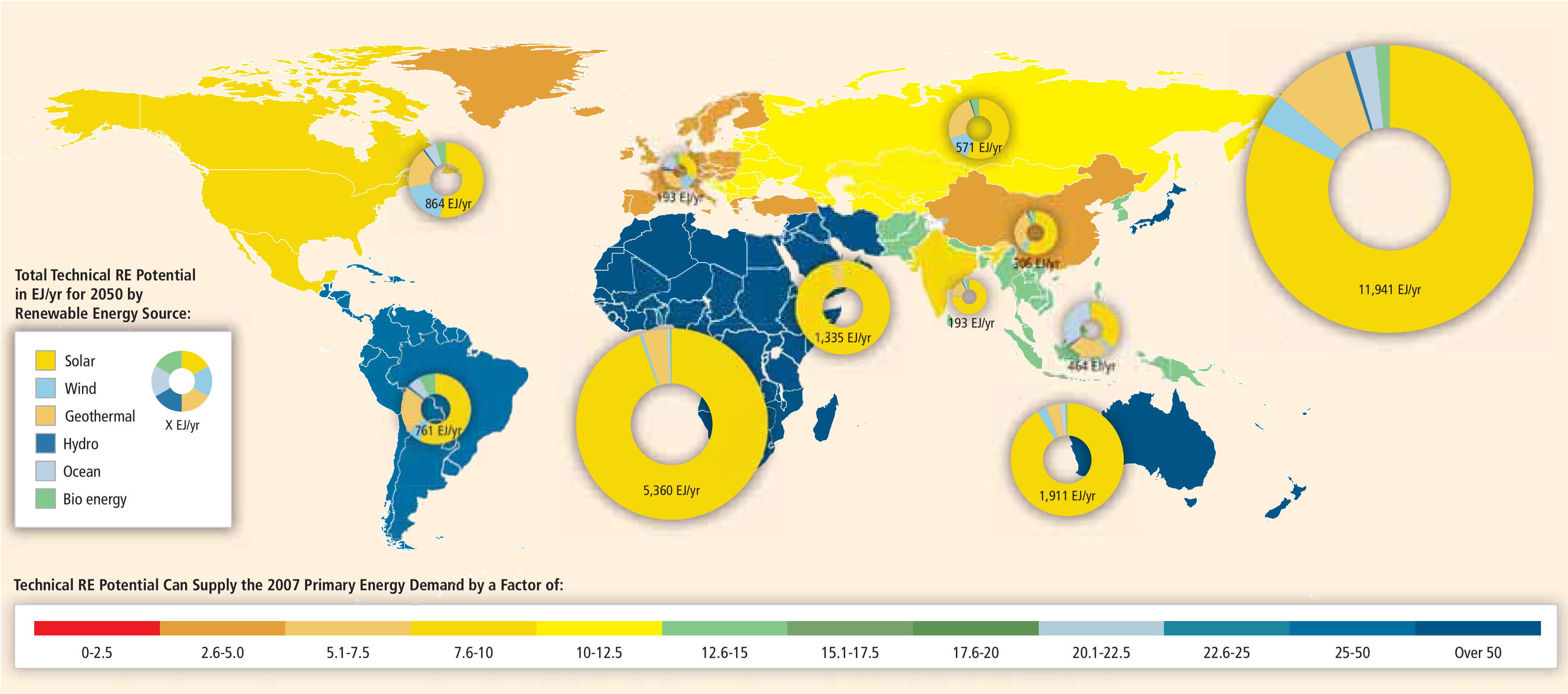


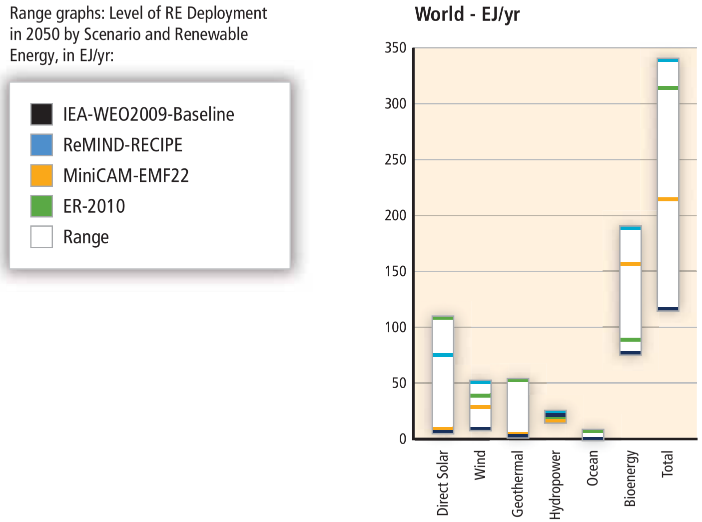
Figure TS.10.8 | Global RE development projections by source and global primary RE shares by source for a set of four illustrative scenarios. [Figure 10.14]



RE potential analysis: Technical RE potentials reported here represent total worldwide and regional potentials based on a review of studies published before 2009 by Krewitt et al. (2009). They do not deduct any potential that is already being utilized for energy production. Due to methodological differences and accounting methods among studies, strict comparability of these estimates across technologies and regions, as well as to primary energy demand, is not possible. Technical RE potential analyses published after 2009 show higher results in some cases but are not included in this figure. However, some RE technologies may compete for land which could lower the overall RE potential.

Scenario data: IEA WEO 2009 Reference Scenario (International Energy Agency (IEA), 2009; Teske et al., 2010), ReMIND-RECIPE 450ppm Stabilization Scenario (Luderer et al., 2009), MiniCAM EMF22 1st-best 2.6 W/2 Overshoot Scenario (Calvin et al., 2009), Advanced Energy
[R]evolution 2010 (Teske et al., 2010)

Range graphs: Level of RE Deployment in 2050 by Scenario and Renewable Energy, in EJ/yr:



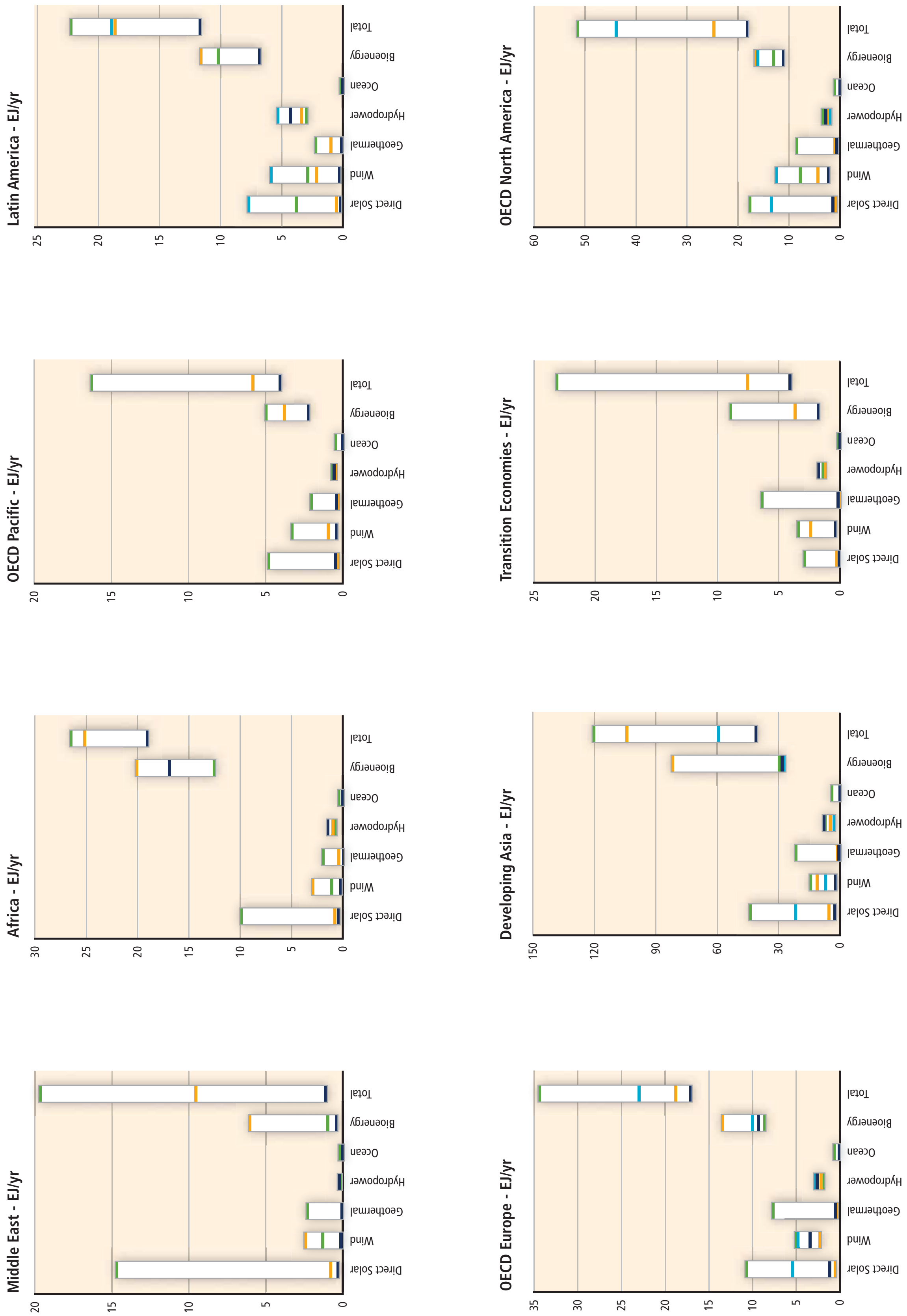

Latin America - EJ/yr
OECD North America - EJ/yr
OECD Pacific - EJ/yr
Transition Economies - EJ/yr
Africa - EJ/yr
Developing Asia - EJ/yr
Middle East - EJ/yr
OECD Europe - EJ/yr
Direct Solar
Wind
Geothermal
Hydropower
Ocean
Bioenergy
Total

Figure TS.10.9 | (Preceding pages) Regional breakdown of RE deployment in 2050 for an illustrative set of four scenarios and comparison of the potential deployment to the corresponding technical potential for different technologies. The selected four illustrative scenarios are a part of the comprehensive survey of 164 scenarios. They represent a span from a reference scenario (IEA WEO 2009) without specific GHG concentration stabilization levels to three scenarios representing different CO_2 concentration categories, one of them (REMind-RECIPE) Category III (440 to 485 ppm) and two of them (MiniCam EMF 22 and ER 2010 Category I (<400 ppm). Of the latter, MiniCam EMF 22 includes nuclear energy and CCS as mitigation options and allows overshoot to get to the concentration level, while ER 2010 follows an optimistic application path for RE. Transition economies are countries that changed from a former centrally planned economy to a free market system. [Figure 10.19]

TS 10.11, TS.10.12 and TS.10.13; instead site, project and/or investor-specific conditions should be taken into account. The technology chapters [2.7, 3.8, 4.7, 5.8, 6.7, 7.8] provide useful sensitivities in this respect. [10.5.1]

The cost ranges provided here do not reflect costs of integration (Chapter 8), external costs or benefits (Chapter 9) or costs of policies (Chapter 11). Given suitable conditions, the lower ends of the ranges indicate that some RE technologies already can compete with traditional forms at current energy market prices in many regions of the world. [10.5.1]

The supply cost curves presented [10.4.4, Figures 10.23, 10.25, 10.26, and 10.27] provide additional information about the available resource base (given as a function of the LCOE associated with harvesting it). The supply cost curves discussed [10.3.2.1, Figures 10.15–10.17], in contrast, illustrate the amount of RE that is harnessed (once again as a function of the associated LCOE) in different regions once specific trajectories for the expansion of RE are followed. In addition, it must be emphasized that most of the supply cost curves refer to future points in time (e.g., 2030 or 2050), whereas the LCOE given in the cost sections of the technology chapters as well as those shown in Figures TS.10.11, TS.10.12, and TS.10.13 (and in Annex III) refer to current costs. [10.5.1]

Significant advances in RE technologies and associated cost reductions have been demonstrated over the last decades, though the contribution and mutual interaction of different drivers (e.g., learning by searching, learning by doing, learning by using, learning by interacting, upsizing of technologies, and economies of scale) is not always understood in detail. [2.7, 3.8, 7.8, 10.5.2]

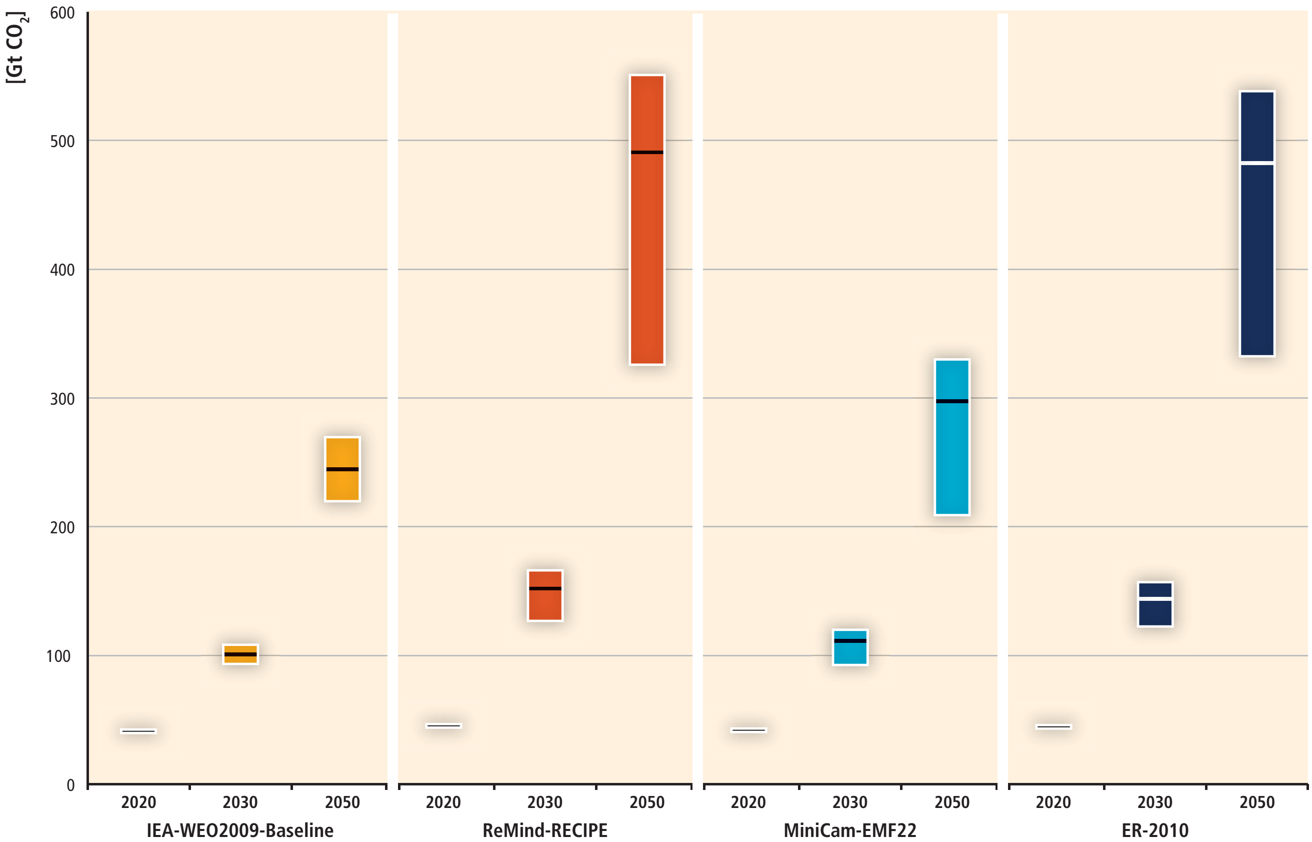


Figure TS.10.10 | Global cumulative CO_2 savings between 2010 and 2050 for four illustrative scenarios. The presented ranges mark the high uncertainties regarding the substituted conventional energy source. While the upper limit assumes a full substitution of high-carbon fossil fuels, the lower limit considers specific CO_2 emissions of the analyzed scenario itself. The line in the middle was calculated assuming that RE displaces the specific energy mix of a reference scenario. [Figure 10.22]

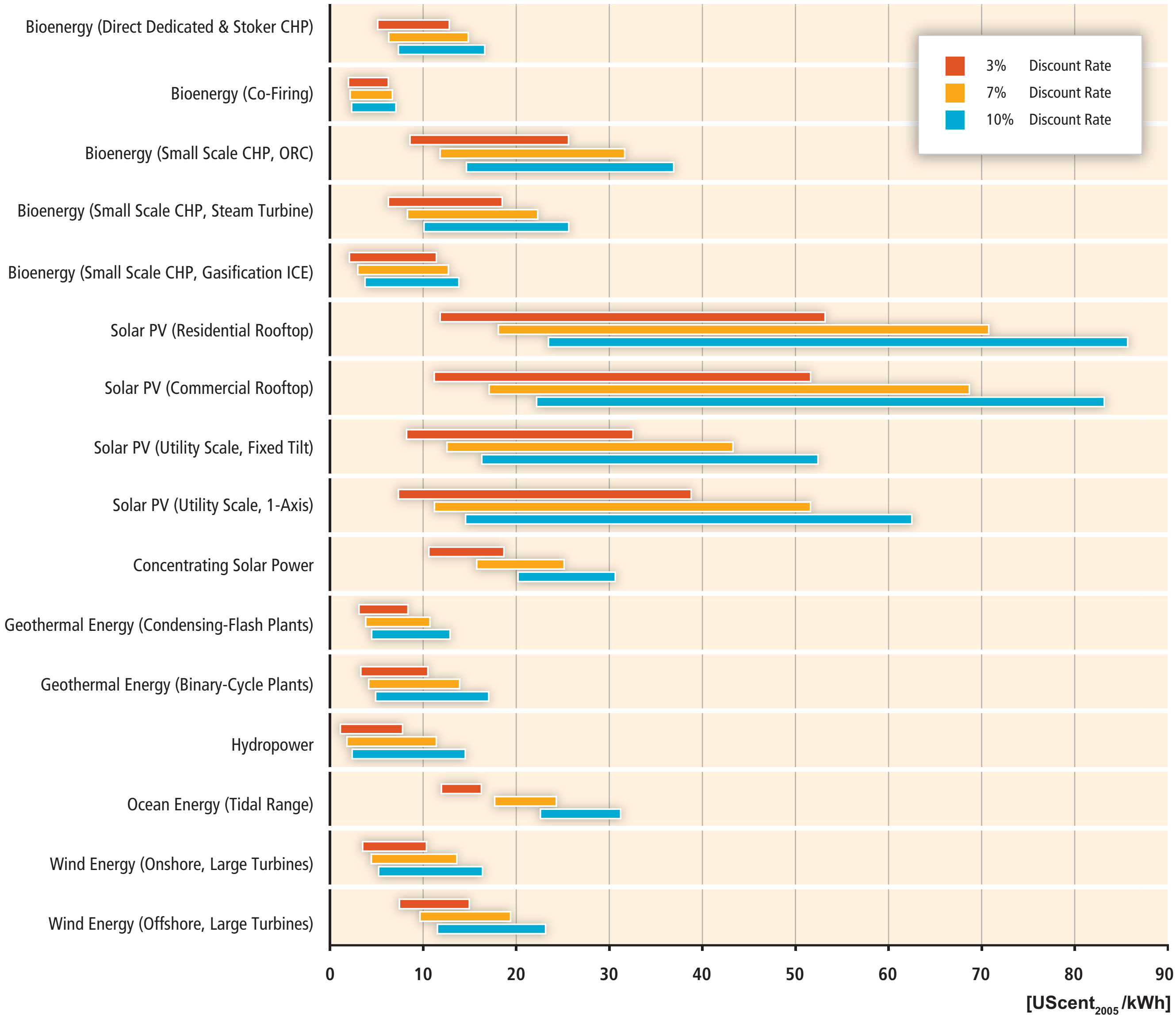


Figure TS.10.11 | Levelized cost of electricity for commercially available RE technologies at 3, 7 and 10% discount rates. The levelized cost of electricity estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on the low ends of the ranges of investment, operations and maintenance (O&M), and (if applicable) feedstock cost and the high ends of the ranges of capacity factors and lifetimes as well as (if applicable) the high ends of the ranges of conversion efficiencies and by-product revenue. The higher bound of the levelized cost range is accordingly based on the high end of the ranges of investment, O&M and (if applicable) feedstock costs and the low end of the ranges of capacity factors and lifetimes as well as (if applicable) the low ends of the ranges of conversion efficiencies and by-product revenue. Note that conversion efficiencies, by-product revenue and lifetimes were in some cases set to standard or average values. For data and supplementary information see Annex III. (CHP: combined heat and power; ORC: organic Rankine cycle, ICE: internal combustion engine.) [Figure 10.29]

From an empirical point of view, the resulting cost decrease can be described by experience (or 'learning') curves. For a doubling of the (cumulative) installed capacity, many technologies showed a more or less constant percentage decrease in the specific investment costs (or in the levelized costs or unit price, depending on the selected cost indicator). The numerical value describing this improvement is called the learning rate (LR). A summary of observed learning rates is provided in Table TS.10.1. [10.5.2]

Any efforts to assess future costs by extrapolating historic experience curves must take into account the uncertainty of learning rates as well as caveats and knowledge gaps discussed. [10.5.6, 7.8.4.1] As a supplementary approach, expert elicitations could be used to gather additional information about future cost reduction potentials, which might be contrasted with the assessments gained by using learning rates. Furthermore, engineering model analyses to identify technology improvement potentials could also provide additional information for developing cost projections. [2.6, 3.7, 4.6, 6.6, 7.7, 10.5.2]

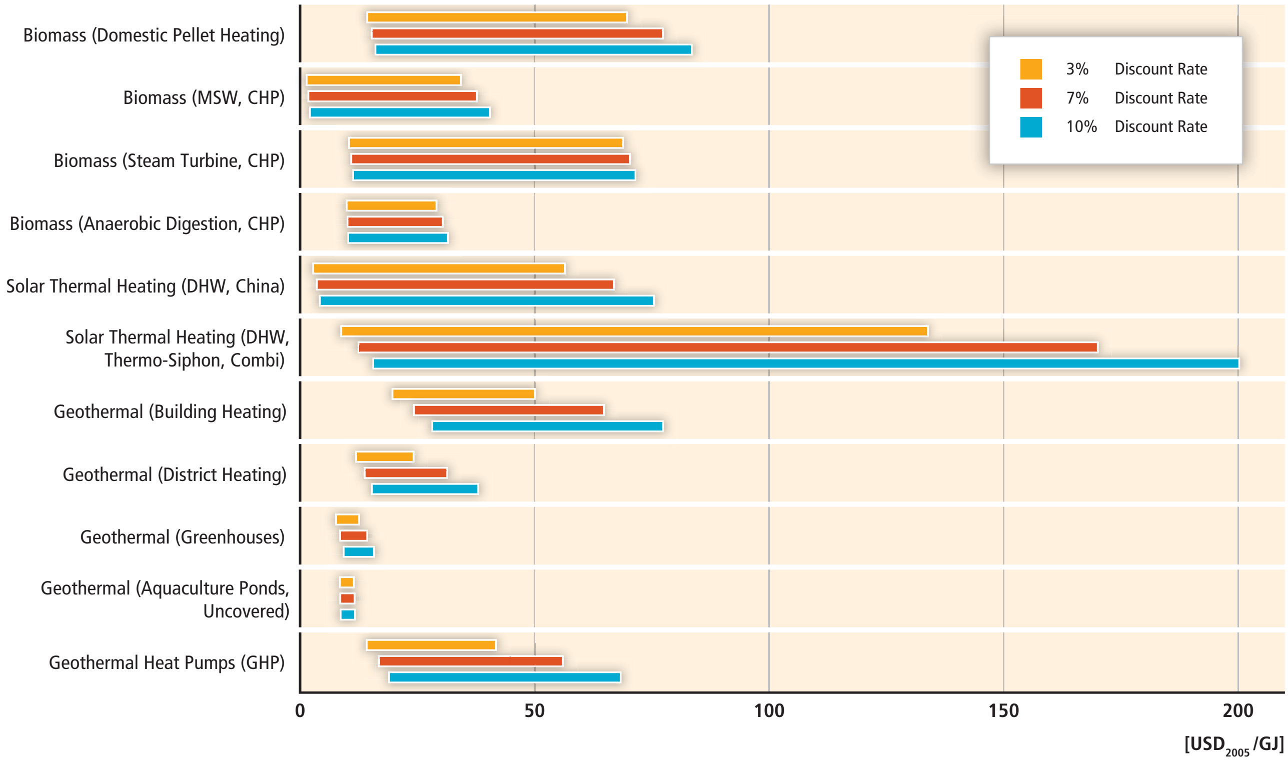


Figure TS.10.12 | Levelized cost of heat (LCOH) for commercially available RE technologies at 3, 7 and 10% discount rates. The LCOH estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on the low ends of the ranges of investment, operations and maintenance (O&M), and (if applicable) feedstock cost and the high ends of the ranges of capacity factors and lifetimes as well as (if applicable) the high ends of the ranges of conversion efficiencies and by-product revenue. The higher bound of the levelized cost range is accordingly based on the high end of the ranges of investment, O&M and (if applicable) feedstock costs and the low end of the ranges of capacity factors and lifetimes as well as (if applicable) the low ends of the ranges of conversion efficiencies and by-product revenue. Note that capacity factors and lifetimes were in some cases set to standard or average values. For data and supplementary information see Annex III. (MSW: municipal solid waste; DHW: domestic hot water.) [Figure 10.30]

Important potential technological advances and associated cost reductions, for instance, are expected in (but are not limited to) the following application fields: next-generation biofuels and biorefineries; advanced PV and CSP technologies and manufacturing processes; enhanced geothermal systems; multiple emerging ocean technologies; and foundation and turbine designs for offshore wind energy. Further cost reductions for hydropower are likely to be less significant than some of the other RE technologies, but R&D opportunities exist to make hydropower projects technically feasible in a wider range of natural conditions and to improve the technical performance of new and existing projects. [2.6, 3.7, 4.6, 5.3, 5.7, 5.8, 6.6, 7.7]

An answer to the question whether or not upfront investments in a specific innovative technology are justified cannot be given as long as the technology is treated in isolation. In a first attempt to clarify this issue and, especially, to investigate the mutual competition of prospective climate protection technologies, integrated assessment modellers have started to model technological learning in an endogenous way. The results obtained from these modelling comparison exercises indicate that—in the context of stringent climate goals—upfront investments in learning technologies can be justified in many cases. [10.5.3.]

However, as the different scenarios considered in Figure TS.10.14 and other studies clearly show, considerable uncertainty surrounds the exact volume and timing of these investments. [10.5.4]

The four illustrative scenarios that were analyzed in detail in Section 10.3 span a range of cumulative global decadal investments (in the power generation sector) ranging from USD_{2005} 1,360 to 5,100 billion (for the decade 2011 to 2020) and from USD_{2005} 1,490 to 7,180 billion (for the decade 2021 to 2030). These numbers allow the assessment of future market volumes and resulting investment opportunities. The lower values refer to the IEA World Energy Outlook 2009 Reference Scenario and the higher ones to a scenario that seeks to stabilize atmospheric CO_2 (only) concentration at 450 ppm. The average annual investments in the reference scenario are slightly lower than the respective investments reported for 2009. Between 2011and 2020, the higher values of the annual averages of the RE power generation sector investment approximately correspond to a three-fold increase in the current global investments in this field. For the next decade (2021 to 2030), a five-fold increase is projected. Even the upper level of the annual investments is smaller than 1% of the world's GDP. Additionally, increasing the installed capacity of

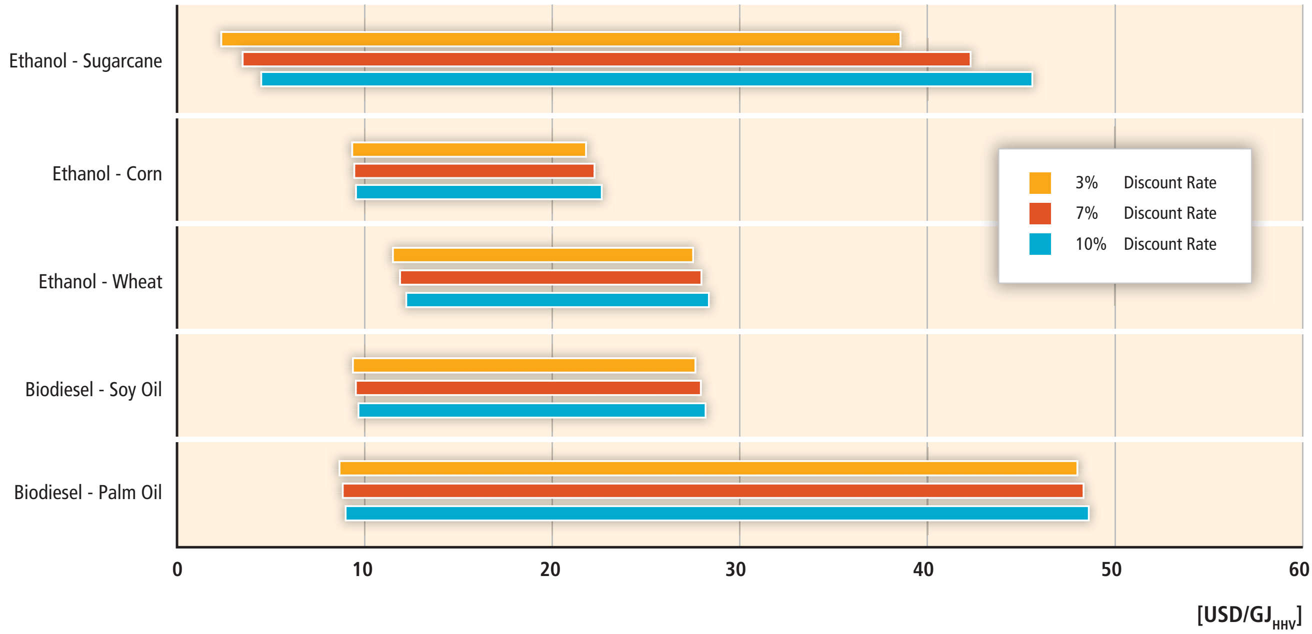


Figure TS.10.13 | Levelized cost of fuels (LCOF) for commercially available biomass conversion technologies at 3, 7 and 10% discount rates. LCOF estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on the low ends of the ranges of investment, O&M and feedstock cost. The higher bound of the levelized cost range is accordingly based on the high end of the ranges of investment, O&M and feedstock costs. Note that conversion efficiencies, by-product revenue, capacity factors and lifetimes were set to average values. For data and supplementary information see Annex III. (HHV: higher heating value.) [Figure 10.31]

RE power plants will reduce the amount of fossil and nuclear fuels that otherwise would be needed in order to meet a given electricity demand. [10.5.4]

10.6 Social and environmental costs and benefits

Energy extraction, conversion and use cause significant environmental impacts and external costs. Although replacing fossil fuel-based energy with RE often can reduce GHG emissions and also to some extent other environmental impacts and external costs, RE technologies can also have environmental impacts and external costs themselves, depending on the energy source and technology. These impacts and costs should be considered if a comprehensive cost assessment is required. [10.6.2]

Figure TS.10.15 shows the large uncertainty ranges of two dominant external cost components, namely climate- and health-related external costs. Small-scale biomass fired CHP plants cause relatively high external costs due to health effects via particulate emissions. Offshore wind energy seems to cause the smallest external cost. External cost estimates for nuclear power are not reported here because the character and assessment of external costs and risk from release of radionuclides due to low-probability accidents or due to leakages from waste repositories in a distant future are very different, for example, from climate change and air pollution, which are practically unavoidable. Those external impacts related to nuclear power can be, however, considered by discussion and judgment in the society. Accident risks in terms of fatalities due to various energy production chains (e.g., coal, oil, gas and hydro) are generally higher in non-OECD countries than in OECD countries. [10.6.3, 9.3.4.7]

As only external costs of individual technologies are shown in Figure TS.10.15, benefits can be derived when assuming that one technology replaces another one. RE sources and the technologies using them for electricity generation have mostly lower external costs per produced electricity than fossil fuel-based technologies. However, case-specific considerations are needed as there can also be exceptions. [10.6.3]

There are, however, considerable uncertainties in the assessment and valuation of external impacts of energy sources. The assessment of physical, biological and health damages includes considerable uncertainty and the estimates are based typically on calculational models, the results of which are often difficult to validate. The damages or changes seldom have market values that could be used in cost estimation, thus indirect information or other approaches must be used for damage valuation. Further, many of the damages will take place far in the future or in societies very different from those benefiting from the use of the considered energy production, which complicates the

Table TS.10.1 | Observed learning rates for various energy supply technologies. Note that values cited by older publications are less reliable as these refer to shorter time periods. [Table 10.10]

Technology	Source	Country / region	Period	Learning rate (%)	Performance measure
Onshore wind					
	Neij, 1997	Denmark	1982-1995	4	Price of wind turbine (USD/kW)
	Mackay and Probert, 1998	USA	1981-1996	14	Price of wind turbine (USD/kW)
	Neij, 1999	Denmark	1982-1997	8	Price of wind turbine (USD/kW)
	Durstewitz, 1999	Germany	1990-1998	8	Price of wind turbine (USD/kW)
	IEA, 2000	USA	1985-1994	32	Electricity production cost (USD/kWh)
	IEA, 2000	EU	1980-1995	18	Electricity production cost (USD/kWh)
	Kouvaritakis et al., 2000	OECD	1981-1995	17	Price of wind turbine (USD/kW)
	Neij, 2003	Denmark	1982-1997	8	Price of wind turbine (USD/kW)
	Junginger et al., 2005a	Spain	1990-2001	15	Turnkey investment costs (EUR/kW)
	Junginger et al., 2005a	UK	1992-2001	19	Turnkey investment costs (EUR/kW)
	Söderholm and Sundqvist, 2007	Germany, UK, Denmark	1986-2000	5	Turnkey investment costs (EUR/kW)
	Neij, 2008	Denmark	1981-2000	17	Electricity production cost (USD/kWh)
	Kahouli-Brahmi, 2009	Global	1979-1997	17	Investment costs (USD/kW)
	Nemet, 2009	Global	1981-2004	11	Investment costs (USD/kW)
	Wiser and Bolinger, 2010	Global	1982-2009	9	Investment costs (USD/kW)
Offshore wind					
	Isles, 2006	8 EU countries	1991-2006	3	Investment cost of wind farms (USD/kW)
Photovoltaics (PV)					
	Harmon, 2000	Global	1968-1998	20	Price PV module (USD/Wpeak)
	IEA, 2000	EU	1976-1996	21	Price PV module (USD/Wpeak)
	Williams, 2002	Global	1976-2002	20	Price PV module (USD/Wpeak)
	ECN, 2004	EU	1976-2001	20-23	Price PV module (USD/Wpeak)
	ECN, 2004	Germany	1992-2001	22	Price of balance of system costs
	van Sark et al., 2007	Global	1976-2006	21	Price PV module (USD/Wpeak)
	Kruck and Eltrop, 2007	Germany	1977-2005	13	Price PV module (EUR/Wpeak)
	Kruck and Eltrop, 2007	Germany	1999-2005	26	Price of balance of system costs
	Nemet, 2009	Global	1976-2006	15-21	Price PV module (USD/Wpeak)
Concentrating Solar Power (CSP)					
	Enermodal, 1999	USA	1984-1998	8-15	Plant investment cost (USD/kW)
Biomass					
	IEA, 2000	EU	1980-1995	15	Electricity production cost (USD/kWh)
	Goldemberg et al., 2004	Brazil	1985-2002	29	Prices for ethanol fuel (USD/m^3)
	Junginger et al., 2005b	Sweden, Finland	1975-2003	15	Forest wood chip prices (EUR/GJ)
	Junginger et al., 2006	Denmark	1984-1991	15	Biogas production costs (EUR/Nm^3)
	Junginger et al., 2006	Sweden	1990-2002	8-9	Biomass CHP power (EUR/kWh)
	Junginger et al., 2006	Denmark	1984-2001	0-15	Biogas production costs (EUR/Nm^3)
	Junginger et al., 2006	Denmark	1984-1998	12	Biogas plants (€/m^3 biogas/day)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	19	Ethanol from sugarcane (USD/m^3)
	Goldemberg et al., 2004	Brazil	1980-1985	7	Ethanol from sugarcane (USD/m^3)
	Goldemberg et al., 2004	Brazil	1985-2002	29	Ethanol from sugarcane (USD/m^3)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	20	Ethanol from sugarcane (USD/m^3)
	Hettinga et al., 2009	USA	1983-2005	18	Ethanol from corn (USD/m^3)
	Hettinga et al., 2009	USA	1975-2005	45	Corn production costs (USD/t corn)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	32	Sugarcane production costs (USD/t)

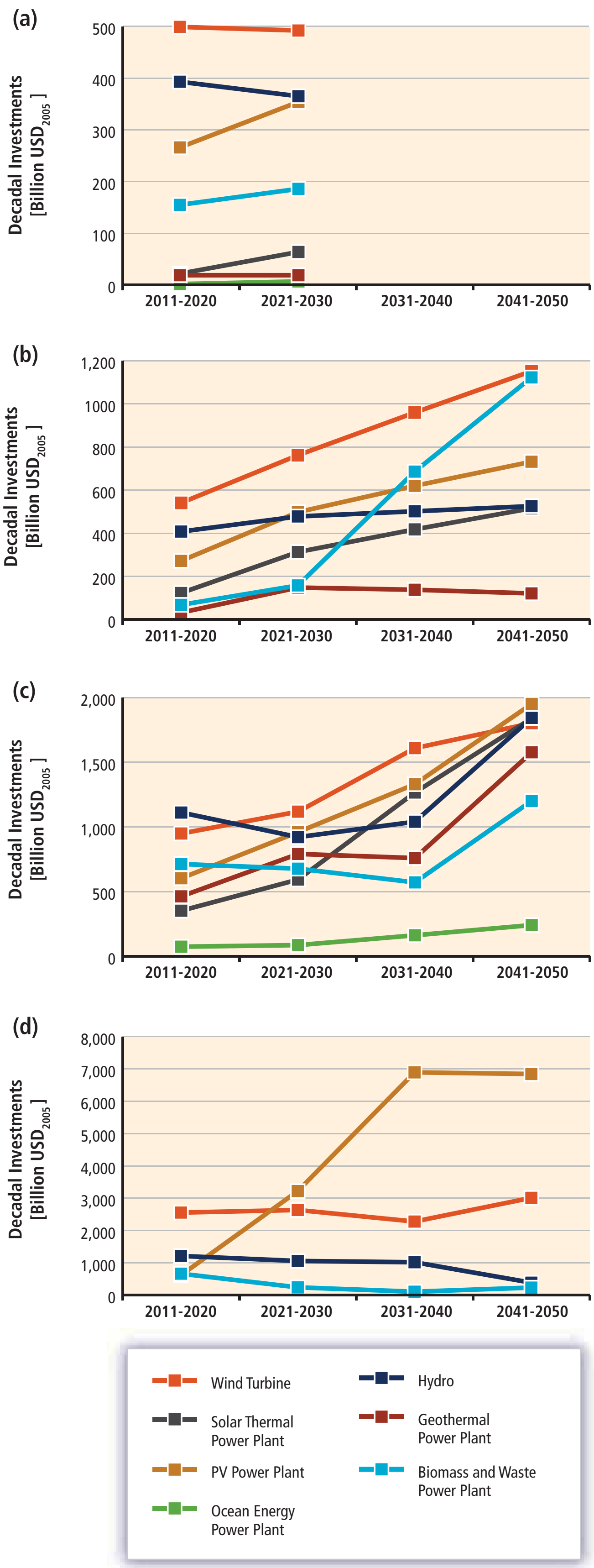


Figure TS.10.14 | Illustrative global *decadal* investments (in billion USD_{2005}) needed in order to achieve ambitious climate protection goals: (b) MiniCAM-EMF22 (first-best 2.6 W/m² overshoot scenario, nuclear and carbon capture technologies are permitted); (c) ER-2010 (450 ppm CO_2eq, nuclear and carbon capture technologies are not permitted); and (d) ReMIND-RECIPE (450 ppm CO_2, nuclear power plants and carbon capture technologies are permitted). Compared to the other scenarios, the PV share is high in (d) as concentrating solar power has not been considered. For comparison, (a) shows the IEA-WEO2009-Baseline (baseline scenario without climate protection). Sources: (a) IEA (2009); (b) Calvin et al. (2009); (c) Teske et al. (2010); and (d) Luderer et al. (2009).

considerations. These factors contribute to the uncertainty of external costs. [10.6.5]

However, the knowledge about external costs and benefits due to RE sources can provide some guidance for society to select best alternatives and to steer the energy system towards overall efficiency and high welfare gains. [10.6.5]

11. Policy, Financing and Implementation

11.1 Introduction

RE capacity is increasing rapidly around the world, but a number of barriers continue to hold back further advances. Therefore, if RE is to contribute substantially to the mitigation of climate change, and to do so quickly, various forms of economic support policies as well as policies to create an enabling environment are likely to be required. [11.1]

RE policies have promoted an increase in RE shares by helping to overcome various barriers that impede technology development and deployment of RE. RE policies might be enacted at all levels of government—from local to state/provincial to national to international—and range from basic R&D for technology development through to support for installed RE systems or the electricity, heat or fuels they produce. In some countries, regulatory agencies and public utilities may be given responsibility for, or on their own initiative, design and implement support mechanisms for RE. Nongovernmental actors, such as international agencies and development banks, also have important roles to play. [1.4, 11.1, 11.4, 11.5]

RE may be measured by additional qualifiers such as time and reliability of delivery (availability) and other metrics related to RE's integration into networks. There is also much that governments and other actors can do to create an environment conducive for RE deployment. [11.1, 11.6]

11.1.1 The rationale of renewable energy-specific policies in addition to climate change policies

Renewable energies can provide a host of benefits to society. Some RE technologies are broadly competitive with current market energy prices.

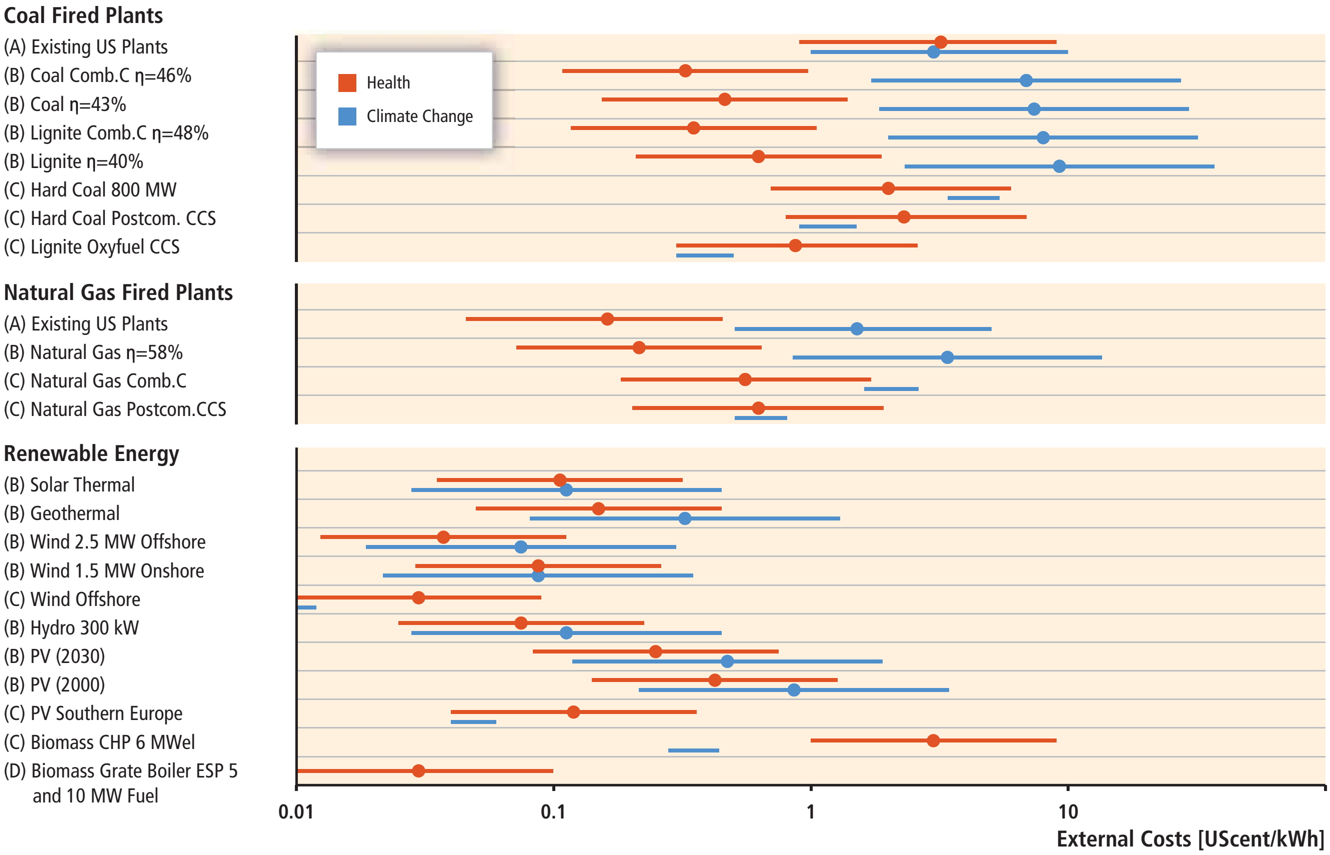


Figure TS.10.15 | Illustration of external costs due to the lifecycle of electricity production based on RE and fossil energy. Note the logarithmic scale of the figure. The black lines indicate the range of the external cost due to climate change and the red lines indicate the range of the external costs due to air pollutant health effects. External costs due to climate change mainly dominate in fossil energy if not equipped with CCS. Comb.C: Combined Cycle; Postcom: Post-Combustion; η: efficiency factor. The results are based on four studies having different assumptions (A–D). The uncertainty for the external costs of health impacts is assumed to be a factor of three. [Figure 10.36]

Of the other RE technologies that are not yet broadly competitive, many can provide competitive energy services in certain circumstances. In most regions of the world, however, policy measures are still required to facilitate an increasing deployment of RE. [11.1, 10.5]

Climate policies (carbon taxes, emissions trading or regulatory policies) decrease the relative costs of low-carbon technologies compared to carbon-intensive technologies. It is questionable, however, whether climate policies (e.g., carbon pricing) alone are capable of promoting RE at sufficient levels to meet the broader environmental, economic and social objectives related to RE. [11.1.1]

Two separate market failures create the rationale for the additional support of innovative RE technologies that have high potential for technological development, even if an emission market (or GHG pricing policy in general) exists. The first market failure refers to the external cost of GHG emissions. The second market failure is in the field of innovation: if firms underestimate the future benefits of investments into learning RE technologies or if they cannot appropriate these benefits, they will invest less than is optimal from a macroeconomic perspective. In addition to GHG pricing policies, RE-specific policies may be appropriate from an economic point of view if the related opportunities for technological development are to be addressed (or if the goals beyond climate change mitigation are pursued). Potentially adverse consequences such as lock-in, carbon leakage and rebound effects should be taken into account in the design of a portfolio of policies. [11.1.1, 11.5.7.3]

11.1.2 Policy timing and strength

The timing, strength and level of coordination of R&D versus deployment policies have implications for the efficiency and effectiveness of the policies, and for the total cost to society in three main ways: 1) whether a country promotes RE immediately or waits until costs have declined further; 2) once a country has decided to support RE, the timing, strength and coordination of when R&D policies give way to deployment policies; and 3) the cost and benefit of accelerated versus slower 'market demand' policy implementation. With regard to the first, in order to achieve full competitiveness with fossil fuel technologies, significant upfront investments in RE will be required until the break-even point is achieved. When those investments should be made depends on the goal. If the international community aims to stabilize global temperature increases at 2°C, then investments in low-carbon technologies must start almost immediately.

11.2 Current trends: Policies, financing and investment

An increasing number and variety of RE policies have driven substantial growth in RE technologies in recent years. Until the early 1990s, few countries had enacted policies to promote RE. Since then, and particularly since the early- to mid-2000s, policies have begun to emerge in a growing number of countries at the municipal, state/provincial and national levels, as well as internationally (see Figure TS.11.1). [1.4, 11.1, 11.2.1, 11.4, 11.5]

Initially, most policies adopted were in developed countries, but an increasing number of developing countries have enacted policy frameworks at various levels of government to promote RE since the late 1990s and early 2000s. Of those countries with RE electricity policies by early 2010, approximately half were developing countries from every region of the world. [11.2.1]

Most countries with RE policies have more than one type of mechanism in place, and many existing policies and targets have been strengthened over time. Beyond national policies, the number of international policies and partnerships is increasing. Several hundred city and local governments around the world have also established goals or enacted renewable promotion policies and other mechanisms to spur local RE deployment. [11.2.1]

The focus of RE policies is shifting from a concentration almost entirely on electricity to include the heating/cooling and transportation sectors. These trends are matched by increasing success in the development of a range of RE technologies and their manufacture and implementation (see Chapters 2 through 7), as well as by a rapid increase in annual investment in RE and a diversification of financing institutions, particularly since 2004/2005. [11.2.2]

In response to the increasingly supportive policy environment, the overall RE sector globally has seen a significant rise in the level of investment since 2004-2005. Financing occurs over what is known as the 'continuum' or stages of technology development. The five segments of the continuum are: 1) R&D; 2) technology development and commercialization; 3) equipment manufacture and sales; 4) project construction; and 5) the refinancing and sale of companies, largely through mergers and acquisitions. Financing has been increasing over time in each of these stages, providing indications of the RE sector's current and expected growth, as follows: [11.2.2]

- Trends in (1) R&D funding and (2) technology investment are indicators of the long- to mid-term expectations for the sector—investments are being made that will begin to pay off in several years' time, once the technology is fully commercialized. [11.2.2.2, 11.2.2.3]
- Trends in (3) manufacturing and sales investment are an indicator of near-term expectations for the sector—essentially, that the growth in market demand will continue. [11.2.2.4]
- Trends in (4) construction investment are an indicator of current sector activity, including the extent to which internalizing costs associated with GHGs can result in new financial flows to RE projects. [11.2.2.5]
- Trends in (5) industry mergers and acquisitions can reflect the overall maturity of the sector, and increasing refinancing activity over time indicates that larger, more conventional investors are entering the sector, buying up successful early investments from first movers. [11.2.2.6]

11.3 Key drivers, opportunities and benefits

Renewable energy can provide a host of benefits to society. In addition to the reduction of CO_2 emissions, governments have enacted RE policies to meet any number of objectives, including the creation of local environmental and health benefits; facilitation of energy access, particularly for rural areas; advancement of energy security goals by diversifying the portfolio of energy technologies and resources; and improving social and economic development through potential employment opportunities and economic growth. [11.3.1–11.3.4]

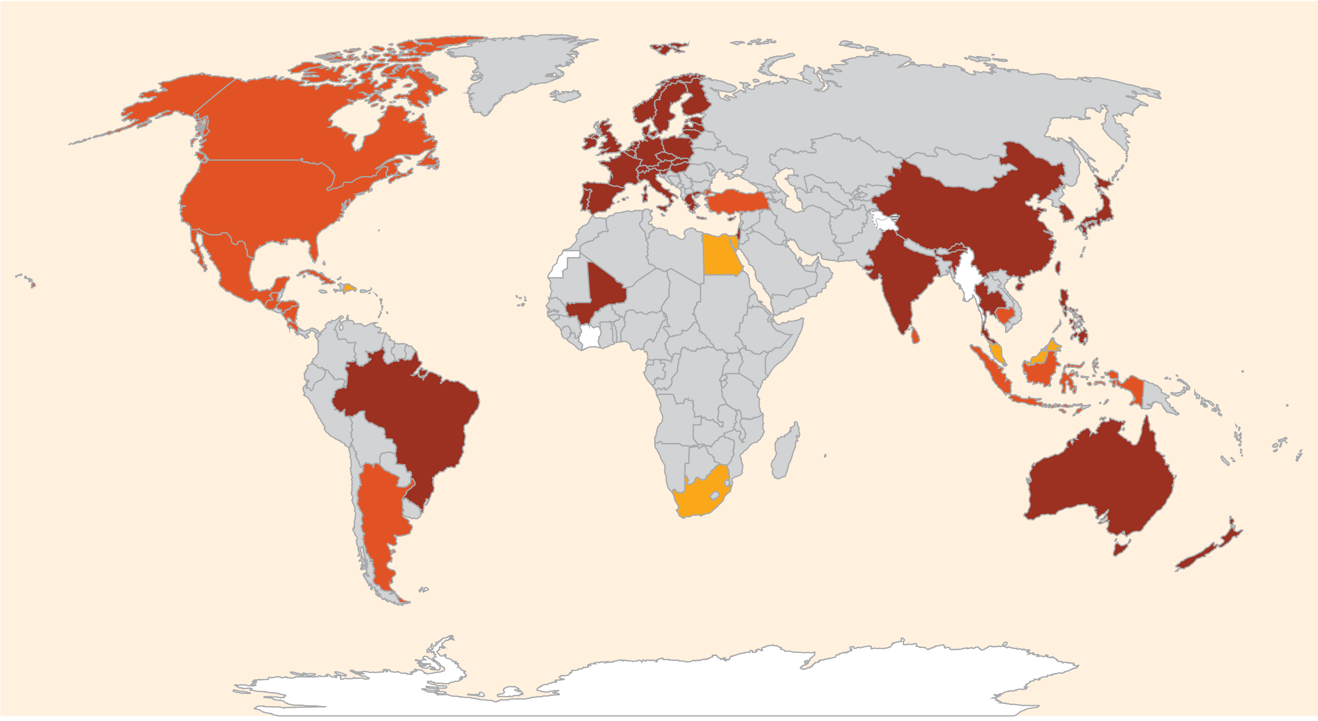
The relative importance of the drivers for RE differ from country to country, and may vary over time. Energy access has been described as the primary driver in developing countries whereas energy security and environmental concerns have been most important in developed countries. [11.3]

11.4 Barriers to renewable energy policymaking, implementation and financing

RE policies have promoted an increase in RE shares by helping to overcome various barriers that impede technology development and deployment of RE. Barriers specific to RE policymaking, to implementation and to financing (e.g., market failures) may further impede deployment of RE. [1.4, 11.4]

Barriers to making and enacting policy include a lack of information and awareness about RE resources, technologies and policy options; lack of understanding about best policy design or how to undertake energy transitions; difficulties associated with quantifying and internalizing external costs and benefits; and lock-in to existing technologies and policies. [11.4.1]

2005



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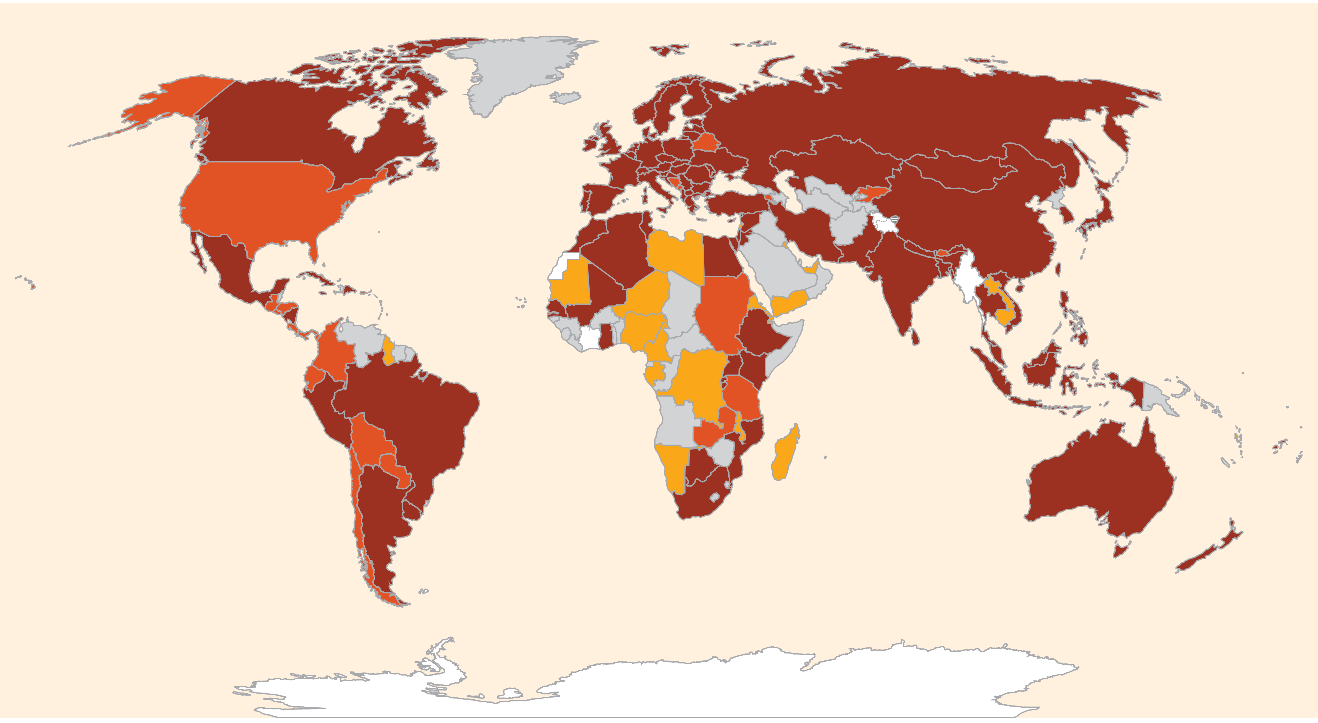

Countries with at least one RE-specific Policy and at least one RE Target	Countries with at least one RE Target
Countries with at least one RE-specific Policy	Countries with neither RE-specific Policies nor RE Targets

Figure TS.11.1 | Countries with at least one RE target and/or at least one RE-specific policy, in mid-2005 and in early 2011. This figure includes only national-level targets and policies (not municipal or state/provincial) and is not necessarily all-inclusive. [Figure 11.1]

Barriers related to policy implementation include conflicts with existing regulations; lack of skilled workers; and/or lack of institutional capacity to implement RE policies. [11.4.2]

Barriers to financing include a lack of awareness among financiers and lack of timely and appropriate information; issues related to financial structure and project scale; issues related to limited track records; and, in some countries, institutional weakness, including imperfect capital markets and insufficient access to affordable financing, all of which increase perceived risk and thus increase costs and/or make it more difficult to obtain RE project financing. Most importantly, many RE technologies are not economically competitive with current energy market prices, making them financially unprofitable for investors absent various forms of policy support, and thereby restricting investment capital. [11.4.3]

11.5 Experience with and assessment of policy options

Many policy options are available to support RE technologies, from their infant stages to demonstration and pre-commercialization, and through to maturity and wide-scale deployment. These include government R&D policies (supply-push) for advancing RE technologies, and deployment policies (demand-pull) that aim to create a market for RE technologies. Policies could be categorized in a variety of ways and no globally-agreed list of RE policy options or groupings exists. For the purpose of simplification, R&D and deployment policies have been organized within the following categories [11.5]:

- **Fiscal incentive:** actors (individuals, households, companies) are allowed a reduction of their contribution to the public treasury via income or other taxes or are provided payments from the public treasury in the form of rebates or grants.

- **Public finance:** public support for which a financial return is expected (loans, equity) or financial liability is incurred (guarantee); and

- **Regulation:** rule to guide or control conduct of those to whom it applies.

Although targets are a central component of policies, policies in place may not need specific targets to be successful. Further, targets without policies to deliver them are unlikely to be met. [11.5]

The success of policy instruments is determined by how well they are able to achieve various objectives or criteria, including:

- **Effectiveness:** extent to which intended objectives are met;

- **Efficiency:** ratio of outcomes to inputs, or RE targets realized for economic resources spent;

- **Equity:** the incidence and distributional consequences of a policy; and

- **Institutional feasibility:** the extent to which a policy instrument is likely to be viewed as legitimate, gain acceptance, and be adopted and implemented, including the ability to implement a policy once it has been designed and adopted. [11.5.1]

Most literature focuses on effectiveness and efficiency of policies. Elements of specific policy options make them more or less apt to achieve the various criteria, and how these policies are designed and implemented can also determine how well they meet these criteria. The selection of policies and details of their design ultimately will depend on the goals and priorities of policymakers. [11.5.1]

11.5.1 Research and development policies for renewable energy

R&D, innovation, diffusion and deployment of new low-carbon technologies create benefits to society beyond those captured by the innovator, resulting in under-investment in such efforts. Thus, government R&D can play an important role in advancing RE technologies. Not all countries can afford to support R&D with public funds, but in the majority of countries where some level of support is possible, public R&D for RE enhances the performance of nascent technologies so that they can meet the demands of initial adopters. Public R&D also improves existing technologies that already function in commercial environments. [11.5.2]

Government R&D policies include fiscal incentives, such as academic R&D funding, grants, prizes, tax credits, and use of public research centres; as well as public finance, such as soft or convertible loans, public equity stakes, and public venture capital funds. Investments falling under the rubric of R&D span a wide variety of activities along the technology development lifecycle, from RE resource mapping to improvements in commercial RE technologies. [11.5.2]

The success of R&D policies depends on a number of factors, some of which can be clearly determined, and others which are debated in the literature. Successful outcomes from R&D programmes are not solely related to the total amount of funding allocated, but are also related to the consistency of funding from year to year. On-off operations in R&D are detrimental to technical learning, and learning and cost reductions depend on continuity, commitment and organization of effort, and where and how funds are directed, as much as they rely on the scale of effort. In the literature, there is some debate as to the most successful approach to R&D policy in terms of timing: bricolage (progress via research aiming at incremental improvements) versus breakthrough (radical technological advances) with arguments favouring either option or a combination of both. Experience has shown that it is important that subsidies for R&D (and beyond) are designed to have an 'exit-strategy' whereby the subsidies are progressively phased out as the technology commercializes, leaving a functioning and sustainable sector in place. [11.5.2.3]

One of the most robust findings, from both the theoretical literature and technology case studies, is that R&D investments are most effective when complemented by other policy instruments—particularly, but not limited to, policies that simultaneously enhance demand for new RE technologies. Relatively early deployment policies in a technology's development accelerate learning, whether learning through R&D or learning through utilization (as a result of manufacture) and cost reduction. Together, R&D and deployment policies create a positive feedback cycle, inducing private sector investment in R&D (See Figure TS.11.2). [11.5.2.4]

11.5.2 Policies for deployment

Policy mechanisms enacted specifically to promote deployment of RE are varied and can apply to all energy sectors. They include fiscal incentives (grants, energy production payments, rebates, tax credits, reductions and exemptions, variable or accelerated depreciation); public finance (equity investment, guarantees, loans, public procurement); and regulations (quotas, tendering/bidding, FITs, green labelling and green energy purchasing, net metering, priority or guaranteed access, priority dispatch). While regulations and their impacts vary quite significantly from one end-use sector to another, fiscal incentives and public finance apply generally to all sectors. [11.5.3.1]

Fiscal incentives can reduce the costs and risks of investing in RE by lowering the upfront investment costs associated with installation, reducing the cost of production, or increasing the payment received for RE generated. Fiscal incentives also compensate for the various market failures that leave RE at a competitive disadvantage compared to fossil fuels and nuclear energy, and help to reduce the financial burden of investing in RE. [11.5.3.1]

Fiscal incentives tend to be most effective when combined with other types of policies. Incentives that subsidize production are generally preferable to investment subsidies because they promote the desired outcome—energy generation. However, policies must be tailored to particular technologies and stages of maturation, and investment subsidies can be helpful when a technology is still relatively expensive or when the technology is applied at a small scale (e.g., small

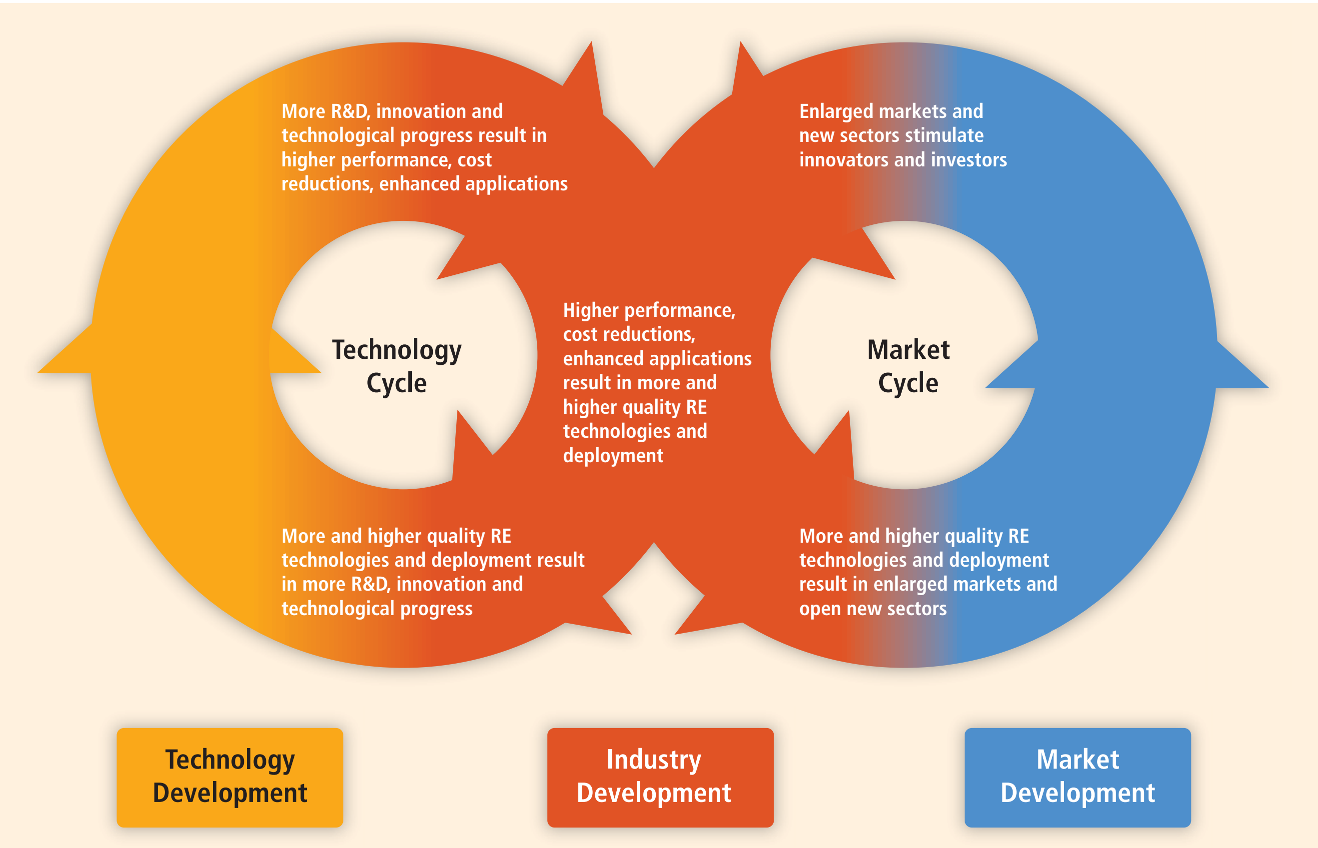

Figure TS.11.2 | The mutually-reinforcing cycles of technology development and market deployment drive down technology costs. [Figure 11.5] rooftop solar systems), particularly if they are paired with technology standards and certification to ensure minimum quality of systems and installation. Experience with wind energy policies suggests that production payments and rebates may be preferable to tax credits because the benefits of payments and rebates are equal for people of all income levels and thus promote broader investment and use. Also, because they are generally provided at or near the time of purchase or production, they result in more even growth over time (rather than the tendency to invest in most capacity toward the end of a tax period). Tax-based incentives have historically tended to be used to promote only the most mature and cheapest available technologies. Generally, tax credits work best in countries where there are numerous profitable, tax-paying private sector firms that are in a position to take advantage of them. [11.5.3.1]

Public finance mechanisms have a twofold objective: to directly mobilize or leverage commercial investment into RE projects, and to indirectly create scaled-up and commercially sustainable markets for these technologies. In addition to the more traditional public finance policies such as soft loans and guarantees, a number of innovative mechanisms are emerging at various levels of government, including the municipal level. These include financing of RE projects through long-term loans to property owners that allow repayment to be matched with energy savings (for example, Property Assessed Clean Energy in California), and the 'recycling' of government funds for multiple purposes (e.g., using public funds saved through energy efficiency improvements for RE projects). [11.5.3.2]

Public procurement of RE technologies and energy supplies is a frequently cited but not often utilized mechanism to stimulate the market for RE. Governments can support RE development by making commitments to purchase RE for their own facilities or encouraging clean energy options for consumers. The potential of this mechanism is significant: in many nations, governments are the largest consumer of energy, and their energy purchases represent the largest components of public expenditures. [11.5.3.2]

Regulatory policies include quantity- and price-driven policies such as quotas and FITs; quality aspects and incentives; and access instruments such as net metering. Quantity-driven policies set the quantity to be achieved and allow the market to determine the price, whereas price-driven policies set the price and allow the market to determine quantity. Quantity-driven policies can be used in all three end-use sectors in the form of obligations or mandates. Quality incentives include green energy purchasing and green labelling programmes (occasionally mandated by governments, but not always), which provide information to consumers about the quality of energy products to enable consumers to make voluntary decisions and drive demand for RE. [11.5.3.3]

Policies for deployment: Electricity
To date, far more policies have been enacted to promote RE for electricity generation than for heating and cooling or transport. These include fiscal incentives and public finance to promote investment in and generation of RE electricity, as well as a variety of electricity-specific regulatory policies. Although governments use a variety of policy types to promote RE electricity, the most common policies in use are FITs and quotas or Renewable Portfolio Standards (RPS). [11.5.4]

There is a wealth of literature assessing quantity-based (quotas, RPS; and tendering/bidding policies) and price-based (fixed-price and premium-price FITs) policies, primarily quotas and FITs, and with a focus on effectiveness and efficiency criteria. A number of historical studies, including those carried out for the European Commission, have concluded that 'well-designed' and 'well–implemented' FITs have to date been the most efficient (defined as comparison of total support received and generation cost) and effective (ability to deliver an increase in the share of RE electricity consumed) support policies for promoting RE electricity. [11.5.4]

One main reason for the success of well-implemented FITs is that they usually guarantee high investment security due to the combination of long-term fixed-price payments, network connection, and guaranteed grid access for all generation. Well-designed FITs have encouraged both technological and geographic diversity, and have been found to be more suitable for promoting projects of varying sizes. The success of FIT policies depends on the details. The most effective and efficient policies have included most or all of the following elements [11.5.4.3]:

- Utility purchase obligation;
- Priority access and dispatch;
- Tariffs based on cost of generation and differentiated by technology type and project size, with carefully calculated starting values;
- Regular long-term design evaluations and short-term payment level adjustments, with incremental adjustments built into law in order to reflect changes in technologies and the marketplace, to encourage innovation and technological change, and to control costs;
- Tariffs for all potential generators, including utilities;
- Tariffs guaranteed for a long enough time period to ensure an adequate rate of return;
- Integration of costs into the rate base and shared equally across country or region;
- Clear connection standards and procedures to allocate costs for transmission and distribution;
- Streamlined administrative and application processes; and
- Attention to preferred exempted groups, for example, major users on competitiveness grounds or low-income and other vulnerable customers.

Experiences in several countries demonstrate that the effectiveness of quota schemes can be high and compliance levels achieved if RE certificates are delivered under well-designed policies with long-term contracts that mute (if not eliminate) price volatility and reduce risk. However, they have been found to benefit the most mature, least-cost technologies. This effect can be addressed in the design of the policy if different RE options are distinguished or are paired with other incentives. The most effective and efficient quantity-based mechanisms have included most if not all of the following elements, particularly those that help to minimize risk [11.5.4.3]:

- Application to large segment of the market (quota only);
- Clearly defined eligibility rules including eligible resources and actors (applies to quotas and tendering/bidding);
- Well-balanced supply-demand conditions with a clear focus on new capacities—quotas should exceed existing supply but be achievable at reasonable cost (quota only);
- Long-term contracts/specific purchase obligations and end dates, and no time gaps between one quota and the next (quota only);
- Adequate penalties for non-compliance, and adequate enforcement (applies to quotas and tendering/bidding);
- Long-term targets, of at least 10 years (quota only);
- Technology-specific bands or carve-outs to provide differentiated support (applies to quotas and tendering/bidding); and
- Minimum payments to enable adequate return and financing (applies to quotas and tendering/bidding).

Net metering enables small producers to 'sell' into the grid, at the retail rate, any renewable electricity that they generate in excess of their total demand in real time as long as that excess generation is compensated for by excess customer load at other times during the designated netting period. It is considered a low-cost, easily administered tool for motivating customers to invest in small-scale, distributed power and to feed it into the grid, while also benefiting providers by improving load factors if RE electricity is produced during peak demand periods. On its own, however, it is generally insufficient to stimulate significant growth of less competitive technologies like PV at least where generation costs are higher than retail prices. [11.5.4]

Policies for deployment: Heating and cooling

An increasing number of governments are adopting incentives and mandates to advance RE heating and cooling (H/C) technologies. Support for RE H/C presents policymakers with a unique challenge due to the often distributed nature of heat generation. Heating and cooling services can be provided via small- to medium-scale installations that service a single dwelling, or can be used in large-scale applications to provide district heating and cooling. Policy instruments for both RE heating (RE-H) and cooling (RE-C) need to specifically address the more heterogeneous characteristics of resources, including their wide range in scale, varying ability to deliver different levels of temperature, widely distributed demand, relationship to heat load, variability of use, and the absence of a central delivery or trading mechanism. [11.5.5]

The number of policies to support RE sources of heating and cooling has increased in recent years, resulting in increasing generation of RE H/C. However, a majority of support mechanisms have been focused on RE-H. Policies in place to promote RE-H include fiscal incentives such as rebates and grants, tax reductions and tax credits; public finance policies like loans; regulations such as use obligations; and educational efforts. [11.5.5.1–11.5.5.3, 11.6]

To date, fiscal incentives have been the prevalent policy in use, with grants being the most commonly applied. Tax credits available after the installation of a RE-H system (i.e., ex-post) may be logistically advantageous over, for example, grants requiring pre-approval before installation, though there is limited experience with this option. Regulatory mechanisms like use obligations and quotas have attracted increased interest for their potential to encourage growth of RE-H independent of public budgets, though there has been little experience with these policies to date. [11.5.5]

Similar to RE electricity and RE transport, RE H/C policies will be better suited to particular circumstances/locations if, in their design, consideration is given to the state of maturity of the particular technology, of the existing markets and of the existing supply chains. Production incentives are considered be more effective for larger H/C systems, such as district heating grids, than they are for smaller, distributed onsite H/C generation installations for which there are few cost-effective metering or monitoring procedures. [11.5.5]

Though there are some examples of policies supporting RE-C technologies, in general policy aiming to drive deployment of RE-C solely is considerably less well-developed than that for RE-H. Many of the mechanisms described in the above paragraphs could also be applied to RE-C, generally with similar advantages and disadvantages. The lack of experience with deployment policies for RE-C is probably linked to the early levels of technological development of many RE-C technologies. R&D support as well as policy support to develop the early market and supply chains may be of particular importance for increasing the deployment of RE-C technologies in the near future. [11.5.5.4]

Policies for deployment: Transportation

A range of policies has been implemented to support the deployment of RE for transport, though the vast majority of these policies and related experiences have been specific to biofuels. Biofuel support policies aim to promote domestic consumption via fiscal incentives (e.g., tax exemptions for biofuel at the pump) or regulations (e.g., blending mandates), or to promote domestic production via public finance (e.g., loans) for production facilities, via feedstock support or tax incentives (e.g., excise tax exemptions). Most commonly, governments enact a combination of policies. [11.5.6]

Tax incentives are commonly used to support biofuels because they change their cost-competitiveness relative to fossil fuels. They can be installed along the whole biofuel value chain, but are most commonly provided to either biofuel producers (e.g., excise tax exemptions/credits) and/or to end consumers (e.g., tax reductions for biofuels at the pump). [11.5.6]

However, several European and other G8+5 countries have begun gradually shifting from the use of tax breaks for biofuels to blending mandates. It is difficult to assess the level of support under biofuel mandates because prices implied by these obligations are generally not public (in contrast to the electricity sector, for example). While mandates are key drivers in the development and growth of most modern biofuels industries, they are found to be less appropriate for the promotion of specific types of biofuel because fuel suppliers tend to blend low-cost biofuels. By nature, mandates need to be carefully designed and accompanied by further requirements in order to reach a broader level of distributional equity and to minimize potential negative social and environmental impacts. Those countries with the highest share of biofuels in transport fuel consumption have had hybrid systems that combine mandates (including penalties) with fiscal incentives (tax exemptions foremost). [11.5.6]

Synthesis

Some policy elements have been shown to be more effective and efficient in rapidly increasing RE deployment and enabling governments and society to achieve specific targets. The details of policy design and implementation can be as important in determining effectiveness and efficiency as the specific policies that are used. Key policy elements include [11.5.7]:

- Adequate value derived from subsidies, FITs, etc. to cover cost such that investors are able to recover their investment at a rate of return that matches their risk.
- Guaranteed access to networks and markets or at a minimum clearly defined exceptions to that guaranteed access.
- Long-term contracts to reduce risk thereby reducing financing costs.
- Provisions that account for diversity of technologies and applications. RE technologies are at varying levels of maturity and with different characteristics, often facing very different barriers. Multiple RE sources and technologies may be needed to mitigate climate change, and some that are currently less mature and/or more costly than others could play a significant role in the future in meeting energy needs and reducing GHG emissions.
- Incentives that decline predictably over time as technologies and/or markets advance.
- Policy that is transparent and easily accessible so that actors can understand the policy and how it works, as well as what is required to enter the market and/or to be in compliance. Also includes longer-term transparency of policy goals, such as medium- and long-term policy targets.
- Inclusive, meaning that the potential for participation is as broad as possible on both the supply side (traditional producers, distributors of technologies or energy supplies, whether electricity, heat or fuel), and the demand side (businesses, households, etc.), which can 'self-generate' with distributed RE, enabling broader participation that unleashes more capital for investment, helps to build broader public support for RE, and creates greater competition.
- Attention to preferred exempted groups, for example, major users on competitiveness grounds or low-income and vulnerable customers on equity and distributional grounds.

It is also important to recognize that there is no one-size-fits-all policy, and policymakers can benefit from the ability to learn from experience and adjust programmes as necessary. Policies need to respond to local political, economic, social, ecological, cultural and financial needs and conditions, as well as factors such as the level of technological maturity, availability of affordable capital, and the local and national RE resource base. In addition, a mix of policies is generally needed to address the various barriers to RE. Policy frameworks that are transparent and sustained—from predictability of a specific policy, to pricing of carbon and other externalities, to long-term targets for RE—have been found to be crucial for reducing investment risks and facilitating deployment of RE and the evolution of low-cost applications. [11.5.7]

Macroeconomic impacts of renewable energy policies

Payment for supply-push type RE support tends to come from public budgets (multinational, national, local), whereas the cost of demand-pull mechanisms often lands on the end users. For example, if a renewable electricity policy is added to a countries' electricity sector, this additional cost is often borne by electricity consumers, although exemptions or re-allocations can reduce costs for industrial or vulnerable customers where necessary. Either way, there are costs to be paid. If the goal is to transform the energy sector over the next several decades, then it is important to minimize costs over this entire period; it is also important to include all costs and benefits to society in that calculation. [11.5.7.2]

Conducting an integrated analysis of costs and benefits of RE is extremely demanding because so many elements are involved in determining net impacts. Effects fall into three categories: direct and indirect costs of the system as well as benefits of RE expansion; distributional effects (in which economic actors or groups enjoy benefits or suffer burdens as a result of RE support); and macroeconomic aspects such as impacts on GDP or employment. For example, RE policies provide opportunities for potential economic growth and job creation, but measuring net effects is complex and uncertain because the additional costs of RE support create distributional and budget effects on the economy. Few studies have examined such impacts on national or regional economies; however, those that have been carried out have generally found net positive economic impacts. [11.3.4, 11.5.7.2]

Interactions and potential unintended consequences of renewable energy and climate policies

Due to overlapping drivers and rationales for RE deployment and overlapping jurisdictions (local, national, international) substantial interplay may occur among policies at times with unintended consequences. Therefore, a clear understanding of the interplay among policies and the cumulative effects of multiple policies is crucial. [11.3, 11.5.7, 11.6.2]

If not applied globally and comprehensively, both carbon pricing and RE policies create risks of 'carbon leakage', where RE policies in one jurisdiction or sector reduce the demand for fossil fuel energy in that jurisdiction or sector, which *ceteris paribus* reduces fossil fuel prices globally and hence increases demand for fossil energy in other jurisdictions or sectors. Even if implemented globally, suboptimal carbon prices and RE policies could potentially lead to higher carbon emissions. For example, if fossil fuel resource owners fear more supportive RE deployment policies in the long term, they could increase resource extraction as long as RE support is moderate. Similarly, the prospect of future carbon price increases may encourage owners of oil and gas wells to extract resources more rapidly, while carbon taxes are lower, undermining policymakers' objectives for both the climate and the spread of RE technology. The conditions of such a 'green paradox' are rather specific: carbon pricing would have to begin at low levels and increase rapidly. Simultaneously, subsidized RE would have to remain more expensive than fossil fuel-based technologies. However, if carbon prices and RE subsidies begin at high levels from the beginning, such green paradoxes become unlikely. [11.5.7]

The cumulative effect of combining policies that set fixed carbon prices, like carbon taxes, with RE subsidies is largely additive: in other words, extending a carbon tax with RE subsidies decreases emissions and increases the deployment of RE. However, the effect on the energy system of combining endogenous-price policies, like emissions trading and/or RE quota obligations, is usually not as straightforward. Adding RE policies on top of an emissions trading scheme usually reduces carbon prices which, in turn, makes carbon-intensive (e.g., coal-based) technologies more attractive compared to other non-RE abatement options such as natural gas, nuclear energy and/or energy efficiency improvements. In such cases, although overall emissions remain fixed by the cap, RE policies reduce the costs of compliance and/or improve social welfare only if RE technologies experience specific externalities and market barriers to a greater extent than other energy technologies. [11.5.7]

Finally, RE policies alone (i.e., without carbon pricing) are not necessarily an efficient instrument to reduce carbon emissions because they do not provide enough incentives to use all available least-cost mitigation options, including non-RE low-carbon technologies and energy efficiency improvements. [11.5.7]

11.6 Enabling environment and regional issues

RE technologies can play a greater role in climate change mitigation if they are implemented in conjunction with broader 'enabling' policies that can facilitate change in the energy system. An 'enabling' environment encompasses different institutions, actors (e.g., the finance community, business community, civil society, government), infrastructures (e.g., networks and markets), and political outcomes (e.g., international agreements/cooperation, climate change strategies) (see Table TS.11.1). [11.6]

A favourable or 'enabling' environment for RE can be created by encouraging innovation in the energy system; addressing the possible interactions of a given policy with other RE policies as well as with other non-RE policies; easing the ability of RE developers to obtain finance and to successfully site a project; removing barriers for access to networks and markets for RE installations and output; enabling technology transfer and capacity building; and by increasing education and awareness raising at the institutional level and within communities. In turn, the existence of an 'enabling' environment can increase the efficiency and effectiveness of policies to promote RE. [11.6.1–11.6.8]

A widely accepted conclusion in innovation literature is that established socio-technical systems tend to narrow the diversity of innovations because the prevailing technologies develop a fitting institutional environment. This may give rise to strong path dependencies and exclude (or lock out) rivalling and potentially better-performing alternatives. For these reasons, socio-technical system change takes time, and it involves change that is systemic rather than linear. RE technologies are being integrated into an energy system that, in much of the world, was constructed to accommodate the existing energy supply mix. As a result, infrastructure favours the currently dominant fuels, and existing lobbies and interests all need to be taken into account. Due to the intricacies of technological change, it is important that all levels of government (from local through to international) encourage RE development through policies, and that nongovernmental actors also be involved in policy formulation and implementation. [11.6.1]

Government policies that complement each other are more likely to be successful, and the design of individual RE policies will also affect the success of their coordination with other policies. Attempting to actively promote the complementarities of policies across multiple sectors—from energy to agriculture to water policy, etc.—while also considering the independent objectives of each, is not an easy task and may create win-win and/or win-lose situations, with possible trade-offs. This implies a need for strong central coordination to eliminate contradictions and conflicts among sectoral policies and to simultaneously coordinate action at more than one level of governance. [11.6.2]

A broader enabling environment includes a financial sector that can offer access to financing on terms that reflect the specific risk/reward profile of a RE technology or project. The cost of financing and access to it depends on the broader financial market conditions prevalent at the time of investment, and on the specific risks of a project, technology, and actors involved. Beyond RE-specific policies, broader conditions can

Table TS.11.1 | Factors and participants contributing to a successful RE governance regime. [Table 11.4]

Dimensions of an Enabling Environment >> Factors and actors contributing to the success of RE policy	Section 11.6.2 Integrating Policies (national/ supranational policies)	Section 11.6.3 Reducing Financial and Investment Risk	Section 11.6.4 Planning and Permitting at the local level	Section 11.6.5 Providing infrastructures networks and markets for RE technology	Section 11.6.6 Technology Transfer and Capacity Building	Section 11.6.7 Learning from actors beyond government
Institutions	Integrating RE policies with other policies at the design level reduces potential for conflict among government policies	Development of financing institutions and agencies can aid cooperation between countries, provide soft loans or international carbon finance (CDM). Long-term commitment can reduce the perception of risk	Planning and permitting processes enable RE policy to be integrated with non-RE policies at the local level	Policymakers and regulators can enact incentives and rules for networks and markets, such as security standards and access rules	Reliability of RE technologies can be ensured through certification Institutional agreements enable technology transfer	Openness to learning from other actors can complement design of policies and enhance their effectiveness by working within existing social conditions
Civil society (individuals, households, NGOs, unions ...)	Municipalities or cities can play a decisive role in integrating state policies at the local level	Community investment can share and reduce investment risk Public-private partnerships in investment and project development can contribute to reducing risks associated with policy instruments Appropriate international institutions can enable an equitable distribution of funds	Participation of civil society in local planning and permitting processes might allow for selection of the most socially relevant RE projects	Civil society can become part of supply networks through co-production of energy and new decentralized models.	Local actors and NGOs can be involved in technology transfer through new business models bringing together multi-national companies / NGOs / Small and Medium Enterprises	Civil society participation in open policy processes can generate new knowledge and induce institutional change Municipalities or cities may develop solutions to make RE technology development possible at the local level People (individually or collectively) have a potential for advancing energy-related behaviours when policy signals and contextual constraints are coherent
Finance and business communities		Public private partnerships in investment and project development can contribute to reducing risks associated with policy instruments	RE project developers can offer know-how and professional networks in : i) aligning project development with planning and permitting requirements ; ii) adapting planning and permitting processes to local needs and conditions Businesses can be active in lobbying for coherent and integrated policies	Clarity of network and market rules improves investor confidence	Financing institutions and agencies can partner with national governments, provide soft loans or international carbon finance (CDM).	Multi-national companies can involve local NGOs or SMEs as partners in new technology development (new business models) Development of corporations and international institutions reduces risk of investment
Infrastructures	Policy integration with network and market rules can enable development of infrastructure suitable for a low-carbon economy	Clarity of network and market rules reduces risk of investment and improves investor confidence		Clear and transparent network and market rules are more likely to lead to infrastructures complementary to a low-carbon future		City and community level frameworks for the development of long-term infrastructure and networks can sustain the involvement of local actors in policy development

Continued next Page →

Dimensions of an Enabling Environment >> Factors and actors contributing to the success of RE policy	Section 11.6.2 Integrating Policies (national/ supranational policies)	Section 11.6.3 Reducing Financial and Investment Risk	Section 11.6.4 Planning and Permitting at the local level	Section 11.6.5 Providing infrastructures networks and markets for RE technology	Section 11.6.6 Technology Transfer and Capacity Building	Section 11.6.7 Learning from actors beyond government
Politics (international agreements / cooperation, climate change strategy, technology transfer...)	Supra-national guidelines (e.g., EU on "streamlining", ocean planning, impact study) may contribute to integrating RE policy with other policies	Long-term political commitment to RE policy reduces investors risk in RE projects	Supra- national guidelines may contribute to evolving planning and permitting processes	Development cooperation helps sustain infrastructure development and allows easier access to low-carbon technologies	CDMs, Intellectual property rights (IPR) and patent agreements can contribute to technology transfer	Appropriate input from non-government institutions stimulates more agreements that are socially connected UNFCCC process mechanisms such as Expert Group on Technology Transfer (EGTT), the Global Environment Facility (GEF), and the Clean Development Mechanism (CDM) and Joint Implementation (JM) may provide guidelines to facilitate the involvement of non-state actors in RE policy development

include political and currency risks, and energy-related issues such as competition for investment from other parts of the energy sector, and the state of energy sector regulations or reform. [11.6.3]

The successful deployment of RE technologies to date has depended on a combination of favourable planning procedures at both national and local levels. Universal procedural fixes, such as 'streamlining' of permitting applications, are unlikely to resolve conflicts among stakeholders at the level of project deployment because they would ignore place- and scale-specific conditions. A planning framework to facilitate the implementation of RE might include the following elements: aligning stakeholder expectations and interests; learning about the importance of context for RE deployment; adopting benefit-sharing mechanisms; building collaborative networks; and implementing mechanisms for articulating conflict for negotiation. [11.6.4]

After a RE project receives planning permission, investment to build it is only forthcoming once its economic connection to a network is agreed; when it has a contract for the 'off-take' of its production into the network; and when its sale of energy, usually via a market, is assured. The ability, ease and cost of fulfilling these requirements is central to the feasibility of a RE project. Moreover, the methods by which RE is integrated into the energy system will have an effect on the total system cost of RE integration and the cost of different scenario pathways. In order to ensure the timely expansion and reinforcement of infrastructure for and connection of RE projects, economic regulators may need to allow 'anticipatory' or 'proactive' network investment and/or allow projects to connect in advance of full infrastructure reinforcement. [11.6.5, 8.2.1.3]

For many countries, a major challenge involves gaining access to RE technologies. Most low-carbon technologies, including RE technologies, are developed and concentrated in a few countries. It has been argued that many developing nations are unlikely to 'leapfrog' pollution-intensive stages of industrial development without access to clean technologies that have been developed in more advanced economies. However, technologies such as RE technologies typically do not flow across borders unless environmental policies in the recipient country provide incentives for their adoption. Further, technology transfer should not replace but rather should complement domestic efforts at capacity building. In order to have the capacity to adapt, install, maintain, repair and improve on RE technologies in communities without ready access to RE, investment in technology transfer must be complemented by investment in community-based extension services that provide expertise, advice and training regarding installation, technology adaptation, repair and maintenance. [11.6.6]

In addition to technology transfer, institutional learning plays an important role in advancing deployment of RE. Institutional learning is conducive to institutional change, which provides space for institutions to improve the choice and design of RE policies. It also encourages a stronger institutional capacity at the deeper, often more local, level where numerous decisions are made on siting and investments in RE projects. Institutional learning can occur if policymakers can draw on nongovernmental actors, including private actors (companies, etc.) and civil society for collaborative approaches in policymaking. Information and education are often emphasized as key policy tools for influencing energy-related behaviours. However, the effectiveness of education- and information-based policies is limited by contextual factors, which cautions against an over-reliance on information- and education-based policies alone. Changes in energy-related behaviours are the outcome of a process in which personal norms or attitudes interact with prices, policy signals, and the RE technologies themselves, as well as the social context in which individuals find themselves. These contextual factors point to the importance of collective action as a more effective, albeit more complex medium for change than individual action. This supports coordinated, systemic policies that go beyond narrow 'attitude-behaviour-change' policies if policymakers wish to involve individuals in the RE transition. [11.6.7, 11.6.8]

11.7 A structural shift

If decision makers intend to increase the share of RE and, at the same time, meet ambitious climate mitigation targets, then long-standing commitments and flexibility to learn from experience will be critical. To achieve GHG concentration stabilization levels with high shares of RE, a structural shift in today's energy systems will be required over the next few decades. Such a transition to low-carbon energy differs from previous energy transitions (e.g., from wood to coal, or coal to oil) because the available time span is restricted to a few decades, and because RE must develop and integrate into a system constructed in the context of an existing energy structure that is very different from what might be required under higher penetration RE futures. [11.7]

A structural shift towards a world energy system that is mainly based on renewable energy might begin with a prominent role for energy efficiency in combination with RE. This requires, however, a reasonable carbon pricing policy in the form of a tax or emission trading scheme that avoids carbon leakage and rebound effects. Additional policies are required that extend beyond R&D to support technology deployment; the creation of an enabling environment that includes education and awareness raising; and the systematic development of integrative policies with broader sectors, including agriculture, transportation, water management and urban planning. [11.6, 11.7] The policy frameworks that induce the most RE investment are those designed to reduce risks and enable attractive returns, and to provide stability over a time frame relevant to the investment. [11.5] The appropriate and reliable mix of instruments is even more important where energy infrastructure is not yet developed and energy demand is expected to increase significantly in the future. [11.7]

III

Chapters 1 to 11

1

Renewable Energy and Climate Change

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Executive Summary

All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility, communication) and to serve productive processes. For development to be sustainable, delivery of energy services needs to be secure and have low environmental impacts. Sustainable social and economic development requires assured and affordable access to the energy resources necessary to provide essential and sustainable energy services. This may mean the application of different strategies at different stages of economic development. To be environmentally benign, energy services must be provided with low environmental impacts and low greenhouse gas (GHG) emissions. However, 85% of current primary energy driving global economies comes from the combustion of fossil fuels and consumption of fossil fuels accounts for 56.6% of all anthropogenic GHG emissions.

Renewable energy sources play a role in providing energy services in a sustainable manner and, in particular, in mitigating climate change. This Special Report on Renewable Energy Sources and Climate Change Mitigation explores the current contribution and potential of renewable energy (RE) sources to provide energy services for a sustainable social and economic development path. It includes assessments of available RE resources and technologies, costs and co-benefits, barriers to up-scaling and integration requirements, future scenarios and policy options.

GHG emissions associated with the provision of energy services are a major cause of climate change. The IPCC Fourth Assessment Report (AR4) concluded that "Most of the observed increase in global average temperature since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." Concentrations of CO_2 have continued to grow and by the end of 2010 had reached 390 ppm CO_2 or 39% above pre-industrial levels.

The long-term baseline scenarios reviewed for the AR4 show that the expected decrease in the energy intensity will not be able to compensate for the effects of the projected increase in the global gross domestic product. As a result, most of the scenarios exhibit a strong increase in primary energy supply throughout this century. In the absence of any climate policy, the overwhelming majority of the baseline scenarios exhibit considerably higher emissions in 2100 compared to 2000, implying rising CO_2 concentrations and, in turn, enhanced global warming. Depending on the underlying socioeconomic scenarios and taking into account additional uncertainties, global mean temperature is expected to rise and to approach a level between 1.1°C and 6.4°C over the 1980 to 1999 average by the end of this century.

To avoid adverse impacts of such climate change on water resources, ecosystems, food security, human health and coastal settlements with potentially irreversible abrupt changes in the climate system, the Cancun Agreements call for limiting global average temperature rises to no more than 2°C above pre-industrial values, and agreed to consider limiting this rise to 1.5°C. In order to be confident of achieving an equilibrium temperature increase of only 2°C to 2.4°C, GHG concentrations would need to be stabilized in the range of 445 to 490 ppm CO_2eq in the atmosphere.

There are multiple means for lowering GHG emissions from the energy system, while still providing desired energy services. RE technologies are diverse and can serve the full range of energy service needs. Various types of RE can supply electricity, thermal energy and mechanical energy, as well as produce fuels that are able to satisfy multiple energy service needs. RE is any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. Unlike fossil fuels, most forms of RE produce little or no CO_2 emissions.

The contribution RE will provide within the portfolio of low carbon technologies heavily depends on the economic competition between these technologies, their relative environmental burden (beyond climate change), as well as on security and societal aspects. A comprehensive evaluation of any portfolio of mitigation options would involve an evaluation of their respective mitigation potential as well as all associated risks, costs and their contribution to sustainable development. Even without a push for climate change mitigation, scenarios that are examined in this report find that the increasing demand for energy services is expected to drive RE to levels exceeding today's energy usage.

On a global basis, it is estimated that RE accounted for 12.9% of the total 492 EJ of primary energy supply in 2008. The largest RE contributor was biomass (10.2%), with the majority (roughly 60%) of the biomass fuel used in traditional cooking and heating applications in developing countries but with rapidly increasing use of modern biomass as well.[1] Hydropower represented 2.3%, whereas other RE sources accounted for 0.4%. In 2008, RE contributed approximately 19% of global electricity supply (16% hydropower, 3% other RE), biofuels contributed 2% of global road transport fuel supply, and traditional biomass (17%), modern biomass (8%), solar thermal and geothermal energy (2%) together fuelled 27% of the total global demand for heat. The contribution of RE to primary energy supply varies substantially by country and region. Scenarios of future low greenhouse gas futures consider RE and RE in combination with nuclear, and coal and natural gas with carbon capture and storage.

While the RE share of global energy consumption is still relatively small, deployment of RE has been increasing rapidly in recent years. Of the approximately 300 GW of new electricity generating capacity added globally over the two-year period from 2008 to 2009, 140 GW came from RE additions. Collectively, developing countries hosted 53% of global RE power generation capacity in 2009. Under most conditions, increasing the share of RE in the energy mix will require policies to stimulate changes in the energy system. Government policy, the declining cost of many RE technologies, changes in the prices of fossil fuels and other factors have supported the continuing increase in the use of RE. These developments suggest the possibility that RE could play a much more prominent role in both developed and developing countries over the coming decades.

Some RE technologies can be deployed at the point of use (decentralized) in rural and urban environments, whereas others are primarily employed within large (centralized) energy networks. Though many RE technologies are technically mature and are being deployed at significant scale, others are in an earlier phase of technical maturity and commercial deployment.

The theoretical potential for RE greatly exceeds all the energy that is used by all economies on Earth. The global technical potential of RE sources will also not limit continued market growth. A wide range of estimates are provided in the literature but studies have consistently found that the total global technical potential for RE is substantially higher than both current and projected future global energy demand. The technical potential for solar energy is the highest among the RE sources, but substantial technical potential exists for all forms of RE. The absolute size of the global technical potential for RE as a whole is unlikely to constrain RE deployment.

Some RE, including wind and solar power, are variable and may not always be available for dispatch when needed. The energy density of some RE is also relatively lower, so that reducing the delivered energy needed to supply end-use energy services is especially important for RE even though benefiting all forms of energy.

The levelized cost of energy for many RE technologies is currently higher than existing energy prices, though in various settings RE is already economically competitive. Ranges of recent levelized costs of energy for selected commercially available RE technologies are wide, depending on a number of factors including, but not limited to, technology characteristics, regional variations in cost and performance and differing discount rates.

RE may provide a number of opportunities and can not only address climate change mitigation but may also address sustainable and equitable economic development, energy access, secure energy supply and local environmental and health impacts. Market failures, up-front costs, financial risk, lack of data as well as capacities and public and institutional awareness, perceived social norms and value structures, present infrastructure and current

1 Not accounted for here or in official databases is the estimated 20 to 40% of additional traditional biomass used in informal sectors (Section 2.1).

energy market regulation, inappropriate intellectual property laws, trade regulations, lack of amenable policies and programs, lower power of RE and land use conflicts are amongst existing barriers and issues to expanding the use of RE.

Some governments have successfully introduced a variety of RE policies, motivated by a variety of factors, to address these various components of RE integration into the energy system. These policies have driven escalated growth in RE technologies in recent years. These policies can be categorized as fiscal incentives, public finance and regulation. They typically address two market failures: 1) the external cost of GHG emissions are not priced at an appropriate level; and 2) RE creates benefits to society beyond those captured by the innovator, leading to under-investment in such efforts. Several studies have concluded that some feed-in tariffs have been effective and efficient at promoting RE electricity. Quota policies can be effective and efficient if designed to reduce risk. An increasing number of governments are adopting fiscal incentives for RE heating and cooling. In the transportation sector, RE fuel mandates or blending requirements are key drivers in the development of most modern biofuel industries. Policies have influenced the development of an international biofuel trade. One important challenge will be finding a way for RE and carbon-pricing policies to interact such that they take advantage of synergies rather than trade-offs. RE technologies can play a greater role if they are implemented in conjunction with 'enabling' policies.

1.1 Background

1.1.1 Introduction

All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility, communication) and to serve productive processes. The quality of energy is important to the development process (Cleveland et al., 1984; Brookes, 2000; Kaufmann, 2004). For development to be sustainable, delivery of energy services needs to be secure and have low environmental impacts. Sustainable social and economic development requires assured and affordable access to the energy resources necessary to provide essential and sustainable energy services. This may mean the application of different strategies at different stages of economic development. To be environmentally benign, energy services must be provided with low environmental impacts, including GHG emissions.

The IPCC Fourth Assessment Report (AR4) reported that fossil fuels provided 85% of the total primary energy in 2004 (Sims et al., 2007),[2] which is the same value as in 2008 (IEA 2010a; Table A.II.1). Furthermore, the combustion of fossil fuels accounted for 56.6% of all anthropogenic GHG emissions (CO_2eq) in 2004 (Rogner et al., 2007).[3] To maintain both a sustainable economy that is capable of providing essential goods and services to the citizens of both developed and developing countries, and to maintain a supportive global climate system, requires a major shift in how energy is produced and utilized (Nfah et al., 2007; Kankam and Boon, 2009). However, renewable energy technologies, which release much lower amounts of CO_2 than fossil fuels are growing. Chapter 10 examines more than 100 scenarios in order to explore the potential for RE to contribute to the development of a low-carbon future.

1.1.2 The Special Report on Renewable Energy Sources and Climate Change Mitigation

Renewable energy (RE) sources play a role in providing energy services in a sustainable manner and, in particular, in mitigating climate change. This Special Report on *Renewable Energy Sources and Climate Change Mitigation* explores the current contribution and potential of RE sources to provide energy services for a sustainable social and economic development path. It includes assessments of available RE resources and technologies, costs and co-benefits, barriers to up-scaling and integration requirements, future scenarios and policy options. It consists of 11 chapters (Figure 1.1). Chapter 1 provides an overview of RE and climate change; Chapters 2 through 7 provide information on six types of RE technologies (biomass, solar, geothermal, hydro, ocean and wind)

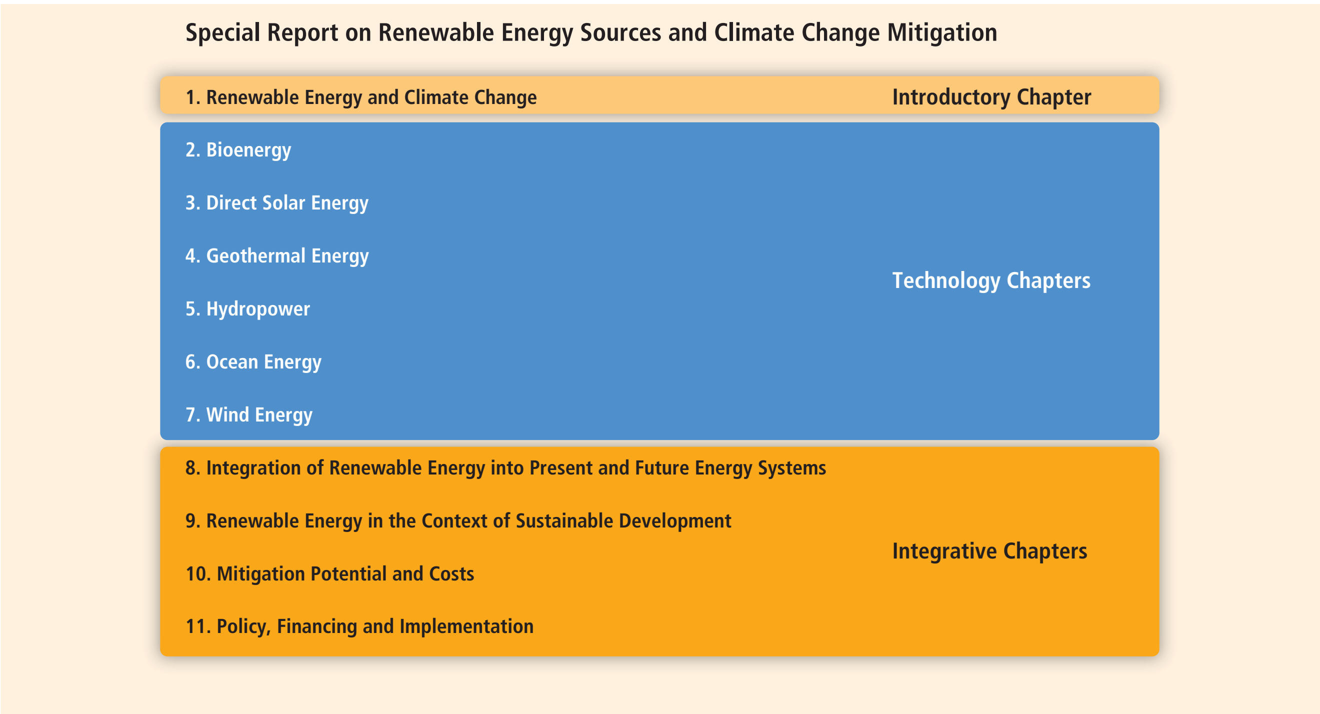


Figure 1.1 | Structure of the report.

2 The number from the AR4 is 80% and has been converted from the physical content method for energy accounting to the direct equivalent method, as the latter method is used in this report. Please refer to Section 1.1.9 and Annex II (Section A.II.4) for methodological details.

3 The contributions from other sources and/or gases (see Figure 1.1b in Rogner et al., 2007) are: CO_2 from deforestation, decay of biomass etc. (17.3%), CO_2 from other (2.8%), CH_4 (14.3%), N_2O (7.9%) and fluorinated gases (1.1%). For further information on sectoral emissions, including from forestry, see also Figure 1.3b in Rogner et al. (2007) and associated footnotes.

while Chapters 8 through 11 deal with integrative issues (integration of RE into present and future energy systems; RE in the context of sustainable development; mitigation potential and costs; and policy, financing and implementation). The report communicates uncertainty where relevant.[4] It provides the following information on the potential for renewable energy sources to meet GHG reduction goals:

- Identification of RE resources and available technologies and impacts of climate change on these resources (Chapters 2 through 7);
- Technology and market status, future developments and projected rates of deployment (Chapters 2 through 7 and 10);
- Options and constraints for integration into the energy supply system and other markets, including energy storage, modes of transmission, integration into existing systems and other options (Chapter 8);
- Linkages among RE growth, opportunities and sustainable develoment (Chapter 9);
- Impacts on secure energy supply (Chapter 9);
- Economic and environmental costs, benefits, risks and impacts of deployment (Chapters 9 and 10);
- Mitigation potential of RE sources (Chapter 10);
- Scenarios that demonstrate how accelerated deployment might be achieved in a sustainable manner (Chapter 10);
- Capacity building, technology transfer and financing (Chapter 11); and
- Policy options, outcomes and conditions for effectiveness (Chapter 11).

1.1.3 Climate change

GHG emissions associated with the provision of energy services are a major cause of climate change. The AR4 concluded that "Most of the observed increase in global average temperature since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." (IPCC, 2007a). Concentrations of CO_2 have continued to grow since the AR4 to about 390 ppm CO_2 or 39% above pre-industrial levels by the end of 2010 (IPCC, 2007b; NOAA, 2010). The global average temperature has increased by 0.76°C (0.57°C to 0.95°C) between 1850 to 1899 and 2001 to 2005, and the warming trend has increased significantly over the last 50 years (IPCC, 2007b). While this report focuses on the energy sector, forest clearing and burning and land use change, and the release of non-CO_2 gases from industry, commerce and agriculture also contribute to global warming (IPCC, 2007b).

An extensive review of long-term scenarios (Fisher et al., 2007) revealed that economic growth is expected to lead to a significant increase in gross domestic product (GDP) during the 21st century (see Figure 1.2 left panel), associated with a corresponding increase in the demand for energy services. Historically, humankind has been able to reduce the primary energy input required to produce one GDP unit (the so-called primary energy intensity) and is expected to do so further in the future (see Figure 1.2 right panel).

Within the considered scenarios, the increase in energy efficiency is more than compensated for by the anticipated economic growth. In the

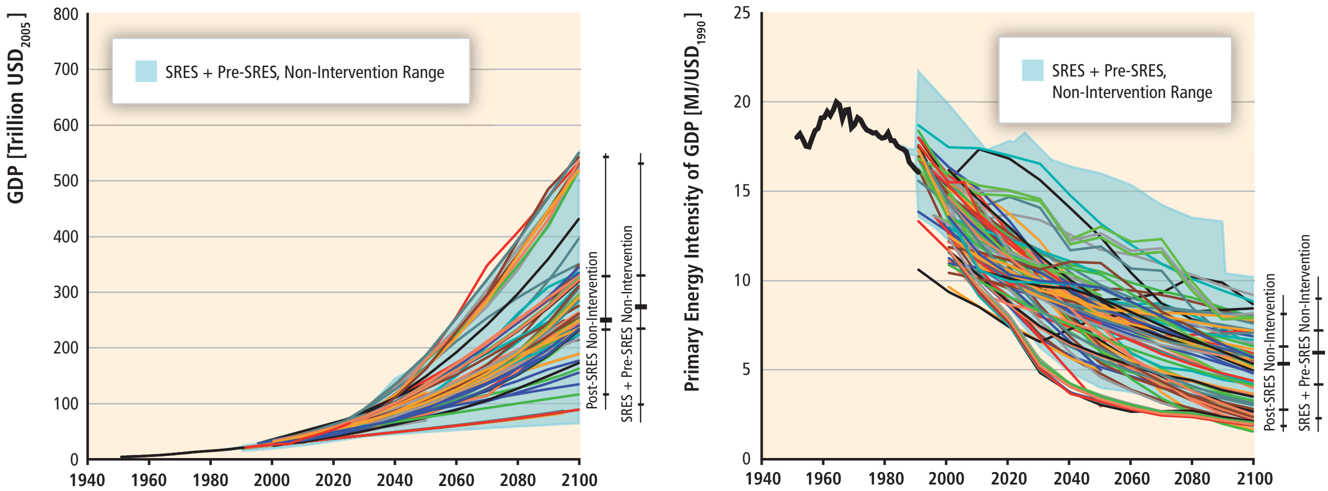


Figure 1.2 | Left panel: Comparison of GDP projections in post-SRES (Special Report on Emission Scenarios) emissions scenarios with those used in previous scenarios. The median of the new scenarios is about 7% below the median of the pre-SRES and SRES scenario literature. The two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios by 2100. Right panel: Development of primary energy intensity of GDP: historical development and projections from SRES and pre-SRES scenarios compared to post-SRES scenarios. Adapted from Fisher et al., 2007, pp. 180 and 184.

4 This report communicates uncertainty, for example, by showing the results of sensitivity analyses and by quantitatively presenting ranges in cost numbers as well as ranges in the scenario results. This report does not apply formal IPCC uncertainty terminology because at the time of the approval of this report, IPCC uncertainty guidance was in the process of being revised.

business-as-usual case, the demand for global primary energy therefore is projected to increase substantially during the 21st century (see Figure 1.3 left panel).

Similarly to the behaviour of primary energy intensity, carbon intensity (the amount of CO_2 emissions per unit of primary energy) is—with few exceptions—expected to decrease as well (see Figure 1.3 right panel). Despite the substantial associated decarbonization, the overwhelming majority of the non-intervention emission projections exhibit considerably higher emissions in 2100 compared with those in 2000 (see the shaded area in Figure 1.4 left panel). Because emission rates substantially exceed natural removal rates, concentrations will continue to increase, which will raise global mean temperature. Figure 1.4 right panel shows the respective changes for representative emission scenarios (so-called SRES (Special Report on Emissions Scenarios) scenarios; see IPCC (2000a)) taken from the set of emissions scenarios shown in Figure 1.4 left panel.

In the absence of additional climate policies, the IPCC (2007a; see Figure 1.4) projected that global average temperature will rise over this century by between 1.1°C and 6.4°C over the 1980 to 1999 average, depending on socioeconomic scenarios (IPCC, 2000a). This range of uncertainty arises from uncertainty about the amount of GHGs that will be emitted in the future, and from uncertainty about the climate sensitivity. In addition to an investigation of potentially irreversible abrupt changes in the climate system, the IPCC assessed the adverse impacts of such climate change (and the associated sea level rise and ocean acidification) on water supply, ecosystems, food security, human health and coastal settlements (IPCC, 2007c).

The Cancun Agreements (2010) call for limiting global average temperature rise to no more than 2°C above pre-industrial values, and agreed to consider a goal of 1.5°C. The analysis shown in Figure 1.5 concludes that in order to be confident of achieving an equilibrium temperature increase of only 2°C to 2.4°C, atmospheric GHG concentrations would need to be in the range of 445 to 490 ppm CO_2eq. This in turn implies that global emissions of CO_2 will need to decrease by 50 to 85% below 2000 levels by 2050 and begin to decrease (instead of continuing their current increase) no later than 2015 (IPCC, 2007a). Note that there is a considerable range of probable temperature outcomes at this concentration range. Additional scenario analysis and mitigation costs under various GHG concentration stabilization levels are analyzed in Chapter 10. This report does not analyze the economic cost of damages from climate change.

1.1.4 Drivers of carbon dioxide emissions

Since about 1850, global use of fossil fuels (coal, oil and gas) has increased to dominate energy supply, both replacing many traditional uses of bioenergy and providing new services. The rapid rise in fossil fuel combustion (including gas flaring) has produced a corresponding rapid growth in CO_2 emissions (Figure 1.6).

The amount of carbon in fossil fuel reserves and resources (unconventional oil and gas resources as well as abundant coal) not yet burned has the potential to add quantities of CO_2 to the atmosphere—if burned over coming centuries—that would exceed the range of any of the scenarios considered in Figure 1.5 or in Chapter 10 (Moomaw et al., 2001; Knopf et al., 2010). Figure 1.7 summarizes current estimates of fossil fuel resources and reserves in terms of carbon content, and compares them with the amount already released to the atmosphere as CO_2. Reserves refer to what is extractable with today's technologies at current energy

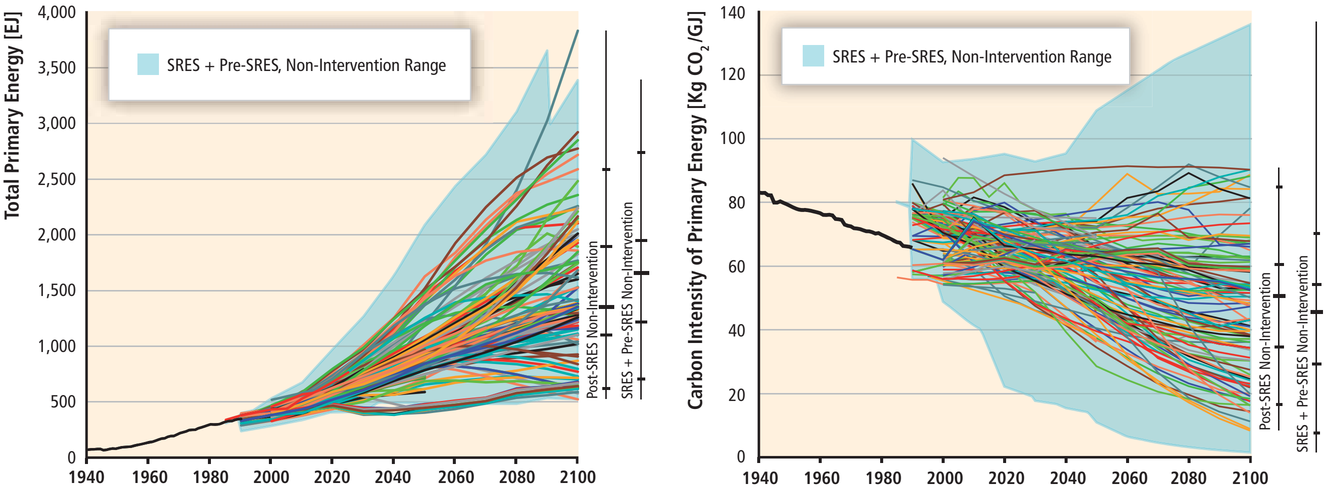


Figure 1.3 | Left panel: Projected increase in primary energy supply. Comparison of 153 SRES and pre-SRES baseline energy scenarios in the literature compared with the 133 more recent, post-SRES scenarios. The ranges are comparable, with small changes in the lower and upper boundaries. Right panel: Expected carbon intensity changes. Historical development and projections from SRES and pre-SRES scenarios compared to post-SRES scenarios. Adapted from Fisher et al., 2007, pp. 183 and 184.

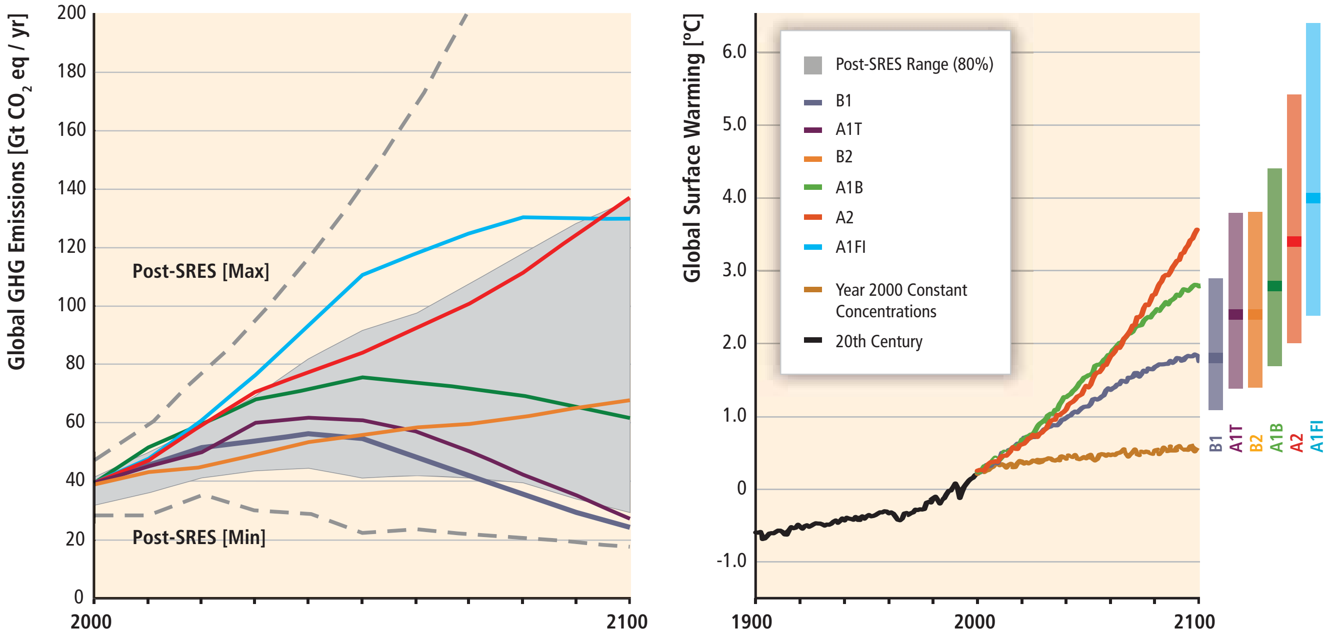


Figure 1.4 | Left panel: Global GHG emissions (Gt CO_2eq) in the absence of climate policies: six illustrative SRES marker scenarios (coloured lines) and the 80th percentile range of recent scenarios published since SRES (post-SRES) (grey shaded area). Dashed lines show the full range of post-SRES scenarios. The emissions include CO_2, methane (CH_4), nitrous oxide (N_2O) and fluorinated gases. Right panel: Solid lines are multi-model global averages of projected surface warming for SRES scenarios A2, A1B and B1, shown as continuations of the 20th-century simulations. These projections also take into account emissions of short-lived GHGs and aerosols. The brown line is not a scenario, but is for atmosphere-ocean general circulation model simulations where atmospheric concentrations are held constant at year 2000 values. The bars at the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios for 2090 to 2099. All temperatures are relative to the period 1980 to 1999 (IPCC, 2007a, Figure SPM 5, page 7).

prices. Resources represent the total amount estimated to be available without regard to the technical or economic feasibility of extracting it (IEA, 2005).

In developing strategies for reducing CO_2 emissions it is useful to consider the Kaya identity that analyzes energy-related CO_2 emissions as a function of four factors: 1) Population; 2) GDP per capita; 3) energy intensity (i.e., total primary energy supply (TPES) per GDP); and 4) carbon intensity (i.e., CO_2 emissions per TPES) (Ehrlich and Holdren, 1971; Kaya, 1990).

The Kaya identity is then:

CO_2 emissions = Population x (GDP/population) x (TPES/GDP) x (CO_2/ TPES)

This is sometimes referred to as:

CO_2 emissions = (Population x Affluence x Energy intensity x Carbon intensity)

Renewable energy supply sources are effective in lowering CO_2 emissions because they have low carbon intensity with emissions per unit of energy output typically 1 to 10% that of fossil fuels (see Figure 1.13 and Chapter 10). Further reductions can also be achieved by lowering the energy intensity required to provide energy services. The role of these two strategies and their interaction is discussed in more detail in Section 1.2.6.

The absolute (a) and percentage (b) annual changes in global CO_2 emissions are shown in terms of the Kaya factors in Figure 1.8 (Edenhofer et al., 2010).

While GDP per capita and population growth had the largest effect on emissions growth in earlier decades, decreasing energy intensity significantly slowed emissions growth in the period from 1971 to 2008. In the past, carbon intensity fell because of improvements in energy efficiency and switching from coal to natural gas and the expansion of nuclear energy in the 1970s and 1980s that was particularly driven by Annex I countries.[5] In recent years (2000 to 2007), increases in carbon intensity have mainly been driven by the expansion of coal use by both developed and developing countries, although coal and petroleum use have fallen slightly since 2007. In 2008 this trend was broken due to the financial crisis. Since the early 2000s, the energy supply has become more carbon intensive, thereby amplifying the increase resulting from growth in GDP per capita (Edenhofer et al., 2010).

5 See Glossary (Annex I) for a definition of Annex I countries.

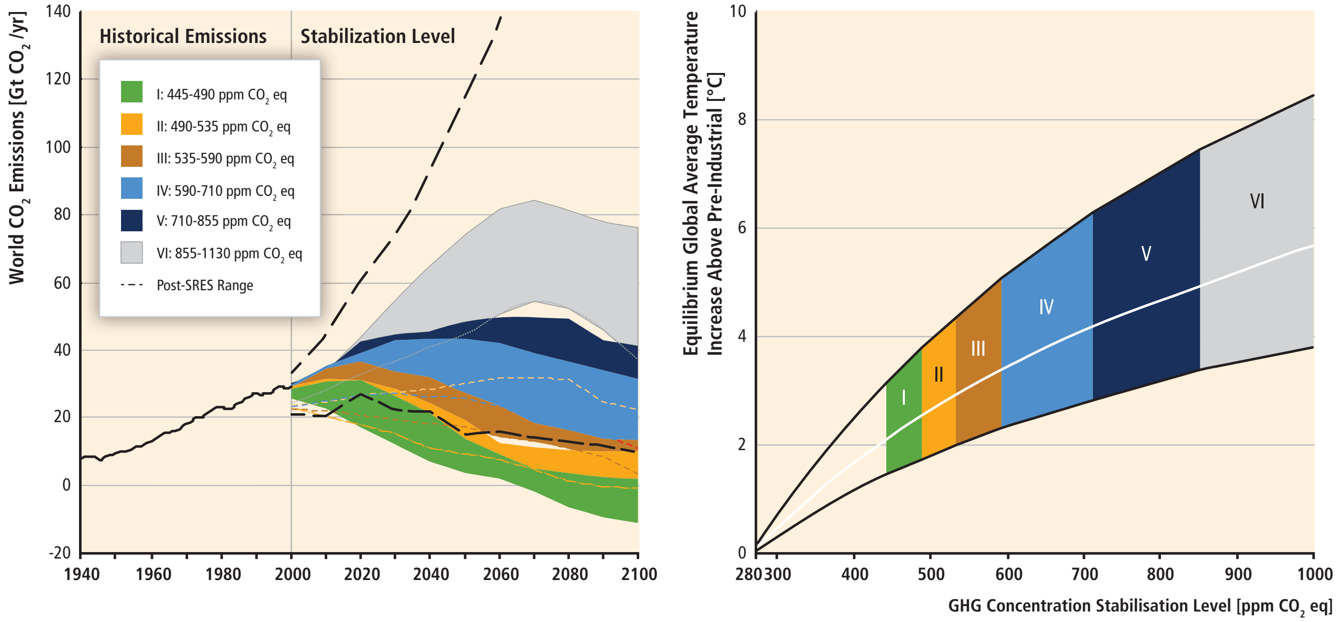


Figure 1.5 | Global CO_2 emissions from 1940 to 2000 and emissions ranges for categories of stabilization scenarios from 2000 to 2100 (left panel); and the corresponding relationship between the stabilization target and the likely equilibrium global average temperature increase above pre-industrial (right panel). Coloured shadings show stabilization scenarios grouped according to different targets (stabilization categories I to VI). The right panel shows ranges of global average temperature change above pre-industrial, using (i) 'best estimate' climate sensitivity of 3°C (line in middle of shaded area); (ii) upper bound of likely range of climate sensitivity of 4.5°C (line at top of shaded area); and (iii) lower bound of likely range of climate sensitivity of 2°C (line at bottom of shaded area) (IPCC, 2007a, Figure SPM-11, page 21).

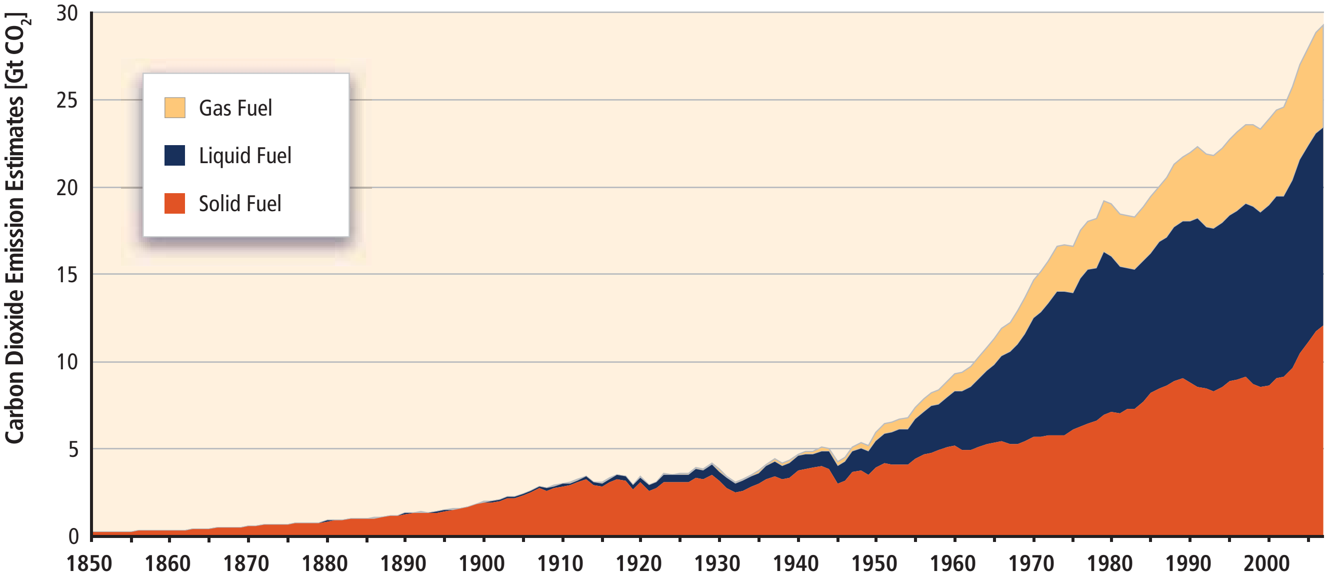


Figure 1.6 | Global CO_2 emissions from fossil fuel burning, 1850 to 2007. Gas fuel includes flaring of natural gas. All emission estimates are expressed in Gt CO_2. Data Source: (Boden and Marland, 2010).

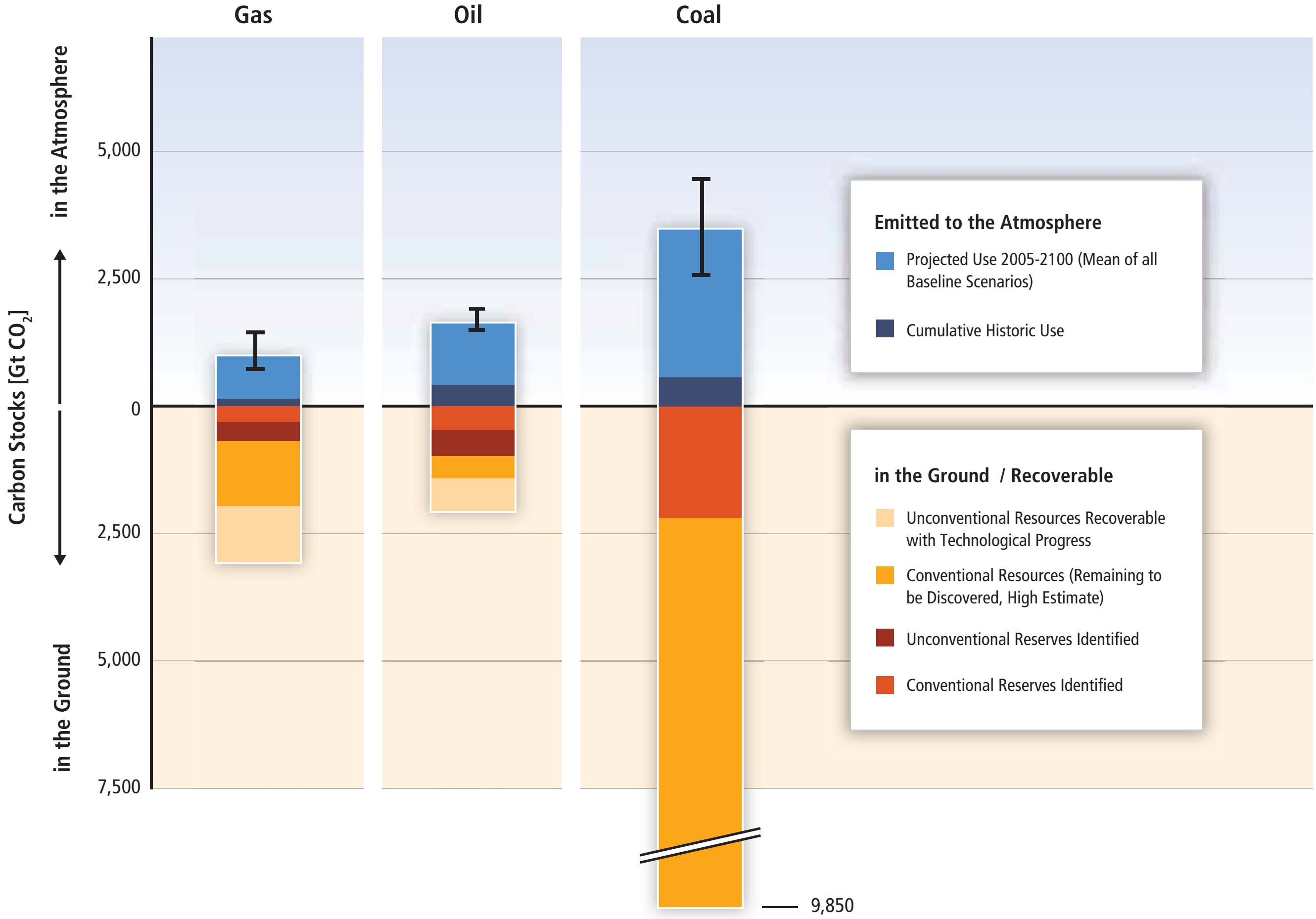


Figure 1.7 | CO_2 released to the atmosphere (above zero) and stocks of recoverable carbon from fossil fuels in the ground (below zero, converted to CO_2). Estimates of carbon stocks in the ground are taken from IPCC (2000a, Table 3-5). Estimates of carbon stocks remaining are provided by BGR (2009), cumulative historic carbon consumption (1750 to 2004) is from Boden et al. (2009) and estimated future consumption (2005 to 2100) from the mean of the baseline scenarios of the energy-economic and integrated assessment models considered in the analysis of Chapter 10 (Table 10.1). Only those scenarios where the full data set until 2100 was available were considered (i.e., 24 scenarios from 12 models). The light blue stacked bar shows the mean and the black error bars show the standard deviation of the baseline projections. Fossil energy stocks were converted to CO_2 emissions by using emission factors from IPCC (2006). Adapted from Knopf et al. (2010).

Historically, developed countries have contributed the most to cumulative global CO_2 emissions, and still have the highest total historical emissions and largest emissions per capita (World Bank, 2009). Recently, developing country annual emissions have risen to more than half of the total, and China surpassed the USA in annual emissions in 2007 (IEA, 2010f). Figure 1.9 examines the annual change in absolute emissions by country and country groups between 1971 and 2008 (Edenhofer et al., 2010).

1.1.5 Renewable energy as an option to mitigate climate change

On a global basis, it is estimated that RE accounted for 12.9% of the total 492 EJ of primary energy supply in 2008 (IEA, 2010a). The largest RE contributor was biomass (10.2%), with the majority (roughly 60%) of the biomass fuel used in traditional cooking and heating applications in developing countries but with rapidly increasing use of modern biomass as well.[6] Hydropower represented 2.3%, whereas other RE sources accounted for 0.4% (Figure 1.10).

RE's contribution to electricity generation is summarized in Figure 1.11. In 2008, RE contributed approximately 19% of global electricity supply (16% hydropower, 3% other RE). Global electricity production in 2008 was 20,181 TWh (or 72.65 EJ) (IEA, 2010a).

Deployment of RE has been increasing rapidly in recent years. Under most conditions, increasing the share of RE in the energy mix will require policies to stimulate changes in the energy system. Government policy, the declining cost of many RE technologies, changes in the prices of fossil fuels and other factors have supported the continuing increase

6 In addition, biomass use estimated to amount to 20 to 40% is not reported in official databases, such as dung, unaccounted production of charcoal, illegal logging, fuelwood gathering, and agricultural residue use (Section 2.1).

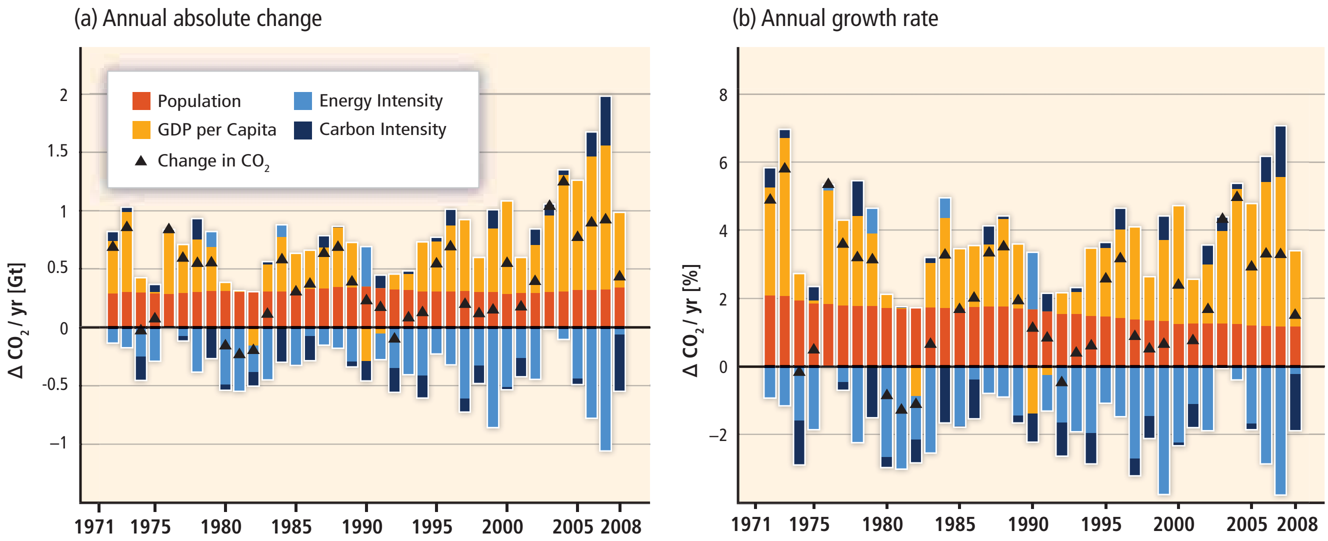


Figure 1.8 | Decomposition of (a) annual absolute change and (b) annual growth rate in global energy-related CO_2 emissions by the factors in the Kaya identity; population (red), GDP per capita (orange), energy intensity (light blue) and carbon intensity (dark blue) from 1971 to 2008. The colours show the changes that would occur due to each factor alone, holding the respective other factors constant. Total annual changes are indicated by a black triangle. Data source: IEA (2010a).

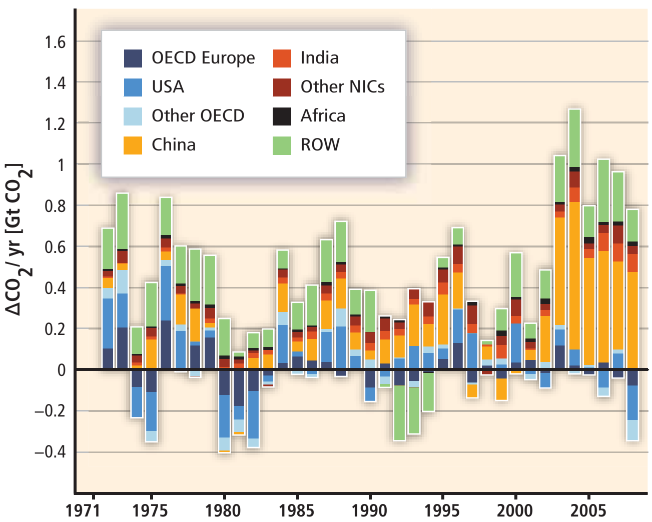


Figure 1.9 | Influence of selected countries and country groups on global changes in CO_2 emissions from 1971 to 2008. ROW: rest of world. Data source: IEA (2010a).

Note: "OECD" is the Organisation for Economic Co-operation and Development; "Other Newly Industrializing Countries (NICs)" include Brazil, Indonesia, the Republic of Korea, Mexico and South Africa; "Other OECD" does not include the Republic of Korea and Mexico; and "Africa" does not include South Africa.

in the use of RE (see Section 1.5.1 and Chapter 11). While RE is still relatively small, its growth has accelerated in recent years, as shown in Figure 1.12. In 2009, despite global financial challenges, RE capacity continued to grow rapidly, including wind power (32%, 38 GW added), hydropower (3%, 31 GW added), grid-connected photovoltaics (53%, 7.5 GW added), geothermal power (4%, 0.4 GW), and solar hot water/heating (21%, 31 GW_{th}) (REN21, 2010). Biofuels accounted for 2% of global road transport fuel demand in 2008 and nearly 3% in 2009 (IEA, 2010c). The annual production of ethanol increased to 1.6 EJ (76 billion litres) by the end of 2009 and biodiesel production increased to 0.6 EJ (17 billion litres). Of the approximate 300 GW of new electricity generating capacity added globally over the two-year period from 2008 to 2009, 140 GW came from RE additions. Collectively, by the end of 2009 developing countries hosted 53% of global RE power generation capacity (including all sizes of hydropower), with China adding more capacity than any other country in 2009. The USA and Brazil accounted for 54 and 35% of global bioethanol production in 2009, respectively, while China led in the use of solar hot water. At the end of 2009, the use of RE in hot water/heating markets included modern biomass (270 GW_{th}), solar (180 GW_{th}) and geothermal (60 GW_{th}). The use of RE (excluding traditional biomass) in meeting rural energy needs is also increasing, including small hydropower stations, various modern bioenergy options, and household or village PV, wind or hybrid systems that combine multiple technologies (REN21, 2010).

UNEP found that in 2008, despite a decline in overall energy investments, global investment in RE power generation rose by 5% to USD 140 billion (USD_{2005} 127 billion), which exceeded the 110 billion (USD_{2005} 100 billion) invested in fossil fuel generation capacity (UNEP, 2009).

These developments suggest the possibility that RE could play a much more prominent role in both developed and developing countries over the coming decades (Demirbas, 2009). New policies, especially in the USA, China and the EU, are supporting this effort (Chapter 11).

Estimates of the lifecycle CO_2 intensity for electric power-producing renewable energy technologies relative to fossil fuels and nuclear power are shown in Figure 1.13 and are discussed in more detail in Chapter 9. Renewable energy and nuclear technologies produce one to two orders of

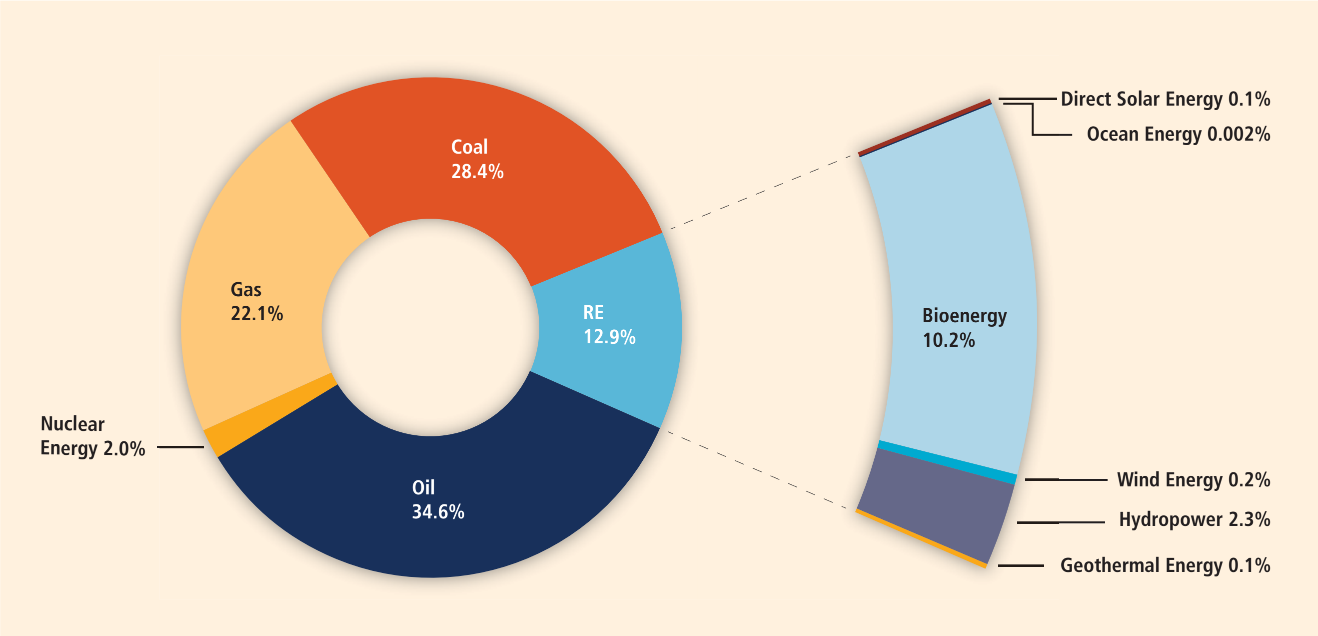


Figure 1.10 | Shares of energy sources in total global primary energy supply in 2008 (492 EJ). Modern biomass contributes 38% to the total biomass share. Data source: IEA (2010a).

Notes: Underlying data for figure have been converted to the direct equivalent method of accounting for primary energy supply (Annex II.4).

magnitude lower CO_2 emissions than fossil fuels in grams of CO_2 per kWh of electricity produced (Weisser, 2007; Sovacool, 2008; Jacobson, 2009).

Most RE technologies have low specific emissions of CO_2 into the atmosphere relative to fossil fuels, which makes them useful tools for addressing climate change (see Figure 1.13). For a RE resource to be sustainable, it must be inexhaustible and not damage the delivery of environmental goods and services including the climate system. For example, to be sustainable, biofuel production should not increase net CO_2 emissions, should not adversely affect food security, or require excessive use of water and chemicals or threaten biodiversity. To be sustainable, energy must also be economically affordable over the long term; it must meet societal needs and be compatible with social norms now and in the future. Indeed, as use of RE technologies accelerates, a balance will have to be struck among the several dimensions of sustainable development. It is important to assess the entire lifecycle of each energy source to ensure that all of the dimensions of sustainability are met (Sections 1.4.1.4 and 9.3.4).

1.1.6 Options for mitigation

There are multiple means for lowering GHG emissions from the energy system while still providing energy services (Pacala and Socolow, 2004; IPCC, 2007d). Energy services are the tasks to be performed using energy. Many options and combinations are possible for reducing emissions. In order to assess the potential contribution of RE to mitigating global climate change, competing mitigation options therefore must be considered as well (Chapter 10).

Chapter 4 of AR4 (Sims et al., 2007) identified a number of ways to lower heat-trapping emissions from energy sources while still providing energy services. They include:

- Improve supply side efficiency of energy conversion, transmission and distribution including combined heat and power.
- Improve demand side efficiency in the respective sectors and applications (e.g., buildings, industrial and agricultural processes, transportation, heating, cooling, lighting) (see also von Weizsäcker et al., 2009).
- Shift from high GHG energy carriers such as coal and oil to lower GHG energy carriers such as natural gas, nuclear fuels and RE sources (Chapters 2 through 7).
- Utilize carbon capture and storage (CCS) to prevent post-combustion or industrial process CO_2 from entering the atmosphere. CCS has the potential for removing CO_2 from the atmosphere when biomass is burned (see also IPCC, 2005).
- Change behaviour to better manage energy use or to use fewer carbon- and energy-intensive goods and services (see also Dietz et al., 2009).

Two additional means of reducing GHGs include enhancing the capacity of forests, soils and grassland sinks to absorb CO_2 from the atmosphere (IPCC, 2000b), and reducing the release of black carbon aerosols and particulates

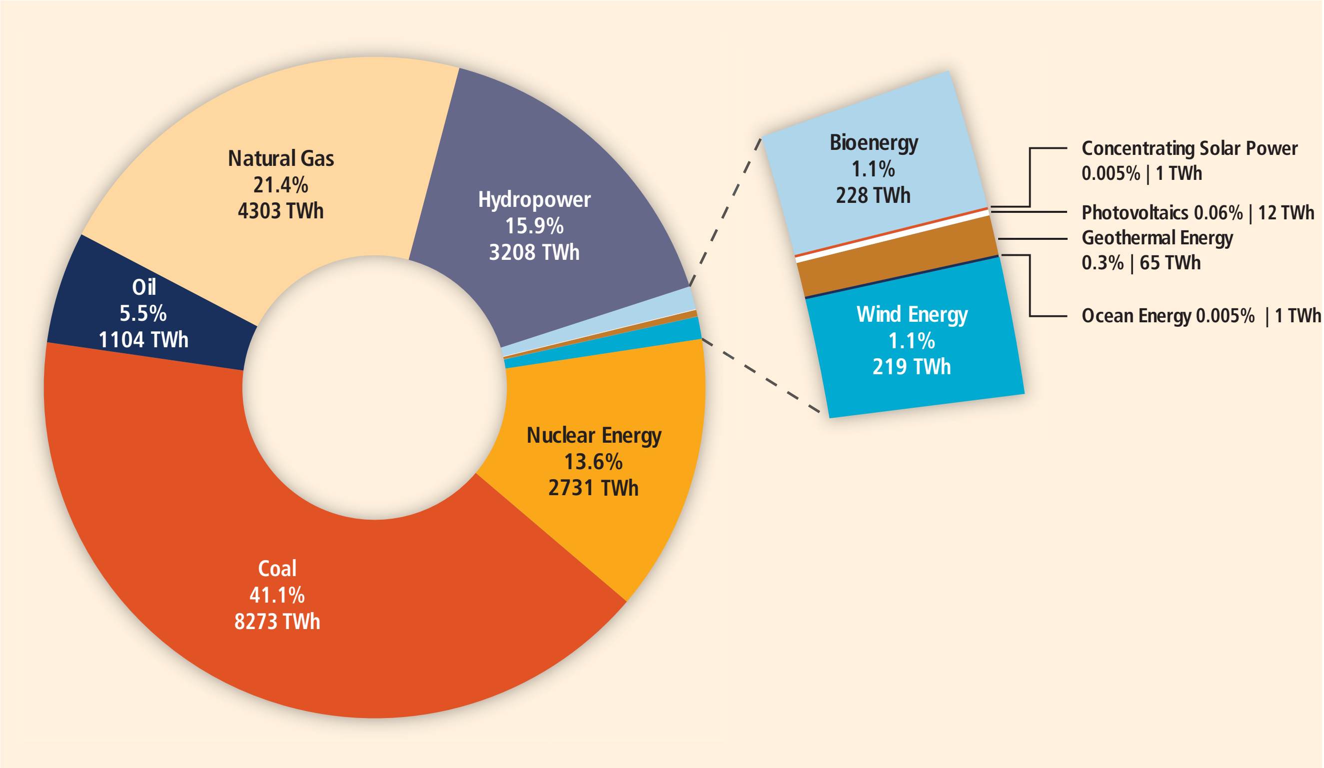


Figure 1.11 | Share of primary energy sources in world electricity generation in 2008. Data for renewable energy sources from IEA (2010a); for fossil and nuclear from IEA (2010d).

from diesel engines, biomass fuels and from the burning of agricultural fields (Bond and Sun, 2005). Additional reductions in non-CO_2 heat-trapping GHGs (CH_4, N_2O, hydrofluorocarbons, sulphur hexafluoride) can also reduce global warming (Moomaw et al., 2001, their Appendix; Sims et al., 2007).

Geoengineering solutions have been proposed to address other aspects of climate change, including altering the heat balance of the Earth by increasing surface albedo (reflectivity), or by reflecting incoming solar radiation with high-altitude mirrors or with atmospheric aerosols. Enhanced CO_2 absorption from the atmosphere through ocean fertilization with iron has also been proposed and tested (Robock et al., 2009; Royal Society, 2009).

There are multiple combinations of these means that can reduce the extent of global warming. A comprehensive evaluation of any portfolio of mitigation options would involve an evaluation of their respective mitigation potential as well as all associated risks, costs and their contribution to sustainable development. This report focuses on substitution of fossil fuels with low-carbon RE to reduce GHGs, and examines the competition between RE and other options to address global climate change (see Figure 1.14).

Setting a climate protection goal in terms of the admissible change in global mean temperature broadly defines (depending on the assumed climate sensitivity) a corresponding atmospheric CO_2 concentration limit and an associated carbon budget over the long term (see Figure 1.5, right panel) (Meinshausen et al., 2009). This budget, in turn, can be broadly translated into a time-dependent emission trajectory that serves as an upper bound or (if the remaining time flexibility is taken into account) in an associated corridor of admissible emissions (Figure 1.5, left panel). Subtracting any expected CO_2 emissions from land use change and land cover change constrains the admissible CO_2 emissions that could be realized by freely emitting carbon fuels (i.e., coal, oil, and gas burned without applying carbon capture technologies).

The corresponding fossil fuel supply is part of the total primary energy supply (see Figure 1.14). The remainder of the TPES is provided by zero- or low-carbon energy technologies, such as RE, nuclear or the combustion of fossil fuels combined with CCS (Clarke et al., 2009).

Whereas the admissible amount of freely emitting fossil fuels is mainly fixed by the climate protection goal, the complementary contribution of zero- or low-carbon energies to the primary energy supply is influenced by the 'scale' of the requested energy services and the overall efficiency with which these services can be provided.

As Figure 1.2 right panel clearly shows, the energy intensity is already expected to decrease significantly in the non-intervention scenarios. Technical improvements and structural changes are expected to result in considerably lower emissions than otherwise would be projected. As many low-cost options to improve the overall energy efficiency are

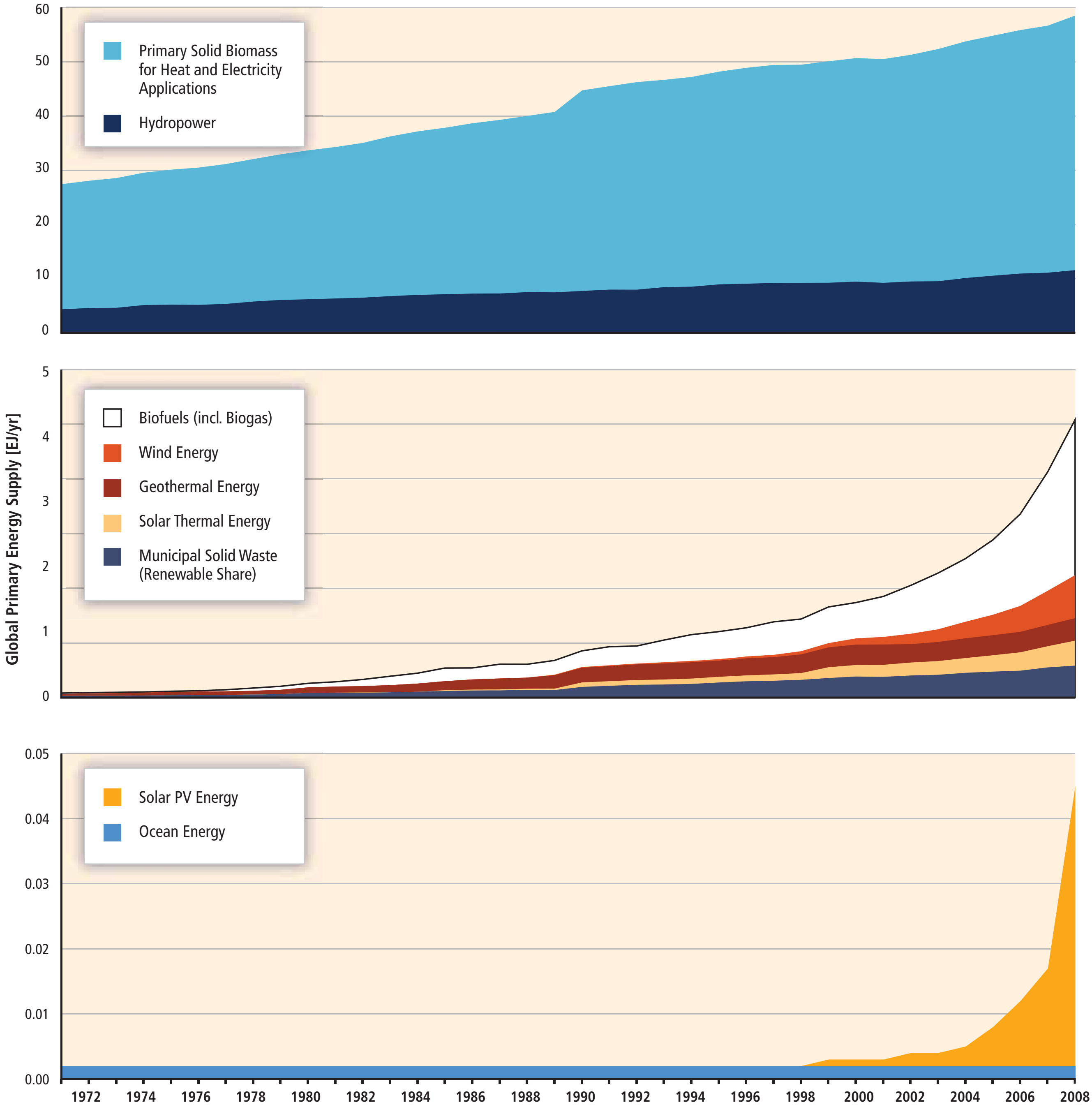


Figure 1.12 | Historical development of global primary energy supply from renewable energy from 1971 to 2008. Data Source: IEA (2010a).

Note: Technologies are referenced to separate vertical units for display purposes only. Underlying data for figure have been converted to the 'direct equivalent' method of accounting for primary energy supply (Section 1.1.9 and Annex II.4), except that the energy content of biofuels is reported in secondary energy terms (the primary biomass used to produce the biofuel would be higher due to conversion losses (Sections 2.3 and 2.4)).

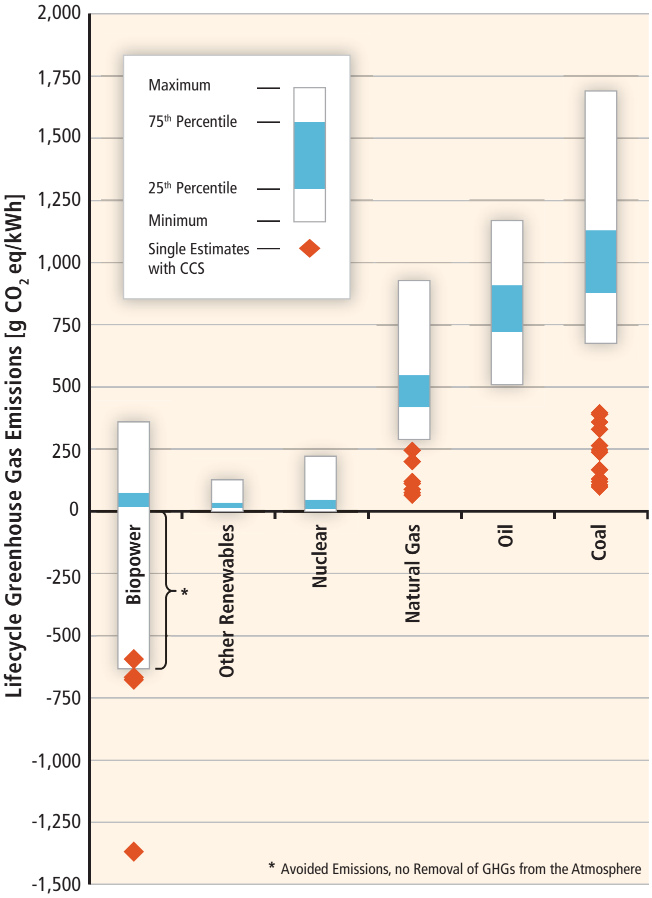


Figure 1.13 | Lifecycle GHG emissions of renewable energy, nuclear energy and fossil fuels (Chapter 9, Figure 9.8).

already part of the non-intervention scenarios (Fisher et al., 2007), the *additional* opportunities to decrease energy intensity in order to mitigate climate change are limited (Bruckner et al., 2010). In order to achieve ambitious climate protection goals, for example, stabilization below the aforementioned 2°C global mean temperature change, energy efficiency improvements alone do not suffice. In addition, low-carbon technologies become imperative.

Chapter 10 includes a comprehensive analysis of over 100 scenarios of energy supply and demand to assess the costs and benefits of RE options to reduce GHG emissions and thereby mitigate climate change. The contribution RE will provide within the portfolio of these low-carbon technologies heavily depends on the economic competition between these technologies (Chapter 10), a comparison of the relative environmental burdens (beyond climate change) associated with them, as well as secure energy supply and societal aspects (Figure 1.14). However, even without a push for climate change mitigation, scenarios that are examined in this report find that the increasing demand for energy services is expected to drive RE to levels exceeding today's energy usage. There are large uncertainties in projections, including economic and population growth, development and deployment of higher efficiency technologies, the ability of RE technologies to overcome initial cost barriers, preferences, environmental considerations and other barriers.

1.1.7 Trends in international policy on renewable energy

The international community's discussions of RE began with the fuel crises of the 1970s, when many countries began exploring alternative energy sources. Since then, RE has featured prominently in the United Nations agenda on environment and development through various initiatives and actions (WIREC, 2008; Hirschl, 2009).

The 1981 UN Conference on New and Renewable Sources of Energy adopted the Nairobi Programme of Action. The 1992 UN Conference on Environment and Development, and Action Plan for implementing sustainable development through sustainable energy and protection of the atmosphere was reinforced by the 2002 World Summit on Sustainable Development where several RE Partnerships were signed. 'Energy for Sustainable Development' highlighted the importance of RE at the 2001 UN Commission on Sustainable Development (CSD, 2001). Major RE meetings were held in Bonn in 2004, Beijing in 2005 and in Washington, DC, in 2008.

The International Energy Agency (IEA) has provided a forum for discussing energy issues among OECD countries, and provides annual reports on all forms of energy including RE. The IEA also prepares scenarios of alternative futures utilizing differing combinations of primary energy

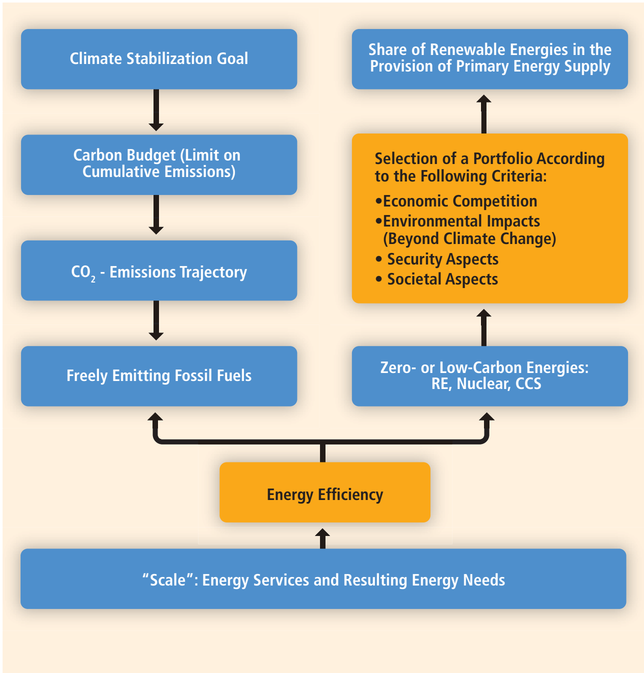


Figure 1.14 | The role of renewable energies within the portfolio of zero- or low-carbon mitigation options (qualitative description).

sources, energy efficiency and CO_2 emissions. REN 21, a nongovernmental organization, compiles recent data on RE resources based upon industrial and governmental reports. A new international organization, the International Renewable Energy Agency (IRENA), was also established in 2009 and has 149 signatories and 57 member countries[7].

1.1.8 Advancing knowledge about renewable energy

The body of scientific knowledge on RE and on the possible contribution of RE towards meeting GHG mitigation goals, as compiled and assessed in this report, is substantial. Nonetheless, due in part to the site-specific nature of RE, the diversity of RE technologies, the multiple end-use energy service needs that those technologies might serve, the range of markets and regulations governing integration, and the complexity of energy system transitions, knowledge about RE and its climate mitigation potential continues to advance. Additional knowledge remains to be gained in a number of broad areas related to RE and its possible role in GHG emissions reductions.

Though much is already known in each of these areas, as compiled in this report, additional research and experience would further reduce uncertainties and thus facilitate decision making related to the use of RE in the mitigation of climate change.

Though not comprehensive, a broad and selective listing of areas of anticipated present and future knowledge advancement is provided in Table 1.1.

1.1.9 Metrics and definitions

A glossary of terms is provided in Annex I. Conventions, conversion factors and methodologies are described in Annex II. A cost table for RE technologies is provided in Annex III.

To have a common comparison for all low-carbon sources, primary energy is measured according to the direct equivalent method rather than the physical content method favoured by IEA. The two methods treat all combustion technologies the same, but the direct equivalent method only counts the electric or thermal energy that is produced as primary energy for nuclear power or geothermal power, while the physical content method counts the total heat that is released. See Box 1.1 and Annex II where the differences between these methods are described in further detail.

7 See www.irena.org/

1.2 Summary of renewable energy resources

1.2.1 Definition, conversion and application of renewable energy

Renewable energy is any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. RE is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes resources such as biomass, solar energy, geothermal heat, hydropower, tide and waves and ocean thermal energy, and wind energy. However, it is possible to utilize biomass at a greater rate than it can grow, or to draw heat from a geothermal field at a faster rate than heat flows can replenish it. On the other hand, the rate of utilization of direct solar energy has no bearing on the rate at which it reaches the Earth. Fossil fuels (coal, oil, natural gas) do not fall under this definition, as they are not replenished within a time frame that is short relative to their rate of utilization.

There is a multi-step process whereby primary energy is converted into an energy carrier (heat, electricity or mechanical work), and then into an energy service. RE technologies are diverse and can serve the full range of energy service needs. Various types of RE can supply electricity, thermal energy and mechanical energy, as well as produce fuels that are able to satisfy multiple energy service needs (Figure 1.16).

Since it is energy services and not energy that people need, the goal is to meet those needs in an efficient manner that requires less primary energy consumption with low-carbon technologies that minimize CO_2 emissions (Haas et al., 2008). Thermal conversion processes to produce electricity (including from biomass and geothermal) suffer losses of approximately 40 to 90%, and losses of around 80% occur when supplying the mechanical energy needed for transport based on internal combustion engines. These conversion losses raise the share of primary energy from fossil fuels, and the primary energy required from fossil fuels to produce electricity and mechanical energy from heat (Jacobson, 2009; LLNL, 2009; Sterner, 2009). Direct energy conversions from solar PV, hydro, ocean, and wind energy to electricity do not suffer thermodynamic power cycle (heat to work) losses although they do experience other conversion inefficiencies in extracting energy from natural energy flows that may also be relatively large and irreducible (Chapters 2 through 7). To better compare low-carbon sources that produce electricity over time, this report has adopted the *direct equivalent method* in which primary energy of *all non-combustible sources* is defined as one unit of secondary energy, for example, electricity,

Table 1.1 | Select areas of possible future knowledge advancement

Future cost and timing of RE deployment	• Cost of emerging and non-electricity RE technologies, in diverse regional contexts • Future cost reduction given uncertainty in research and development (R&D)-driven advances and deployment-oriented learning • Cost of competing conventional and low-carbon energy technologies • Ability to analyze variable and location-dependent RE technologies in large-scale energy models, including the contribution of RE towards sustainable development and energy access • Further assessments of RE deployment potentials at global, regional and local scales • Analysis of technology-specific mitigation potential through comparative scenario exercises considering uncertainties • Impacts of policies, barriers and enabling environments on deployment volume and timing
Realizable technical potential for RE at all geographic scales	• Regional/local RE resource assessments • Improved resource assessments for emerging technologies and non-electricity RE technologies • Future impacts of climate change on RE technical potential • Competition for RE resources, such as biomass, between RE technologies and other human activities and needs • Location of RE resources relative to the location of energy demand (i.e., population centres)
Technical and institutional challenges and costs of integrating diverse RE technologies into energy systems and markets	• Comparative assessment of the short- and long-term technical/institutional solutions and costs of integrating high penetrations of RE • Specific technical/institutional challenges of integrating variable RE into electricity markets that differ from those of the OECD, for RE resources other than wind, and the challenges and costs of cycling coal and nuclear plants • Benefits and costs of combining multiple RE sources for the purpose of integration into energy markets • Institutional and technical barriers to integrating RE into heating and transport networks • Impacts of possible future changes in energy systems (including more or less centralization or decentralization, degree of demand response, and the level of integration of the electricity sector with the presently distinct heating and transport sectors) on integration challenges and cost
Comprehensive assessment of socioeconomic and environmental aspects of RE and other energy technologies	• Net lifecycle carbon emissions of certain RE technologies (e.g., some forms of bioenergy, hydropower) • Assessment of local and regional impacts on ecosystems and the environment • Assessment of local and regional impacts on human activities and well-being • Balancing widely varying positive and negative impacts over different geographic and temporal scales • Policies to effectively minimize and manage negative impacts, and realize positive benefits • Understanding and methods to address public acceptance concerns of local communities
Opportunities for meeting the needs of developing countries with sustainable RE services	• Impacts of RE deployment on multiple indicators of sustainable development • Regional/local RE resource assessments in developing countries • Advantages and limitations of improving energy access with decentralized forms of RE • Local human resource needs to ensure effective use of RE technologies • Financing mechanisms and investment tools to ensure affordability • Effective capacity building, as well as technology and knowledge transfer
Policy, institutional and financial mechanisms to enable cost-effective deployment of RE in a wide variety of contexts	• The combination of policies that are most efficient and effective for deploying different RE technologies in different countries. • How to address equity concerns while encouraging significant increases in RE investment. • How to design a policy such that potential co-benefits of RE deployment are maximized, for example security, equity and environmental benefits • Optimizing the balance of design and of timing of RE-specific versus carbon-pricing policies to take best advantage of the synergies between these two policy types. • Finding the most effective way to overcome the inherent advantage of current energy technologies including regulations and standards that lock-out RE technologies and what needs to change in order to allow RE to penetrate the energy system

Box 1.1 | Implications of different primary energy accounting conventions for energy and emission scenarios.

Primary energy for combustible energy sources is defined as the heat released when it is burned in air. As discussed in Annex II (A.II.4) and Table 1.A.1, there is no single, unambiguous accounting method for calculating primary energy from non-combustible energy sources such as nuclear energy and all RE sources with the exception of bioenergy. The *direct equivalent method* is used throughout this report. The direct equivalent method treats all non-combustible energy sources in an identical way by counting one unit of secondary energy provided from non-combustible sources as one unit of primary energy, that is, 1 kWh of electricity or heat is accounted for as 1 kWh = 3.6 MJ of primary energy. Depending on the type of secondary energy produced, this may lead to an understatement of the contribution of non-combustible RE and nuclear compared to bioenergy and fossil fuels by a factor of roughly 1.2 up to 3 (using indicative fossil fuel to electricity and heat conversion efficiencies of 38 and 85%, respectively). The implications of adopting the direct equivalent method in contrast to the other two most prominent methods—the physical energy content method and the substitution method—are illustrated in Figure 1.15 and Table 1.2 based on a selected climate stabilization scenario. The scenario is from Loulou et al. (2009) and is referred to as 1B3.7MAX in that publication. CO_2-equivalent concentrations of the Kyoto gases reach 550 ppm by 2100.

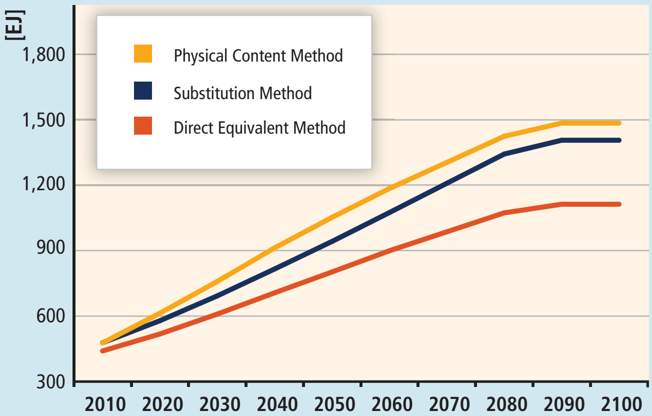


Figure 1.15 | Comparison of global total primary energy supply between 2010 and 2100 using different primary energy accounting methods based on a 550 ppm CO_2eq stabilization scenario.

Differences from applying the three accounting methods to current energy consumption remain limited. However, substantial differences arise when applying the methods to long-term scenarios when RE reaches higher shares. For the selected scenario, the accounting gap between methods grows substantially over time, reaching about 370 EJ by 2100. There are significant differences in the accounting for individual non-combustible sources by 2050, and even the share of total renewable primary energy supply varies between 24 and 37% across the three methods. The biggest absolute gap for a single source is geothermal energy, with about 200 EJ difference between the direct equivalent and the physical energy content method. The gaps for hydro and nuclear energy remain considerable. For more details on the different approaches, see Annex II.

Table 1.2 | Comparison of global total primary energy supply in 2050 using different primary energy accounting methods based on a 550 ppm CO_2eq stabilization scenario.

	Physical content method		Direct equivalent method		Substitution method	
	EJ	%	EJ	%	EJ	%
Fossil fuels	586.56	55.24	581.56	72.47	581.56	61.71
Nuclear	81.10	7.70	26.76	3.34	70.43	7.47
RE	390.08	37.05	194.15	24.19	290.37	30.81
Bioenergy	119.99	11.40	119.99	14.95	119.99	12.73
Solar	23.54	2.24	22.04	2.75	35.32	3.75
Geothermal	217.31	20.64	22.88	2.85	58.12	6.17
Hydro	23.79	2.26	23.79	2.96	62.61	6.64
Ocean	0.00	0.00	0.00	0.00	0.00	0.00
Wind	5.45	0.52	5.45	0.68	14.33	1.52
Total	1,052.75	100.00	802.47	100.00	942.36	100.00

instead of wind kinetic energy, geothermal heat, uranium fuel or solar radiation (Macknick, 2009; Nakicenovic et al., 1998). Hence any losses between the original sources and electricity are not counted in the amount of primary energy from these non-combustible sources (Annex II, A.II.4). Hence, primary energy requirements to produce a unit of electricity or other work from these sources are generally lower than for fossil fuels or biomass combustion processes.

Some RE technologies can be deployed at the point of use (decentralized) in rural and urban environments, whereas others are primarily employed within large (centralized) energy networks. Though many RE technologies are technically mature and are being deployed at significant scale, others are in an earlier phase of technical maturity and commercial deployment. The overview of RE technologies and applications in Table 1.3 provides an abbreviated list of the major renewable primary energy sources and technologies, the status of their development and the typical or primary distribution method (centralized network/grid required or decentralized, local standalone supply). The list is not considered to be comprehensive, for example, domestic animals and obtaining energy from plant biomass provide an important energy service in transportation and agriculture in many cultures but are not considered in this report. The table is constructed from the information and findings in the respective technology chapters.

1.2.2 Theoretical potential of renewable energy

The theoretical potential of RE is much greater than all of the energy that is used by all the economies on Earth. The challenge is to capture it and utilize it to provide desired energy services in a cost-effective manner. Estimated annual fluxes of RE and a comparison with fossil fuel reserves and 2008 annual consumption of 492 EJ are provided in Table 1.4.

1.2.3 Technical potential of renewable energy technologies

Technical potential is defined as the amount of RE output obtainable by full implementation of demonstrated and likely to develop technologies or practices.[8] The literature related to the technical potential of the different RE types assessed in this report varies considerably (Chapters 2 through 7 contain details and references). Among other things, this variation is due to methodological differences among studies, variant definitions of technical potential and variation due to differences between authors about how technologies and resource capture techniques may change over time. The global technical potential of RE sources will not limit continued market growth. A wide range of estimates is

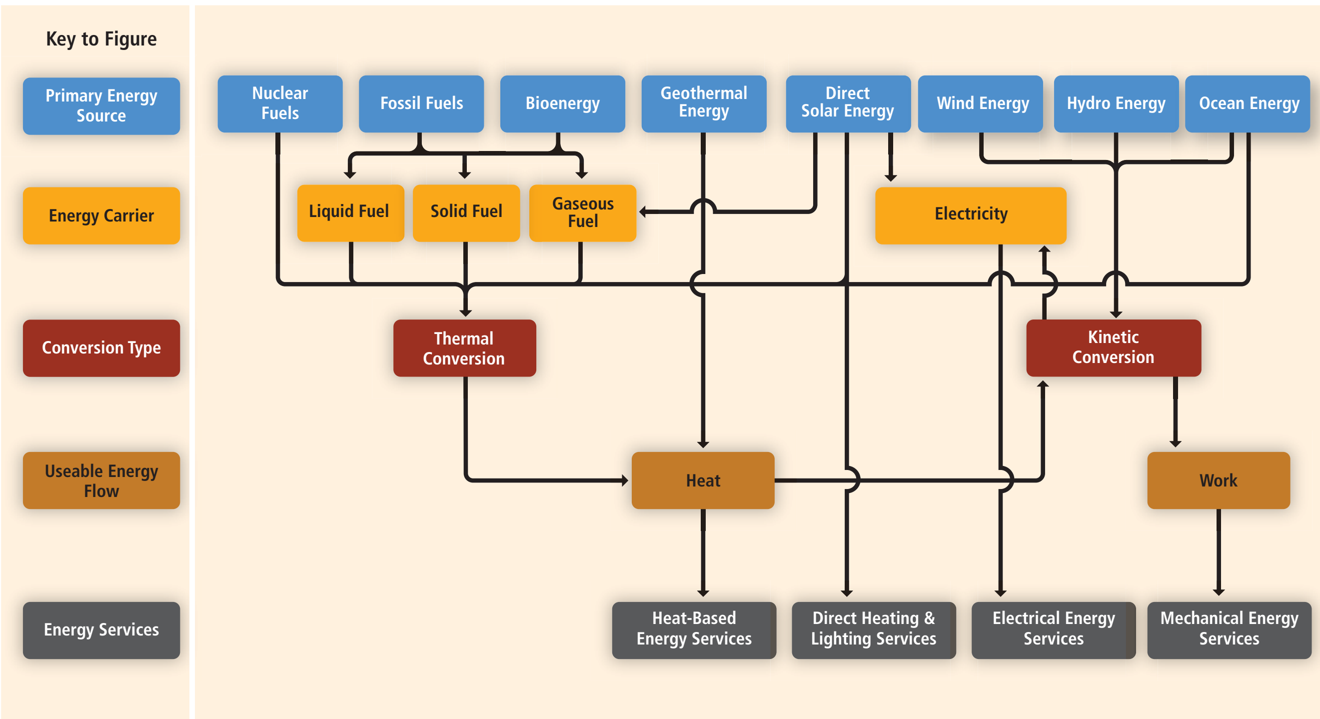


Figure 1.16 | Illustrative paths of energy from source to service. All connected lines indicate possible energy pathways. The energy services delivered to the users can be provided with differing amounts of end-use energy. This in turn can be provided with more or less primary energy from different sources, and with differing emissions of CO_2 and other environmental impacts.

8 The Glossary (Annex I) provides a more comprehensive definition of this term and of economic and market potential.

Table 1.3 | Overview of renewable energy technologies and applications (Chapters 2 through 7)

Renewable Energy Source	Select Renewable Energy Technologies	Primary Energy Sector (Electricity, Thermal, Mechanical, Transport)[1]	Technology Maturity[2]				Primary Distribution Method[3]	
			R & D	Demo & Pilot Project	Early-Stage Com'l	Later-Stage Com'l	Centralized	Decentralized
Bioenergy[4]	Traditional Use of Fuelwood/Charcoal	Thermal				●		●
	Cookstoves (Primitive and Advanced)	Thermal				●		●
	Domestic Heating Systems (pelletbased)	Thermal				●		●
	Small- and Large-Scale Boilers	Thermal				●	●	●
	Anaerobic Digestion for Biogas Production	Electricity/Thermal/Transport				●	●	●
	Combined Heat and Power (CHP)	Electricity/Thermal				●	●	●
	Co-firing in Fossil Fuel Power Plant	Electricity				●	●	
	Combustion-based Power Plant	Electricity				●	●	●
	Gasification-based Power Plant	Electricity			●		●	●
	Sugar- and Starch-Based Crop Ethanol	Transport				●	●	
	Plant- and Seed Oil-Based Biodiesel	Transport				●	●	
	Lignocellulose Sugar-Based Biofuels	Transport		●			●	
	Lignocellulose Syngas-Based Biofuels	Transport			●		●	
	Pyrolysis-Based Biofuels	Transport		●			●	
	Aquatic Plant-Derived Fuels	Transport	●				●	
	Gaseous Biofuels	Thermal				●	●	
Direct Solar	Photovoltaic (PV)	Electricity				●	●	●
	Concentrating PV (CPV)	Electricity			●		●	●
	Concentrating Solar Thermal Power (CSP)	Electricity			●		●	●
	Low Temperature Solar Thermal	Thermal				●		●
	Solar Cooling	Thermal		●				●
	Passive Solar Architecture	Thermal				●		●
	Solar Cooking	Thermal			●			●
	Solar Fuels	Transport	●				●	
Geothermal	Hydrothermal, Condensing Flash	Electricity				●	●	
	Hydrothermal, Binary Cycle	Electricity				●	●	
	Engineered Geothermal Systems (EGS)	Electricity		●			●	
	Submarine Geothermal	Electricity	●				●	
	Direct Use Applications	Thermal				●	●	●
	Geothermal Heat Pumps (GHP)	Thermal				●		●
Hydropower	Run-of-River	Electricity/Mechanical				●	●	●
	Reservoirs	Electricity				●	●	●
	Pumped Storage	Electricity				●	●	
	Hydrokinetic Turbines	Electricity/Mechanical		●			●	●
Ocean Energy	Wave	Electricity		?			?	
	Tidal Range	Electricity				?	?	
	Tidal Currents	Electricity		?			?	
	Ocean Currents	Electricity	?				?	
	Ocean Thermal Energy Conversion	Electricity/Thermal		?			?	
	Salinity Gradients	Electricity		?			?	

Continued next Page →

Renewable Energy Source	Select Renewable Energy Technologies	Primary Energy Sector (Electricity, Thermal, Mechanical, Transport)[1]	Technology Maturity[2]				Primary Distribution Method[3]	
			R & D	Demo & Pilot Project	Early-Stage Com'l	Later-Stage Com'l	Centralized	Decentralized
Wind Energy	Onshore, Large Turbines	Electricity				•	•	
	Offshore, Large Turbines	Electricity			•		•	
	Distributed, Small Turbines	Electricity				•		•
	Turbines for Water Pumping / Other Mechanical	Mechanical				•		•
	Wind Kites	Transport		•				•
	Higher-Altitude Wind Generators	Electricity	•				•	

Notes: 1. Primary energy sector as used here is intended to refer to the primary current or expected use(s) of the RE technology. In practice, RE-generated fuels may be used to meet a variety of energy service needs (not only transportation); electricity can be used to meet thermal and transportation needs; etc. 2. The highest level of maturity within each technology category is identified in the table; less mature technologies exist within some technology categories. 3. Centralized refers to energy supply that is distributed to end users through a network; decentralized refers to energy supply that is created onsite. Categorization is based on the 'primary' distribution method, recognizing that virtually all technologies can, in some circumstances, be used in both a centralized and decentralized fashion. 4. Bioenergy technologies can also be combined with CCS, though CCS technology is at an earlier stage of maturity.

Table 1.4 | Renewable energy theoretical potential expressed as annual energy fluxes of EJ/yr compared to 2008 global primary energy supply.

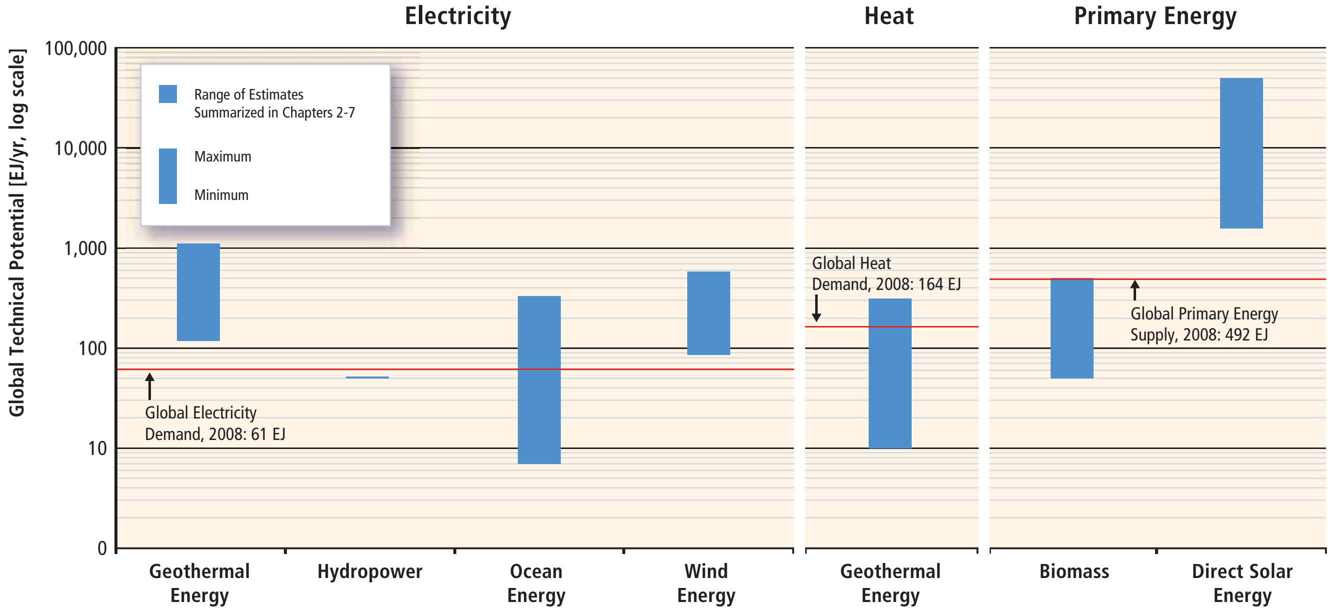
Renewable source	Annual Flux (EJ/yr)	Ratio (Annual energy flux/ 2008 primary energy supply)	Total reserve
Bioenergy	1,548[d]	3.1	—
Solar Energy	3,900,000[a]	7,900	—
Geothermal Energy	1,400[c]	2.8	—
Hydropower	147[a]	0.30	—
Ocean Energy	7,400[a]	15	—
Wind Energy	6,000[a]	12	—
Annual Primary energy source	**Annual Use 2008 (EJ/yr)**	**Lifetime of Proven Reserve (years)**	**Total Reserve (EJ)**
Total Fossil	418[b]	112	46,700
Total Uranium	10[b]	100–350	1,000–3,500
Total RE	64[b]	—	—
Primary Energy Supply	492 (2008)[b]	—	—

Sources: a. Rogner et al. (2000); b. IEA (2010c) converted to direct equivalent method (Annex II; IEA, 2010d); c. Pollack et al. (1993); d. Smeets et al. (2007).

provided in the literature but studies have consistently found that the total global technical potential for RE is substantially higher than both current and projected future global energy demand. Figure 1.17 summarizes the ranges of technical potential for the different RE technologies based on the respective chapter discussions. These ranges are compared to a comprehensive literature review by Krewitt et al. (2009) in Table 1.A.1 including more detailed notes and explanations in the Appendix to this chapter.[9] The technical potential for solar energy is the highest among the RE sources, but substantial technical potential exists for all forms of RE. According to the definition of technical potential in the Glossary (Annex I), many of the studies summarized in Table 1.A.1 to some extent take into account broader economic and socio-political considerations. For example, for some technologies, land suitability or other sustainability factors are included, which result in lower technical potential estimates. However, the absolute size of the global technical potential for RE as a whole is unlikely to constrain RE deployment.

Taking into account the uncertainty of the technical potential estimates, Figure 1.17 and Table 1.A.1 provide a perspective for the reader to understand the relative technical potential of the RE resources in the context of current global electricity and heat demand as well as of global primary energy supply. Aspects related to technology evolution, sustainability, resource availability, land use and other factors that relate to this technical potential are explored in the various

9 The definition of technical potential in Loulou et al. (2009) is similar but not identical to the definition here in that it is bounded by local/geographical availability and technological limitations associated with conversion efficiencies and the capture and transfer of the energy. See footnotes to Table 1.A.1.



Range of Estimates of Global Technical Potentials

	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Geothermal Energy	Biomass	Direct Solar Energy
Max (in EJ/yr)	1109	52	331	580	312	500	49837
Min (in EJ/yr)	118	50	7	85	10	50	1575

Figure 1.17 | Ranges of global technical potentials of RE sources derived from studies presented in Chapters 2 through 7. Biomass and solar are shown as primary energy due to their multiple uses. Note that the figure is presented in logarithmic scale due to the wide range of assessed data.

Notes: Technical potentials reported here represent total worldwide potentials for annual RE supply and do not deduct any potential that is already being utilized. Note that RE electricity sources could also be used for heating applications, whereas biomass and solar resources are reported only in primary energy terms but could be used to meet various energy service needs. Ranges are based on various methods and apply to different future years; consequently, the resulting ranges are not strictly comparable across technologies. For the data behind the figure and additional notes that apply, see Table 1.A.1 (as well as the underlying chapters).

chapters. The regional distribution of technical potential is addressed in Chapter 10.

Note also that the various types of energy cannot necessarily be added together to estimate a total, because each type was estimated independently of the others (e.g., the assessment did not take into account land use allocation; for example, PV and concentrating solar power cannot occupy the same space even though a particular site is suitable for either of them).

In addition to the theoretical and technical potential discussions, this report also considers the economic potential of RE sources that takes into account all social costs and assumes perfect information (covered in Section 10.6) and the market potential of RE sources that depends upon existing and expected real-world market conditions (covered in Section 10.3) shaped by policies, availability of capital and other factors, each of which is discussed in AR4 and defined in Annex I.

1.2.4 Special features of renewable energy with regard to integration

The costs and challenges of integrating increasing shares of RE into an existing energy supply system depend on the system characteristics, the current share of RE, the RE resources available and how the system evolves and develops in the future. Whether for electricity, heating, cooling, gaseous fuels or liquid fuels, RE integration is contextual, site specific and complex. The characteristics of RE specific to integration in existing energy networks are discussed in detail in Chapter 8.

RE can be integrated into all types of electricity systems from large, interconnected continental-scale grids (Section 8.2.1) down to small autonomous buildings (Section 1.3.1, 8.2.5). System characteristics are important, including the generation mix, network infrastructure, energy market designs and institutional rules, demand location, demand profiles, and control and communication capability. Combined with the location, distribution, variability and predictability of the RE resources, these characteristics determine the scale of the integration challenge. Partially dispatchable wind and solar energy can be more difficult to integrate than fully dispatchable hydropower, bioenergy and geothermal energy. Partly because of the geographical distribution and fixed remote locations of many RE resources, as the penetration level of RE increases, there is need for a mixture of inexpensive and effective communications systems and technologies, as well as smart meters (Section 8.2.1).

As the penetration of partially dispatchable RE electricity increases, maintaining system reliability becomes more challenging and costly. A portfolio of solutions to minimize the risks and costs of RE integration can include the development of complementary flexible generation, strengthening and extending network infrastructure and interconnections, electricity demand that can respond in relation to supply availability, energy storage technologies (including reservoir hydropower), and modified institutional arrangements including regulatory and market mechanisms (Section 8.2.1).

Integration of RE into district heating and cooling networks (Section 8.2.2), gas distribution grids (Section 8.2.3) and liquid fuel systems (Section 8.2.4) has different system requirements and challenges than those of electrical power systems. Storage is an option for heating and cooling networks that incorporate variable RE sources. For RE integration into gas distribution grids, it is important that appropriate gas quality standards are met. Various RE technologies can also be utilized directly in all end-use sectors (such as first-generation biofuels, building-integrated solar water heaters and wind power) (Section 8.3).

The full utilization of variable renewable sources such as wind and solar power can be enhanced by energy storage. Storing energy as heat is commonly practised today, and multiple means of storing electricity have been developed. Pumped water storage is a well-developed technology that can utilize existing dams to provide electricity when variable sources are not providing. Other technologies include flywheel storage of kinetic energy, compressed air storage and batteries. Battery and other storage technologies are discussed in Chapter 8. If electric vehicles become a major fraction of the fleet, it is possible to utilize their batteries in a vehicle-to-grid system for managing the variability of RE supply (Moomaw, 1991; Kempton and Tomic, 2005; Hawken et al., 2010).

1.2.5 Energy efficiency and renewable energy

Energy services are the tasks to be performed using energy. A specific energy service can be provided in many ways. Lighting, for example, may be provided by daylight, candles or oil lamps or by a multitude of different electric lamps. The efficiency of the multiple conversions of energy from primary source to final output may be high or low, and may involve the release of large or small amounts of CO_2 (under a given energy mix). Hence there are many options as to how to supply any particular service.

In this report, some specific definitions for different dimensions of efficiency are utilized.

Energy efficiency is the ratio of useful energy or other useful physical outputs obtained from a system, conversion process, transmission or storage activity to its energy input (measured as kWh/kWh, tonnes/kWh or any other physical measure of useful output like tonne-km transported, etc.). Energy efficiency can be understood as the reciprocal of energy intensity. Hence the fraction of solar, wind or fossil fuel energy that can be converted to electricity is the conversion efficiency. There are fundamental limitations on the efficiency of conversions of heat to work in an automobile engine or a steam or gas turbine, and the attained conversion efficiency is always significantly below these limits. Current supercritical coal-fired steam turbines seldom exceed a 45% conversion of heat to electric work (Bugge et al., 2006), but a combined-cycle steam and gas turbine operating at higher temperatures has achieved 60% efficiencies (Pilavachi, 2000; Najjar et al., 2004).

Energy intensity is the ratio of energy use to output. If output is expressed in physical terms (e.g., tonnes of steel output), energy intensity is the reciprocal of energy productivity or energy efficiency. Alternatively (and often more commonly), output is measured in terms of populations (i.e., per capita) or monetary units such as contribution to gross domestic product (GDP) or total value of shipments or similar terms. At the national level, energy intensity is the ratio of total domestic primary (or final) energy use to GDP. Energy intensity can be decomposed as a sum of intensities of particular activities weighted by the activities' shares of GDP. At an aggregate macro level, energy intensity stated in terms of energy per unit of GDP or in energy per capita is often used for a sector such as transportation, industry or buildings, or to refer to an entire economy.

Energy savings arise from decreasing energy intensity by changing the activities that demand energy inputs. For example, turning off lights when not needed, walking instead of taking vehicular transportation, changing the controls for heating or air conditioning to avoid excessive heating or cooling or eliminating a particular appliance and performing a task in a less energy intensive manner are all examples of energy savings (Dietz et al., 2009). Energy savings can be realized by technical, organizational, institutional and structural changes and by changed behaviour.

Studies suggest that energy savings resulting from efficiency measures are not always fully realized in practice. There may be a rebound effect in which some fraction of the measure is offset because the lower total cost of energy to perform a specific energy service may lead to utilization of more energy services. Rebound effects can be distinguished at the micro and macro level. At the micro level, a successful energy efficiency measure may be expected to lead to lower energy costs for the entity subject to the measure because it uses less energy. However, the full energy saving may not occur because a more efficient vehicle reduces the cost of operation per kilometre, so the user may drive more kilometres. Or a better-insulated home may not achieve the full saving because it is now possible to achieve greater comfort by using some of the saved energy. The analysis of this effect is filled with many methodological difficulties (Guerra and Sancho, 2010), but it is estimated that the rebound effect is probably limited by saturation effects to between 10 and 30% for home heating and vehicle use in OECD countries, and is very small for more efficient appliances and water heating (Sorrell et al., 2009). An efficiency measure that is successful in lowering economy-wide energy demand, however, lowers the price of energy as well. This leads to a decrease in economy-wide energy costs leading to additional cost savings for the entities that are subject to the efficiency measure (lower energy price and less energy use) as well as cost savings for the rest of the economy that may not be subject to the measure but benefits from the lower energy price. Studies that examine changes in energy intensity in OECD countries find that at the macro level, there is a reduction that appears related to energy efficiency gains, and any rebound effect is small (Schipper and Grubb, 2000). One analysis suggests that when all effects of lower energy prices are taken into account, there are offsetting factors that can outweigh a positive rebound effect (Turner, 2009). It is expected that the rebound effect may be greater in developing countries and among poor consumers (Orasch and Wirl, 1997). These analyses of the rebound effect do not examine whether an energy user might spend his economic savings on something other than the energy use whose efficiency was just improved (i.e., on other activities that involve either higher or lower energy intensity than the saved energy service), nor do there appear to be studies of corporate efficiency, where the savings might pass through to the bottom profit line. For climate change, the main concern with any rebound effect is its influence on CO_2 emissions, which can be addressed effectively with a price on carbon (Chapter 11).

The role of energy efficiency in combination with RE is somewhat more complex and less studied. It is necessary to examine the total cost of end-use efficiency measures plus RE technology, and then determine whether there is rebound effect for a specific case.

Furthermore, carbon leakage may also reduce the effectiveness of carbon reduction policies. Carbon leakage is defined as the increase in CO_2 emissions outside of the countries taking domestic mitigation action divided by the reduction in the emissions of these countries. If carbon reduction policies are not applied uniformly across sectors and political jurisdictions, then it is possible for carbon-emitting activities that are controlled in one place to move to another sector or country where such activities are not restricted (Kallbekken, 2007; IEA, 2008a). Recent research suggests, however, that estimates of carbon leakage are too high (Paltsev, 2001; Barker et al., 2007; Di Maria and van der Werf, 2008).

Reducing energy needed at the energy services delivery stage is an important means of reducing the primary energy required for all energy supply fuels and technologies. Because RE sources usually have a lower power density than fossil or nuclear fuels, energy savings at the end-use stage are often required to utilize a RE technology for a specific energy service (Twidell and Weir, 2005). For example, it may not be possible to fuel all vehicles on the planet with biofuels at their current low engine efficiencies, but if vehicle fuel efficiency were greater, a larger fraction of vehicles could be run on biofuels. Similarly, by lowering demand, the size and cost of a distributed solar system may become competitive (Rezaie et al., 2011). The importance of end-use efficiency in buildings in order for renewable technology to be a viable option has been documented (Frankl et al., 1998). Furthermore, electricity distribution and management is simplified and system balancing costs are lower if the energy demands are smaller (see Chapter 8). Energy efficiency at the end-use stage thus facilitates the use of RE.

Often the lowest cost option is to reduce end-use energy demand through efficiency measures, which include both new technologies and more efficient practices (Hamada et al., 2001; Venema and Rehman, 2007; Ambrose, 2009; Harvey, 2009). Examples can be found in efficient appliances for lighting, as well as heating and cooling in the building sector. For example, compact fluorescent or light-emitting diode lamps use much less electricity to produce a lumen of light than does a traditional incandescent lamp (Mehta et al., 2008). Properly sized variable-speed electric motors and improved efficiency compressors for refrigerators, air conditioners and heat pumps can lower primary energy use in many applications (Ionel, 1986; Sims et al., 2007; von Weizsäcker et al., 2009). Efficient houses and small commercial buildings such as the Passivhaus design from Germany are so air tight and well insulated that they require only about one-tenth the energy of more conventional dwellings (Passivhaus, 2010). Energy efficient design of high-rise buildings in tropical countries could reduce emissions from cooling at a substantial cost savings (Ossen et al., 2005; Ambrose, 2009).

Examples from the transportation sector include utilizing engineering improvements in traditional internal combustion engines to reduce fuel consumption rather than enhancing acceleration and performance (Ahman and Nilsson, 2008). Significant efficiency gains and substantial CO_2 emission reductions have also been achieved through the use of hybrid electric systems, battery electric systems and fuel cells (see Section 8.3.1). Biofuels become more economically feasible for aircraft as engine efficiency improves (Lee, 2010). Examples that raise energy efficiency in the power supply and industrial sectors include combined heat and power systems (Casten, 2008; Roberts, 2008), and recovery of otherwise wasted thermal or mechanical energy (Bailey and Worrell, 2005; Brown et al., 2005) thereby avoiding burning additional fuel for commercial and industrial heat. These latter examples are also applicable to enhancing the overall delivery of energy from RE such as capturing and utilizing the heat from PV or biomass electricity systems, which is done frequently in the forest products industry.

1.3 Meeting energy service needs and current status

1.3.1 Current renewable energy flows

Global renewable energy flows from primary energy through carriers to end uses and losses in 2008 (IEA, 2010a) are shown in Figure 1.18. 'RE' here includes combustible biomass, forest and crop residues and renewable municipal waste as well as the other types of RE considered in this report: direct solar (PV and solar thermal) energy, geothermal energy, hydropower, and ocean and wind energy.

'Other sectors' include agriculture, commercial and residential buildings, public services and non-specified other sectors. The 'transport sector' includes international aviation and international marine bunkers. Data for the renewable electricity and heat flows to the end-use sectors are not available. Considering that most of the renewable electricity is grid-connected, they are estimated on the assumption that their allocations to industries, transport and other sectors are proportional to those of the total electricity and heat, which are available from the IEA (IEA, 2010a).

At the global level, on average, RE supplies increased by 1.8% per annum between 1990 and 2007 (IEA, 2009b), nearly matching the growth rate in total primary energy consumption (1.9%).

Globally in 2008, around 56% of RE was used to supply heat in private households and in the public and services sector. Essentially, this refers to wood and charcoal, widely used in developing countries for cooking. On the other hand, only a small amount of RE is used in the transport sector. Electricity production accounts for 24% of the end-use consumption (IEA, 2010a). Biofuels contributed 2% of global road transport fuel supply in 2008, and traditional biomass (17%), modern biomass (8%), solar thermal and geothermal energy (2%) together fuelled 27% of the total global demand for heat in 2008 (IEA, 2010c).

1.3.2 Current cost of renewable energy

While the resource is obviously large and could theoretically supply all energy needs long into the future, the levelized cost of energy (LCOE) for many RE technologies is currently higher than existing energy prices,

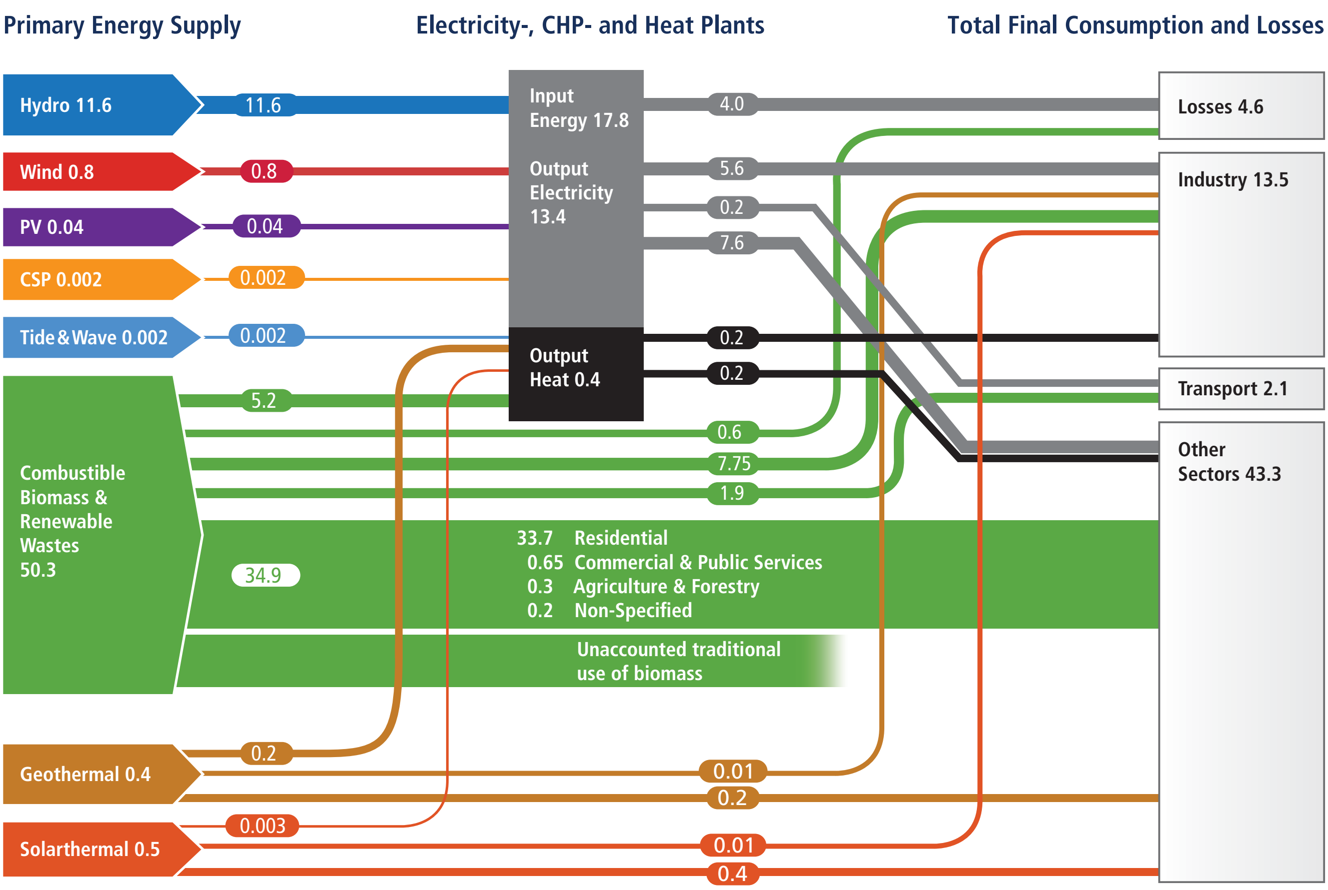


Figure 1.18 | Global energy flows (EJ) in 2008 from primary RE through carriers to end uses and losses. Data Source: (IEA, 2010a).

though in various settings RE is already economically competitive. Even though the LCOE of a particular energy technology is not the sole determinant of its value or economic competitiveness, ranges of recent LCOE are provided in this report as one of several benchmark values.[10] Figures 1.19, 1.20 and 1.21 provide a comparison of LCOE ranges associated with selected RE technologies that are currently commercially available to provide electricity, heat and transportation fuels, respectively. The ranges of recent LCOE for some of these RE technologies are wide and depend, inter alia, on technology characteristics, regional variations in cost and performance, and differing discount rates.

These cost ranges in these figures are broad and do not resolve the significant uncertainties surrounding the costs, if looked at from a very general perspective. Hence, as with the technical potential described above, the data are meant to provide context only (as opposed to precise comparison).

The levelized costs of identical technologies can vary across the globe, depending on services rendered, RE quality and local costs of investment, financing, operation and maintenance. The breadth of the ranges can be narrowed if region-, country-, project- and/or investor-specific conditions are taken into account. Chapters 2 through 7 provide some detail on the sensitivity of LCOE to such framework conditions; Section 10.5 shows the effect of the choice of the discount rate on levelized costs; and Annex III provides the full set of data and additional sensitivity analysis.

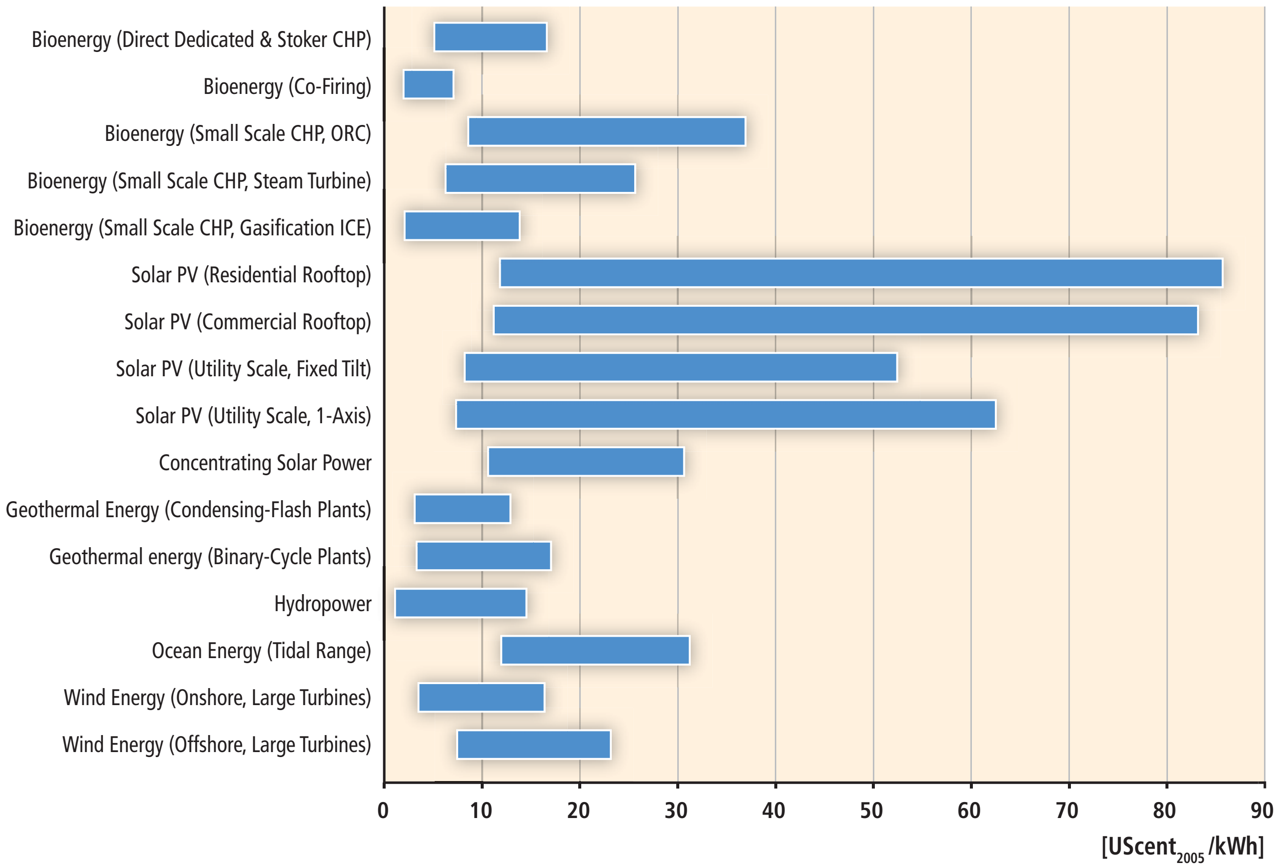


Figure 1.19 | Levelized cost of electricity (LCOE) for commercially available RE technologies covering a range of different discount rates. The LCOE estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on a 3% discount rate applied to the low ends of the ranges of investment, operations and maintenance (O&M), and (if applicable) feedstock cost and the high ends of the ranges of capacity factors and lifetimes as well as (if applicable) the high ends of the ranges of conversion efficiencies and by-product revenue. The higher bound of the levelized cost range is accordingly based on a 10% discount rate applied to the high end of the ranges of investment, O&M and (if applicable) feedstock costs and the low end of the ranges of capacity factors and lifetimes as well as (if applicable) the low ends of the ranges of conversion efficiencies and by-product revenue. Note that conversion efficiencies, by-product revenue and lifetimes were in some cases set to standard or average values. For data and supplementary information see Annex III.

10 Cost and performance data were gathered by the authors of Chapters 2 through 7 from a variety of sources in the available literature. They are based on the most recent information available in the literature. Details can be found in the respective chapters and are summarized in a data table in Annex III. All costs were assessed using standard discounting analysis at 3, 7 and 10% as described in the Annex II. A number of default assumptions about costs and performance parameters were made to define the levelized cost if data were unavailable and are also laid out in Annex III.

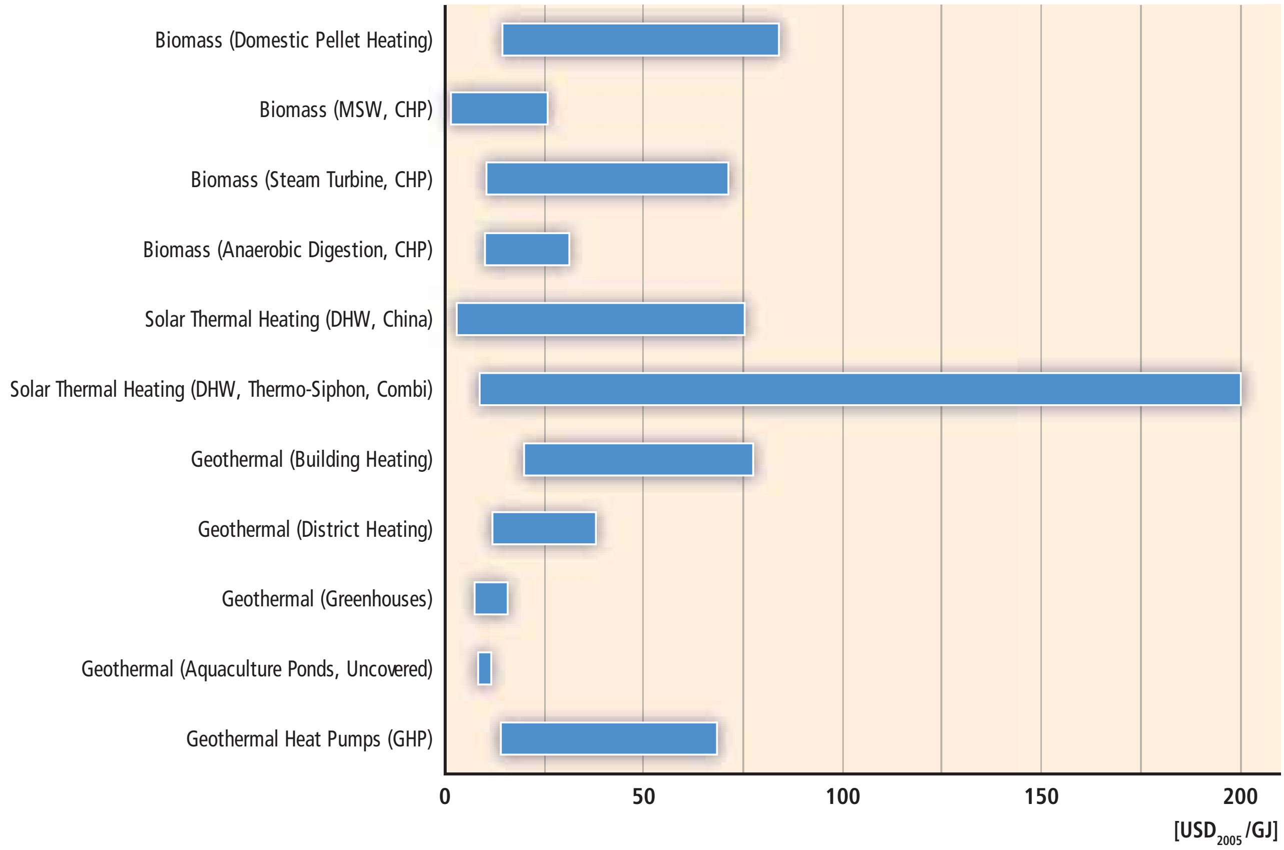


Figure 1.20 | Levelized cost of heat (LCOH) for commercially available RE technologies covering a range of different discount rates. The LCOH estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on a 3% discount rate applied to the low ends of the ranges of investment, operations and maintenance (O&M), and (if applicable) feedstock cost and the high ends of the ranges of capacity factors and lifetimes as well as (if applicable) the high ends of the ranges of conversion efficiencies and by-product revenue. The higher bound of the levelized cost range is accordingly based on a 10% discount rate applied to the high end of the ranges of investment, O&M and (if applicable) feedstock costs and the low end of the ranges of capacity factors and lifetimes as well as (if applicable) the low ends of the ranges of conversion efficiencies and by-product revenue. Note that capacity factors and lifetimes were in some cases set to standard or average values. For data and supplementary information see Annex III.

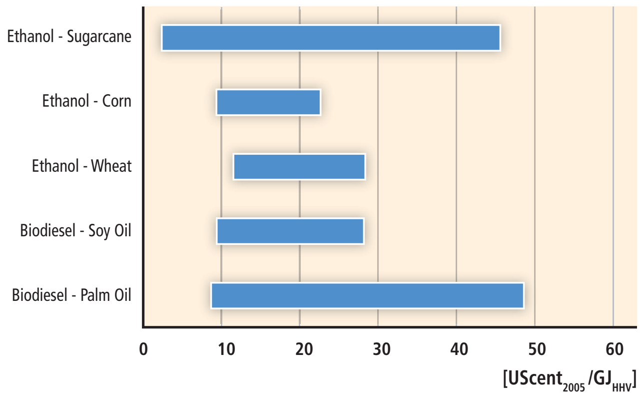


Figure 1.21 | Levelized Cost of Fuels (LCOF) for commercially available biomass conversion technologies covering a range of different discount rates. LCOF estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on a 3% discount rate applied to the low ends of the ranges of investment, operations and maintenance (O&M) and feedstock cost. The higher bound of the levelized cost range is accordingly based on a 10% discount rate applied to the high end of the ranges of investment, O&M and feedstock costs. Note that conversion efficiencies, by-product revenue, capacity factors and lifetimes were set to average values. HHV stands for 'higher heating value'. For data and supplementary information see Annex III.

Given favourable conditions, however, the lower ends of the ranges indicate that some RE technologies are broadly competitive at existing energy prices (see also Section 10.5). Monetizing the external costs of energy supply would improve the relative competitiveness of RE. The same applies if market prices increase due to other reasons (see Section 10.6). That said, these graphs provide no indication of the technical potential that can be utilized. Section 10.4 provides more information in this regard, for example, in discussing the concept of energy supply curves.

Furthermore, the levelized cost for a technology is not the sole determinant of its value or economic competitiveness. The attractiveness of a specific energy supply option depends also on broader economic as well as environmental and social aspects and the contribution that the technology makes to meeting specific energy services (e.g., peak electricity demands) or imposes in the form of ancillary costs on the energy system (e.g., the costs of integration). Chapters 8 to 11 offer important complementary perspectives on such cost issues covering, for example, the cost of integration, external costs and benefits, economy-wide costs and costs of policies.

The costs of most RE technologies have declined and additional expected technical advances would result in further cost reductions. Significant advances in RE technologies and associated long-term cost reductions have been demonstrated over the last decades, though periods of rising prices have sometimes been experienced (due to, for example, increasing demand for RE in excess of available supply) (see Section 10.5). The contribution of different drivers (e.g., R&D, economies of scale, deployment-oriented learning and increased market competition among RE suppliers) is not always understood in detail (see Sections 2.7, 3.8, 7.8, and 10.5).

Historical and potential future cost drivers are discussed in most of the technology chapters (Chapters 2 through 7) as well as in Chapter 10, including in some cases an assessment of historical learning rates and the future prospects for cost reductions under specific framework conditions. Further cost reductions are expected, resulting in greater potential deployment and consequent climate change mitigation. Examples of important areas of potential technological advancement include: new and improved feedstock production and supply systems; biofuels produced via new processes (also called next-generation or advanced biofuels, e.g., lignocellulosic) and advanced biorefining (Section 2.6); advanced PV and CSP technologies and manufacturing processes (Section 3.7); enhanced geothermal systems (EGS) (Section 4.6); multiple emerging ocean technologies (Section 6.6); and foundation and turbine designs for offshore wind energy (Section 7.7). Further cost reductions for hydropower are expected to be less significant than some of the other RE technologies, but R&D opportunities exist to make hydropower projects technically feasible in a wider range of locations and to improve the technical performance of new and existing projects (Sections 5.3, 5.7, and 5.8).

1.3.3 Regional aspects of renewable energy

The contribution of RE to primary energy supply varies substantially by country and region. Geographic distribution of RE manufacturing, use and export is now being diversified from the developed world to other developing regions, notably Asia including China (UNStats, 2010). In China, growing energy needs for solar cooking and hot water production have promoted RE development. China is now the leading producer, user and exporter of solar thermal panels for hot water production, and has been rapidly expanding its production of solar PV, most of which is exported, and has recently become the leading global producer. In terms of capacity, in 2008, China was the largest investor in thermal water heating and third in bioethanol production (REN21, 2009). China has been doubling its wind turbine installations every year since 2006, and was second in the world in installed capacity in 2009. India has also become a major producer of wind turbines and now is among the top five countries in terms of installation. In terms of installed renewable power capacity, China now leads the world followed by the USA, Germany, Spain and India (REN21, 2009, 2010).

As noted earlier, RE is more evenly distributed than fossil fuels. There are countries or regions rich in specific RE resources. Twenty-four countries utilize geothermal heat to produce electricity. The share of geothermal energy in national electricity production is above 15% in El Salvador, Kenya, the Philippines and Iceland (Bromley et al., 2010). More than 60% of primary energy is supplied by hydropower and geothermal energy in Iceland (IEA, 2010a). In some years, depending on the level of precipitation, Norway produces more hydroelectricity than it needs and exports its surplus to the rest of Europe. Brazil, New Zealand and Canada also have a high share of hydroelectricity in total electricity: 80, 65 and 60%, respectively (IEA, 2010c). Brazil relies heavily on and is the second-largest producer of bioethanol, which it produces from sugarcane (EIA, 2010; IEA, 2010e).

As regards biomass as a share of regional primary energy consumption, Africa is particularly high, with a share of 48.0%, followed by India at 26.5%, non-OECD Asia excluding China and India at 23.5%, and China at 10% (IEA, 2010a). Heat pump systems that extract stored solar energy from the air, ground or water have penetrated the market in developed countries, sometimes in combination with renewable technologies such as PV and wind. Heat pump technology is discussed in Chapter 4.

Sun-belt areas such as deserts and the Mediterranean littoral are abundant in direct normal radiation (cloudless skies) and suitable for concentrated solar thermal power plants. Export of solar- and wind-generated electricity from the countries rich in these resources could become important in the future (Desertec, 2010).

1.4 Opportunities, barriers and issues

The major global energy challenges are securing energy supply to meet growing demand, providing everybody with access to energy services and curbing energy's contribution to climate change. For developing countries, especially the poorest, energy is needed to stimulate production, income generation and social development, and to reduce the serious health problems caused by the use of fuel wood, charcoal, dung and agricultural waste. For industrialized countries, the primary reasons to encourage RE include emission reductions to mitigate climate change, secure energy supply concerns and employment creation. RE can open opportunities for addressing these multiple environmental, social and economic development dimensions, including adaptation to climate change, which is described in Section 1.4.1.

Some form of renewable resource is available everywhere in the world—for example, solar radiation, wind, falling water, waves, tides and stored ocean heat, heat from the earth or biomass—furthermore, technologies that can harness these forms of energy are available and are improving rapidly (Asif and Muneer, 2007). While the opportunities seem great and are discussed in Section 1.4.1, there are barriers (Section 1.4.2) and issues (Section 1.4.3) that slow the introduction of RE into modern economies.

1.4.1 Opportunities

Opportunities can be defined as circumstances for action with the attribute of a chance character. In the policy context, that could be the anticipation of additional benefits that may go along with the deployment of RE (and laid out below) but that are not intentionally targeted. There are four major opportunity areas that RE is well suited to address, and these are briefly described here and in more detail in Section 9.2.2. The four areas are social and economic development, energy access, energy security, and climate change mitigation and the reduction of environmental and health impacts.

1.4.1.1 Social and economic development

Globally, per capita incomes as well as broader indicators such as the Human Development Index are positively correlated with per capita energy use, and economic growth can be identified as the most relevant factor behind increasing energy consumption in the last decades. As economic activity expands and diversifies, demands for more sophisticated and flexible energy sources arise. Economic development has therefore been associated with a shift from direct combustion of fuels to higher quality electricity (Kaufmann, 2004; see Section 9.3.1).

Particularly for developing countries, the link between social and economic development and the need for modern energy services is evident. Access to clean and reliable energy constitutes an important prerequisite for fundamental determinants of human development, contributing, inter alia, to economic activity, income generation, poverty alleviation, health, education and gender equality (Kaygusuz, 2007; UNDP, 2007). Because of their decentralized nature, RE technologies can play an important role in fostering rural development (see Section 1.4.1.2).

The creation of (new) employment opportunities is seen as a positive long-term effect of RE both in developed and developing countries and was stressed in many national green-growth strategies. Also, policymakers have supported the development of domestic markets for RE as a means to gain competitive advantage in supplying international markets (see Sections 9.3.1.4 and 11.3.4).

1.4.1.2 Energy access

In 2009, more than 1.4 billion people globally lacked access to electricity, 85% of them in rural areas, and the number of people relying on traditional biomass for cooking was estimated to be around 2.7 billion (IEA, 2010c). By 2015, almost 1.2 billion more people will need access to electricity and 1.9 billion more people will need access to modern fuels to meet the Millennium Development Goal of halving the proportion of people living in poverty (UNDP/WHO, 2009).

The transition to modern energy access is referred to as moving up the energy ladder and implies a progression from traditional to more modern devices/fuels that are more environmentally benign and have fewer negative health impacts. Various initiatives, some of them based on RE, particularly in the developing countries, aim at improving universal access to modern energy services through increased access to electricity and cleaner cooking facilities (REN 21, 2009; see Sections 9.3.2 and 11.3.2). In particular, reliance on RE in rural applications, use of locally produced bioenergy to produce electricity, and access to clean cooking facilities will contribute to attainment of universal access to modern energy services (IEA, 2010d).

For electricity, small and standalone configurations of RE technologies such as PV (Chapter 3), hydropower (Chapter 5), and bioenergy (Chapter 2) can often meet energy needs of rural communities more cheaply than fossil fuel alternatives such as diesel generators. For example, PV is attractive as a source of electric power to provide basic services, such as lighting and clean drinking water. For greater local demand, small-scale hydropower or biomass combustion and gasification technologies may offer better solutions (IEA, 2010d). For bioenergy, the progression implies moving from the use of, for example, firewood, cow dung and agricultural residues to, for example, liquid propane gas stoves, RE-based advanced biomass cookstoves or biogas systems (Clancy et al., 2007; UNDP, 2005; IEA, 2010d; see Sections 2.4.2 and 9.3.2).

1.4.1.3 Energy security

At a general level, energy security can best be understood as robustness against (sudden) disruptions of energy supply. More specifically, availability and distribution of resources, as well as variability and reliability of energy supply can be identified as the two main themes.

Current energy supplies are dominated by fossil fuels (petroleum and natural gas) whose price volatility can have significant impacts, in particular for oil-importing developing countries (ESMAP, 2007). National security concerns about the geopolitical availability of fuels have also been a major driver for a number of countries to consider RE. For example, in the USA, the military has led the effort to expand and diversify fuel supplies for aviation and cites improved energy supply security as the major driving force for sustainable alternative fuels (Hileman et al., 2009; Secretary of the Air Force, 2009; USDOD, 2010).

Local RE options can contribute to energy security goals by means of diversifying energy supplies and diminishing dependence on limited suppliers, although RE-specific challenges to integration must be considered. In addition, the increased uptake of RE technologies could be an avenue to redirect foreign exchange flows away from energy imports towards imports of goods that cannot be produced locally, such as high-tech capital goods. This may be particularly important for oil-importing developing countries with high import shares (Sections 9.3.3, 9.4.3 and 11.3.3).

1.4.1.4 Climate change mitigation and reduction of environmental and health impacts

Climate change mitigation is one of the key driving forces behind a growing demand for RE technologies (see Section 11.3.1). In addition to reducing GHG emissions, RE technologies can also offer benefits with respect to air pollution and health compared to fossil fuels (see Section 9.3.4). Despite these important advantages of RE, no large-scale technology deployment comes without trade-offs, such as, for example, induced land use change. This mandates an assessment of the overall burden from the energy system on the environment and society, taking account of the broad range of impact categories with the aim of identifying possible trade-offs and potential synergies.

Lifecycle assessments facilitate a quantitative comparison of 'cradle to grave' emissions across different energy technologies (see Section 9.3.4.1). Figure 1.22 illustrates the lifecycle structure for CO_2 emission analysis, and qualitatively indicates the relative GHG implications for RE, nuclear power and fossil fuels. Alongside the commonly known CO_2 production pathways from fossil fuel combustion, natural gas production (and transportation) and coal mines are a source of methane, a potent greenhouse gas, and uncontrolled coal mine fires release significant amounts of CO_2 to the atmosphere.

Traditional biomass use results in health impacts from the high concentrations of particulate matter and carbon monoxide, among other pollutants. Long-term exposure to biomass smoke increases the risk of a child developing an acute respiratory infection and is a major cause of morbidity and mortality in developing countries (WEC/FAO, 1999).

In this context, non-combustion-based RE power generation technologies have the potential to significantly reduce local and regional air pollution and lower associated health impacts compared to fossil-based power generation. Improving traditional biomass use can reduce negative impacts on sustainable development, including local and indoor air pollution, GHG emissions, deforestation and forest degradation (see Sections 2.5.4, 9.3.4.2, 9.3.4.3 and 9.4.2).

Impacts on water resources from energy systems strongly depend on technology choice and local conditions. Electricity production with wind and solar PV, for example, requires very little water compared to thermal conversion technologies, and has no impacts on water quality. Limited water availability for cooling thermal power plants decreases their efficiency, which can affect plants operating on coal, biomass, gas, nuclear and concentrating solar power (see Section 9.3.4.4). There have been significant power reductions from nuclear and coal plants during drought conditions in the USA and France in recent years.

Surface-mined coal in particular produces major alterations of land; coal mines can create acid mine drainage and the storage of coal ash can contaminate surface and ground waters. Oil production and transportation have lead to significant land and water spills. Most renewable technologies produce lower conventional air and water pollutants than fossil fuels, but may require large amounts of land as, for example, reservoir hydropower (which can also release methane from submerged vegetation), wind energy and biofuels (see Section 9.3.4.5).

Since a degree of climate change is now inevitable, adaptation to climate change is an essential component of sustainable development (IPCC, 2007e). Adaptation can be either anticipatory or reactive to an altered climate. Some RE technologies may assist in adapting to change, and are usually anticipatory in nature. AR4 includes a chapter on the linkage between climate mitigation (reducing emissions of GHGs) and climate adaptation including the potential to assist adaptation to climate change (Klein et al., 2007a, b).

- Active and passive solar cooling of buildings helps counter the direct impacts on humans of rising mean temperatures (Chapter 3);
- Dams (used for hydropower) may also be important in managing the impacts of droughts and floods, which are projected to increase with climate change. Indeed, this is one of reasons for building such dams in the first place (Section 5.10; see also World Commission on Dams (WCD, 2000);
- Solar PV and wind require no water for their operation, and hence may become increasingly important as droughts and high river temperatures limit the power output of thermal power plants (Section 9.3.4);
- Water pumps in rural areas remote from the power grid can utilize PV (Chapter 3) or wind (Chapter 7) for raising agricultural productivity during climate-induced increases in dry seasons and droughts; and
- Tree planting and forest preservation along coasts and riverbanks is a key strategy for lessening the coastal erosion impacts of climate change. With suitable choice of species and silvicultural practices, these plantings can also yield a sustainable source of biomass for energy, for example, by coppicing (Section 2.5).

1.4.2 Barriers

A barrier was defined in the AR4 as 'any obstacle to reaching a goal, adaptation or mitigation potential that can be overcome or attenuated by a policy, programme or measure'(IPCC, 2007d; Verbruggen et al., 2010). For example, the technology as currently available may not suit the desired scale of application. This barrier could be attenuated in principle by a program of technology development (R&D).

This section describes some of the main barriers and issues to using RE for climate change mitigation, adaptation and sustainable development. As throughout this introductory chapter, the examples are illustrative and not comprehensive. Section 1.5 (briefly) and Section 11.4 (in more

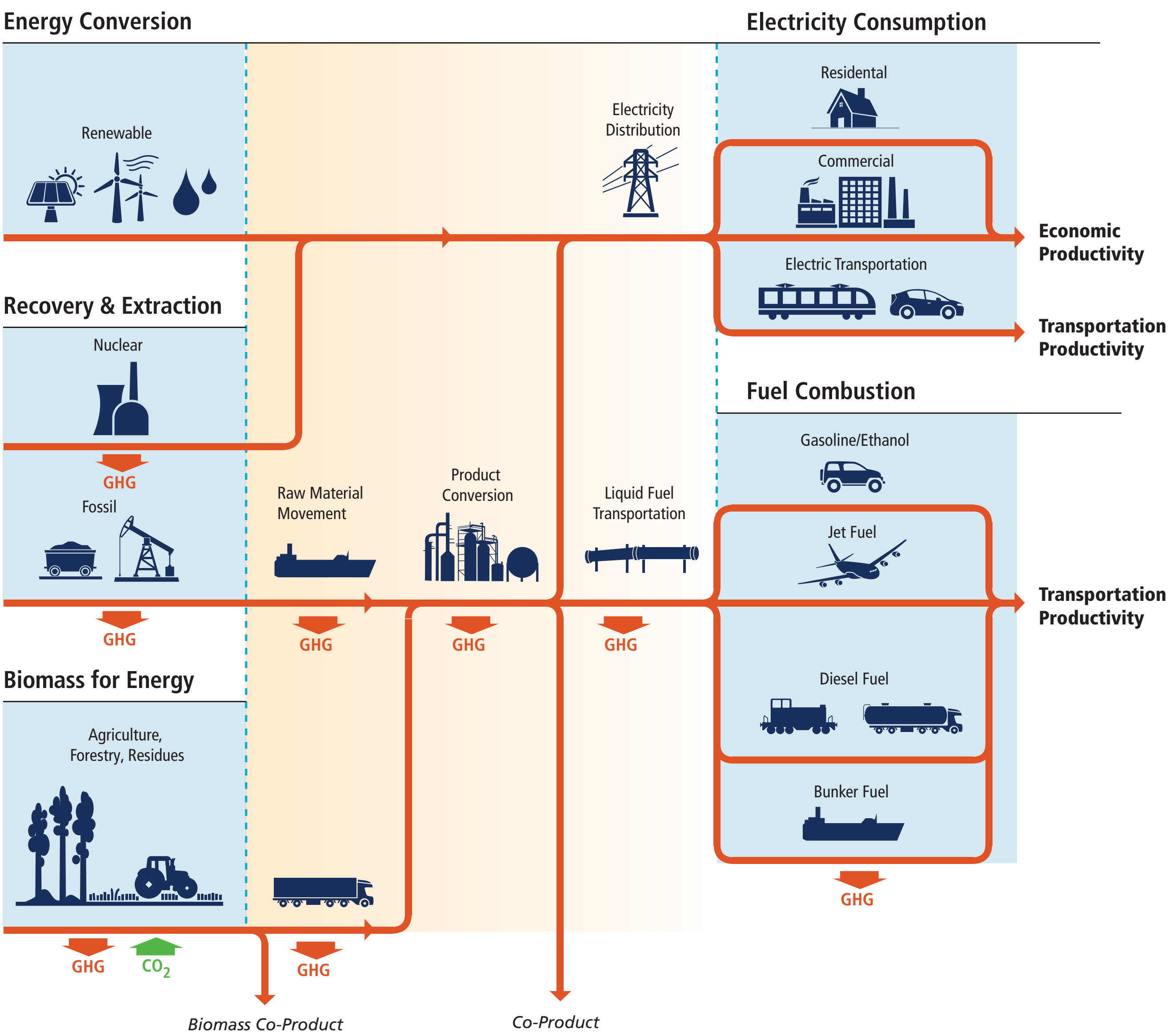


Figure 1.22 | Illustrative system for energy production and use illustrating the role of RE along with other production options. A systemic approach is needed to conduct lifecycle systems analysis.

detail) look at policies and financing mechanisms that may overcome them. When a barrier is particularly pertinent to a specific technology, it is examined in the appropriate technology chapter (i.e., Chapters 2 to 7).

The various barriers are categorized as 1) market failures and economic barriers, 2) information and awareness barriers, 3) socio-cultural barriers and 4) institutional and policy barriers (see Table 1.5). This categorization is somewhat arbitrary since, in many cases, barriers extend across several categories. More importantly, for a particular project or set of circumstances it will usually be difficult to single out one particular barrier. They are interrelated and need to be dealt with in a comprehensive manner.

1.4.2.1 Market failures and economic barriers

Market Failures

In economics a distinction is often made between *market failures* and *barriers*. With reference to the theoretical ideal market conditions (Debreu, 1959; Becker, 1971), all real-life markets fail to some degree (Bator, 1958; Meade, 1971; Williamson, 1985), evidenced by losses in welfare. Market failures (imperfections) are often due to externalities or external effects. These arise from a human activity when agents responsible for the activity do not take full account of the activity's impact on others. Externalities may be negative (external costs) or positive (external benefits). External benefits lead to an undersupply of beneficial

Table 1.5 | A categorization of barriers to RE deployment

Section	Type of barrier	Some potential policy instruments (see Chapter 11)
1.4.2.1	Market failures and economic barriers	Carbon taxes, emission trading schemes, public support for R&D, economic climate that supports investment, microfinance
1.4.2.2	Information and awareness barriers	Energy standards, information campaigns, technical training
1.4.2.3	Socio-cultural barriers	Improved processes for land use planning
1.4.2.4	Institutional and policy barriers	Enabling environment for innovation, revised technical regulations, international support for technology transfer (e.g., under the UNFCCC), liberalization of energy industries

activities (e.g., public goods) from a societal point of view because the producer is not fully rewarded. External costs lead to a too-high demand for harmful activities because the consumer does not bear the full (societal) cost. Another market failure is rent appropriation by monopolistic entities. In the case of RE deployment, these may appear as:

- Underinvestment in invention and innovation in RE technologies because initiators cannot benefit from exclusive property rights for their efforts (Margolis and Kammen, 1999; Foxon and Pearson, 2008).

- Un-priced environmental impacts and risks of energy use when economic agents have no obligation to internalize the full costs of their actions (Beck, 1995; Baumol and Oates, 1998). The release of GHG emissions and the resulting climate change is a clear example (Stern, 2007; Halsnaes et al., 2008), but the impacts and risks of some RE projects and of other low-carbon technologies (nuclear, CCS) may not always be fully priced either.

- The occurrence of monopoly (one seller) or monopsony (one buyer) powers in energy markets limits competition among suppliers or demanders and reduces opportunities for free market entry and exit (see Section 1.4.2.4). Monopoly and oligopoly power may be due to deliberate concentration, control and collusion. Regulated interconnected network industries (e.g., electric, gas and heat transmission grids) within a given area are natural monopolies because network services are least-cost when provided by a single operator (Baumol et al., 1982, p.135).

Characterizing these imperfections as market failures, with high likelihoods of welfare losses and of the impotence of market forces in clearing the imperfections, provides strong economic arguments for public policy intervention to repair the failures (Coase, 1960; Bromley, 1986). On top of imperfections classified as market failures, various factors affect the behaviour of market agents, and are categorized here as other types of barriers.

Up-front Investment Cost

The initial investment cost of a unit of RE capacity may be higher than for a non-RE energy system. Because the cost of such systems is largely up-front, it would be unaffordable to most potential customers, especially in developing countries, unless a financial mechanism is established to allow them to pay for the RE energy service month by month as they do for kerosene. Even if the initial equipment is donated by an overseas agency, such a financial mechanism is still needed to pay for the technical support, spare parts and eventual replacement of the system. Failure to have these institutional factors properly set up has been a major inhibitor to the use of RE in the Pacific Islands, where small-scale PV systems would appear to be a natural fit to the scattered tropical island communities (Johnston and Vos, 2005; Chaurey and Kandpal, 2010).

Financial risk

All power projects carry financial risk because of uncertainty in future electricity prices, regardless of its source, making it difficult for a private or public investor to anticipate future financial returns on investment. Moreover, the financial viability of an RE system strongly depends on the availability of capital and its cost (interest rates) because the initial capital cost comprises most of the economic cost of an RE system. While the predictability of such costs is a relative advantage of RE systems, many RE technologies are still in their early development phase, so that the risks related to the first commercial projects are high. The private capital market requires higher returns for such risky investments than for established technologies, raising the cost of RE projects (Gross et al., 2010; Bazilian and Roques, 2008).

An example of financial risk from an RE system outside the power sector is the development of biofuels for aviation. In 2009, neither the potential bio-jet fuel refiners nor the airlines fully understood how to structure a transaction that was credit worthy and as a result might get financed if there were interested financial institutions. (Slade et al., 2009)

1.4.2.2 Informational and awareness barriers

Deficient data about natural resources

RE is widely distributed but is site-specific in a way that fossil fuel systems are not. For example, the output of a wind turbine depends strongly on the wind regime at that place, unlike the output of a diesel generator. While broad-scale data on wind is reasonably well available from meteorological records, it takes little account of local topography, which may mean that the output of a particular turbine could be 10 to 50 % higher on top of a local hill than in the valley a few hundred metres away (Petersen et al., 1998). To obtain such site-specific data requires onsite measurement for at least a year and/or detailed modelling. Similar data deficiencies apply to most RE resources, but can be attenuated by specific programs to better measure those resources (Hammer et al., 2003).

Skilled human resources (capacity)

To develop RE resources takes skills in mechanical, chemical and electrical engineering, business management and social science, as with other energy sources. But the required skill set differs in detail for different technologies and people require specific training. Developing the skills to operate and maintain the RE 'hardware' is exceedingly important for a successful RE project (Martinot, 1998). Where these barriers are overcome as in Bangladesh, significant installations of RE systems in developing countries has occurred (Barua et al., 2001; Ashden Awards for Sustainable Energy, 2008; Mondal et al., 2010). It is also important that the user of RE technology understand the specific operational aspects and availability of the RE source. One case where this is important is in the rural areas of developing countries. Technical support for dispersed RE, such as PV systems in the rural areas of developing countries, requires many people with basic technical skill rather than a few with high technical skill as tends to be the case with conventional energy systems. Training such people and ensuring that they have ready access to spare parts requires establishment of new infrastructure.

More generally, in some developing countries, the lack of an ancillary industry for RE (such as specialized consulting, engineering and procurement, maintenance, etc.) implies higher costs for project development and is an additional barrier to deployment.

Public and institutional awareness

The oil (and gas) price peaks of 1973, 1980, 1991 and 2008 made consumers, governments and industry in both industrialized and developing counties search for alternative sources of energy. While these price surges caused some shift to coal for power production, they also generated actions to adopt more RE, especially solar, wind and biomass (Rout et al., 2008; van Ruijven and van Vuuren, 2009; Chapter 7). There is, however, limited awareness of the technical and financial issues of implementing a sustained transition to alternative primary energy sources—especially RE (Henriques and Sadorsky, 2008). The economic and transactional costs of shifting away from vulnerable and volatile fossil fuels like oil are overestimated, and there is always a shift back to these fuels once price shocks abate. The reluctance to make a shift away from a known energy source is very high because of institutional, economic and social lock-in (Unruh and Carillo-Hermosilla, 2006). One means of motivation might be a realization that the economic welfare cost of high oil prices exceeds that of effective climate polices (Viguier and Vielle, 2007).

1.4.2.3 Socio-cultural barriers

Socio-cultural barriers or concerns have different origins and are intrinsically linked to societal and personal values and norms. Such values and norms affect the perception and acceptance of RE technologies and the potential impacts of their deployment by individuals, groups and societies. Barriers may arise from inadequate attention to such socio-cultural concerns and may relate to impacts on behaviour, natural habitats and natural and human heritage sites, including impacts on biodiversity and ecosystems, landscape aesthetics, and water/land use and water/land use rights as well as their availability for competing uses (see Section 9.5.1.1).

Farmers on whose land wind farms are built rarely object; in fact they usually see turbines as a welcome extra source of income either as owners (Denmark) or as leasers of their land (USA), as they can continue to carry on agricultural and grazing activities beneath the turbines. Other forms of RE, however, preclude multiple uses of the land (Kotzebue et al., 2010). Dams for hydropower compete for recreational or scenic use of rivers (Hynes and Hanley, 2006), and the reservoirs may remove land from use for agriculture, forests or urban development. Large-scale solar or wind may conflict with other values (Simon, 2009) and may conflict with other social values of land such as nature preserves or scenic vistas (Groothuis et al., 2008; Valentine, 2010). Specific projects may also have negative implications for poor populations (Mariita, 2002). Land use can be just as contentious in some developing countries. In Papua New Guinea, for example, villagers may insist on being paid for the use of their land, for example, for a mini-hydro system of which they are the sole beneficiaries (Johnston and Vos, 2005).

Hence, social acceptance is an important element in the need to rapidly and significantly scale up RE deployment to help meet climate change mitigation goals, as large-scale implementation can only be successfully undertaken with the understanding and support of the public. Social acceptance of RE is generally increasing; having domestic solar energy PV or domestic hot water systems on one's roof has become a mark of the owner's environmental commitment (Bruce et al., 2009). However, wind farms still have to battle local opposition before they can be established (Pasqualetti et al., 2002; Klick and Smith, 2010; Webler and Tuler, 2010) and there is opposition to aboveground transmission lines from larger-scale renewable generation facilities (as well as from conventional power sources) (Furby et al., 1988; Hirst and Kirby, 2001; Gerlach, 2004; Vajjhala and Fischbeck, 2007; Puga and Lesser, 2009).

To overcome such barriers may require dedicated communication efforts related to such subjective and psychological aspects as well as the more objective opportunities associated with wider-scale applications of RE technologies. At the same time, public participation in planning decisions as well as fairness and equity considerations in the distribution of the benefits and costs of RE deployment play an equally important role and cannot be side-stepped (see Section 9.5.2). See Chapters 7 and 11 for more discussion of how such local planning issues impact the uptake of RE. Chapter 11 also includes a wider discussion of the enabling social and institutional environment required for the transition to RE systems. Opposition to unwanted projects can be influenced by policies but social acceptance may be slow to change.

1.4.2.4 Institutional and policy barriers

Existing industry, infrastructure and energy market regulation
Apart from constituting a market failure (see above), monopoly power can be perceived as an institutional barrier if not addressed adequately by energy market regulation.

The energy industry in most countries is based on a small number of companies (sometimes only one in a particular segment such as electricity or gas supply) operating a highly centralized infrastructure. These systems evolved as vertically integrated monopolies that may become committed to large conventional central power facilities supported by policies to ensure they deliver affordable and reliable electricity or gas. They are sometimes unreceptive to distributed smaller supply technologies (World Bank, 2006).

Therefore, regulations governing energy businesses in many countries are still designed around monopoly or near-monopoly providers and technical regulations and standards have evolved under the assumption that energy systems are large and centralized and of high power density and/or high voltage, and may therefore be unnecessarily restrictive for RE systems. In the process of historical development, most of the rules governing sea lanes and coastal areas were written long before offshore wind power and ocean energy systems were being developed and do not consider the possibility of multiple uses that include such systems (See Chapter 7).

Liberalization of energy markets occurred in several countries in the 1990s and more extensively in Europe in the past decade. Some of these changes in regulations allow independent power producers to operate, although in the USA many smaller proposed RE projects were often excluded due to the scales required by regulation (Markard and Truffer, 2006). In many countries, current regulations remain that protect the dominant centralized production, transmission and distribution system and make the introduction of alternative technologies, including RE, difficult. An examination and modification of existing laws and regulations is a first step in the introduction of RE technologies, especially for integrating them into the electric power system (Casten, 2008).

In addition to regulations that address the power generation sector, local building codes sometimes prevent the installation of rooftop solar panels or the introduction of wind turbines for aesthetic or historical preservation reasons (Bronin, 2009; Kooles, 2009).

Intellectual property rights
Intellectual property rights play a complex and conflicting role. Technological development of RE has been rapid in recent years, particularly in PV and wind power (Lior, 2010; see Chapters 8 and 11). Much of the basic technology is in the public domain, which can lead to underinvestment in the industry. Patents protect many of these new developments thereby promoting more private investment in R&D (Beck, 1995; Baumol and Oates, 1998). Countering this benefit are concerns that have been raised that patents may unduly restrict low-cost access to these new technologies by developing countries, as has happened with many new pharmaceuticals (Barton, 2007; Ockwell et al., 2010; Chapters 3 and 7). There are certainly circumstances where developing country companies need patent protection for their products as well.

Tariffs in international trade
Tariff barriers (import levies) and non-trade barriers imposed by some countries significantly reduce trade in some RE technologies. Discussions about lowering or eliminating tariffs on environmental goods and services including RE technologies have been part of the Doha round of trade negotiations since 2001. Many developing countries argue that reducing these tariffs would primarily benefit developed countries economically, and no resolution has been achieved so far. Developed countries have levied tariffs on imported biofuels, much of which originates in developing countries, thereby discouraging their wider use (Elobeid and Tokgoz, 2008; see Section 2.4.6.2).

Allocation of government financial support
Since the 1940s, governments in industrialized countries have spent considerable amounts of public money on energy-related research, development, and demonstration. By far the greatest proportion of this has been on nuclear energy systems (IEA, 2008b; see also Section 10.5). However, following the financial crisis of 2008 and 2009, some governments used part of their 'stimulus packages' to encourage RE or energy efficiency (Section 9.3.1.3). Tax write-offs for private spending have been similarly biased towards non-RE sources (e.g., in favour of oil exploration or new coal-burning systems), notwithstanding some recent tax incentives for RE (GAO, 2007; Lior, 2010). The policy rationale for government support for developing new energy systems is discussed in Section 1.5 and Chapter 11.

1.4.3 Issues

Issues are not readily amenable to policies and programs.

An issue is that the resource may be too small to be useful at a particular location or for a particular purpose. For example, the wind speed may be too low or too variable to produce reliable power, the topography may be either too flat or there may be insufficient flow to sustain low-head hydro or run-of-river systems for hydropower, or the demands of industry may be too large to be supplied by a local renewable source (Painuly, 2001).

Some renewable resources such as wind and solar are variable and may not always be available for dispatch when needed (Chapter 8). Furthermore, the energy density of many renewable sources is relatively low, so that their power levels may be insufficient on their own for some purposes such as very large-scale industrial facilities. Extensive planting for biomass production or building of large-area reservoirs can lead to displacement of forests with associated negative effects, such as the direct and indirect release of CO_2 and/or methane and soil loss (Melillo et al., 2009; Chapter 2 and Section 5.6.1).

1.5 Role of policy, research and development, deployment, scaling up and implementation strategies

An increasing number and variety of RE policies—motivated by a variety of factors—have driven escalated growth in RE technologies in recent years (Section 11.2). In addition to the reduction of CO_2 emissions, governments have enacted RE policies to meet a number of objectives, including the creation of local environmental and health benefits; facilitation of energy access, particularly for rural areas; advancement of energy security goals by diversifying the portfolio of energy technologies and resources; and improving social and economic development through potential employment opportunities. In general, energy access has been the primary driver in developing countries whereas energy security and environmental concerns have been most important in developed countries (Chapter 9 and Section 11.3).

For policymakers wishing to support the development and deployment of RE technologies for climate change mitigation goals, it is critical to consider the potential of RE to reduce emissions from a lifecycle perspective, an issue that each technology chapter addresses. For example, while the use of biofuels can offset GHG emissions from fossil fuels, direct and indirect land use changes must be also be evaluated in order to determine net benefits.[11] In some cases, this may even result in increased GHG emissions, potentially overwhelming the gains from CO_2 absorption (Fargione et al., 2008; Scharlemann and Laurance, 2008; Searchinger et al., 2008; Krewitt et al., 2009; Melillo et al., 2009). A full discussion of this effect can be found in Sections 2.5.3 and 9.3.4.

Various policies have been designed to address every stage of the development chain, involving R&D, testing, deployment, commercialization, market preparation, market penetration, maintenance and monitoring, as well as integration into the existing system. These policies are designed and implemented to overcome the barriers and markets failures discussed above (Sections 1.4.2, 11.1.1, 11.4 and 11.5).

Two key market failures are typically addressed: 1) the external costs of GHG emissions are not priced at an appropriate level; and 2) deployment of low-carbon technologies such as RE creates benefits to society beyond those captured by the innovator, leading to under-investment in such efforts (Sections 11.1 and 11.4). Implementing RE policies (i.e., those promoting exclusively RE) in addition to climate change mitigation policies (i.e., encouraging low-carbon technologies in general) can be justified if a) the negative consequences of innovation market failures should be mitigated and/or b) other goals beyond climate protections are to be addressed.

11 Note that such land use changes are not restricted to biomass based RE. For example, wind generation and hydro developments as well as surface mining for coal and storage of combustion ash also incur land use impacts.

1.5.1 Policy options: trends, experience and assessment

The focus of RE policies is shifting from a concentration almost entirely on electricity to include the heating/cooling and transportation sectors. These trends are matched by increasing success in the development of a range of RE technologies and their manufacture and implementation (see Chapters 2 through 7), as well as by a rapid increase in annual investment in RE and a diversification of financing institutions, particularly since 2004/2005 (Section 11.2.2).

Policy and decision makers approach the market in a variety of ways: level the playing field in terms of taxes and subsidies; create a regulatory environment for effective utilization of the resource; internalize externalities of all options or modify or establish prices through taxes and subsidies; create command and control regulations; provide government support for R&D; provide for government procurement priorities; or establish market oriented regulations, all of which shape the markets for new technologies. Some of these options, such as price, modify relative consumer preferences, provide a demand pull and enhance utilization for a particular technology. Others, such as government-supported R&D, attempt to create new products through supply push (Freeman and Soete, 2000; Sawin, 2001; Moore, 2002). No globally-agreed list of RE policy options or groupings exists. For the purpose of simplification, R&D and deployment policies have been organized within the following categories in this report (Section 11.5):

- **Fiscal incentives:** actors (individuals, households, companies) are granted a reduction of their contribution to the public treasury via income or other taxes;
- **Public finance:** public support for which a financial return is expected (loans, equity) or financial liability is incurred (guarantee); and
- **Regulation:** rule to guide or control conduct of those to whom it applies.

Research and development, innovation, diffusion and deployment of new low-carbon technologies create benefits to society beyond those captured by the innovator, resulting in under-investment in such efforts. Thus, government R&D can play an important role in advancing RE technologies. Not all countries can afford to support R&D with public funds, but in the majority of countries where some level of support is possible, public R&D for RE enhances the performance of nascent technologies so that they can meet the demands of initial adopters. Public R&D also improves existing technologies that already function in commercial environments. A full discussion of R&D policy options can be found in Section 11.5.2.

Public R&D investments are most effective when complemented by other policy instruments, particularly RE deployment policies that simultaneously enhance demand for new RE technologies. Together R&D and deployment policies create a positive feedback cycle, inducing private sector investment in R&D. Relatively early deployment policies in a technology's development accelerate learning through private R&D and/or through utilization and cost reduction (Section 11.5.2).The failure of many worthy technologies to move from R&D to commercialization has been coined the 'valley of death' for new products (Markham, 2002; Murphy and Edwards, 2003; IEA, 2009b; Section 11.5). Attempts to move renewable technology into mainstream markets following the oil price shocks failed in most developed countries (Roulleau and Loyd, 2008). Many of the technologies were not sufficiently developed or had not reached cost competitiveness and, once the price of oil came back down, interest in implementing these technologies faded. Solar hot water heaters were a technology that was ready for the market and with tax incentives many such systems were installed. But once the tax advantage was withdrawn, the market largely collapsed (Dixit and Pindyck, 1994).

Some policy elements have been shown to be more effective and efficient in rapidly increasing RE deployment, but there is no one-size-fits-all policy, and the mix of policies and their design and implementation vary regionally and depend on prevailing conditions. Experience shows that different policies or combinations of policies can be more effective and efficient depending on factors such as the level of technological maturity, availability of affordable capital, and the local and national RE resource base. Key policy elements include adequate value to cover costs and account for social benefits, inclusiveness and ease of administration. Further, the details of policy design and implementation—including flexibility to adjust as technologies, markets and other factors evolve—can be as important in determining effectiveness and efficiency as the specific policies that are used (Section 11.5). Transparent, sustained, consistent signals—from predictability of a specific policy, to pricing of carbon and other externalities, to long-term targets for RE—have been found to be crucial for reducing the risk of investment sufficiently to enable appropriate rates of deployment and the evolution of low-cost applications (Sections 11.2, 11.4 and 11.5).

For deployment policies with a focus on RE electricity, there is a wealth of literature assessing quantity-based (quotas, renewable portfolio standards that define the degree to which electricity generated must be from renewable sources, and tendering/bidding policies) and price-based (fixed-price and premium-price feed-in tariffs (FIT)) policies, primarily quotas and FITs, and with a focus on effectiveness and efficiency criteria. Several studies have concluded that some FITs have been effective and efficient at promoting RE electricity, mainly due to the combination of long-term fixed price or premium payments, network connections, and guaranteed purchase of all RE electricity generated. A number of studies have concluded that 'well-designed' and 'well-implemented' FITs have to date been the most efficient (defined as comparison of total support received and generation cost) and effective (ability to deliver an increase in the share of RE electricity consumed) support policies for promoting RE electricity (Ragwitz et al., 2005; Stern, 2007; de Jager and Rathmann, 2008; Section 11.5.4). Quota policies have been moderately successful in some cases. They can be effective and efficient if designed to reduce risk; for example, with long-term contracts.

An increasing number of governments are adopting fiscal incentives for RE heating and cooling. To date, fiscal incentives have been the prevalent policy in use to support RE heating and cooling, with grants the most commonly applied incentive. Obligations to use RE heat are gaining attention for their potential to encourage growth independent of public financial support (Section 11.5.5).

A range of policies has been implemented to support the deployment of RE for transport, though the vast majority of these policies and related experiences have been specific to biofuels. RE fuel mandates or blending requirements are key drivers in the development of most modern biofuel industries. Other policies include direct government payments or tax reductions. Those countries with the highest share of biofuels in transport fuel consumption have had hybrid systems that combine mandates (including penalties) with fiscal incentives (foremost tax exemptions). Policies have influenced the development of an international biofuel trade (Section 11.5.6).

There is now considerable experience with several types of policies designed to increase the use of renewable technology. Denmark became a world leader in the manufacture and deployment of large-scale wind turbines by setting long-term contracts for renewably generated electricity production (REN21, 2009). Germany and Spain (among others) have used a similar demand-pull mechanism through FITs that assured producers of RE electricity sufficiently high rates for a long and certain time period. Germany is the world's leading installer of solar PV, and in 2008 had the largest installed capacity of wind turbines (REN21, 2009). The USA has relied mostly on government subsidies for RE technologies and this supply-push approach has been less successful than demand pull (Lewis and Wiser, 2007; Butler and Neuhoff, 2008). China has encouraged renewable technology for water heating, solar PV and wind turbines by investing in these technologies directly. China is already the leading producer of solar hot water systems for both export and domestic use, and is now the largest producer of PV technology (REN 21, 2009).

One important challenge will be finding a way for RE and carbon-pricing policies to interact such that they take advantage of synergies rather than tradeoffs (Section 11.5.7). Impacts can be positive or negative, depending on policy choice, design and the level of implementation (local, regional, national or global). Negative effects would include the risk of carbon leakage and rebound effects, which need to be taken into account when designing policies. In the long term, enhancing knowledge for the implementers and regulators of RE supply technologies and processes can help reduce costs of mitigation, and putting a price on carbon can increase the competitiveness of RE (Sections 11.1.1 and 11.5.7).

1.5.2 Enabling environment

RE technologies can play a greater role if they are implemented in conjunction with 'enabling' policies. A favourable, or 'enabling', environment for RE can be created by addressing the possible interactions of a given policy with other RE policies as well as with other non-RE policies; by understanding the ability of RE developers to obtain finance and planning permission to build and site a project; by removing barriers for access to networks and markets for RE installations and output; by increasing education and awareness raising; and by enabling technology transfer. In turn, existence of an 'enabling' environment can increase the efficiency and effectiveness of policies to promote RE (Section 11.6).

1.5.2.1 Complementing renewable energy policies and non-renewable energy policies

Since all forms of RE capture and production involve spatial considerations, policies need to consider land use, employment, transportation, agricultural, water, food security, trade concerns, existing infrastructure and other sector-specific issues. Government policies that complement each other are more likely to be successful, and the design of individual RE policies will also affect the success of their coordination with other policies. Attempting to actively promote the complementarities of policies across multiple sectors—from energy to agriculture to water policy, etc.—while also considering the independent objectives of each, is not an easy task and may create win-lose and/or win-win situations, with possible trade-offs.

1.5.2.2 Providing infrastructure, networks and markets for renewable energy

Advancing RE in the electric power sector, for example, will require policies to address its integration into transmission and distribution systems both technically (Chapter 8) and institutionally (Chapter 11). The grid must be able to handle both traditional, often more central, supply as well as modern RE supply, which is often variable and distributed (Quezada et al., 2006; Cossent et al., 2009) and the governance of the system may need to be adjusted to ease or harmonize access; current regulations and laws, designed to assure the reliability of the current centralized grid, may prevent the wide-scale introduction of renewable electric generating technology.

In the transport sector, issues exist related to the necessary infrastructure for biofuels, recharging hydrogen, battery or hybrid electric vehicles that are 'fuelled' by the electric grid or from off-grid renewable electrical production (Tomic and Kempton, 2007; Sections 1.4.2.4 and 11.6.5).

Brazil has been especially effective in establishing a rural agricultural development program around sugarcane. Bioethanol produced from sugarcane in Brazil is currently responsible for about 40% of the spark ignition travel and it has been demonstrated for use in diesel buses and even in a crop duster aircraft. The bagasse, which is otherwise wasted, is gasified and used to operate gas turbines for electricity production while the 'waste' heat is used in the sugar to bioethanol refining process (Pousa et al., 2007; Searchinger et al., 2008).

1.5.3 A structural shift

If decision makers intend to increase the share of RE and, at the same time, to meet ambitious climate mitigation targets, then long-standing commitments and flexibility to learn from experience will be critical. Some analyses conclude that large, low-carbon facilities such as nuclear power, or large coal (and natural gas) plants with CCS can be scaled up rapidly enough to meet CO_2 reduction goals if they are available (MIT, 2003, 2007, 2009). Alternatively, the expansion of natural gas-fired turbines during the past few decades in North America and Europe, and the rapid growth in wind and solar technologies for electric power generation (see Figure 1.12) demonstrate that modularity and more widely distributed smaller-scale units can also scale rapidly to meet large-scale energy demands. The technological and economic potential for each of these approaches and their costs have important implications for the scale and role of RE in addressing climate change (Pilavachi, 2002; MIT, 2003, 2007, 2009; Onovwiona and Ugursal, 2006). To achieve GHG concentration stabilization levels that incorporate high shares of RE, a structural shift in today's energy systems will be required over the next few decades. Such a transition to low-carbon energy differs from previous ones (e.g., from wood to coal, or coal to oil) because the available time span is restricted to a few decades, and because RE must develop and integrate into a system constructed in the context of an existing energy structure that is very different from what might be required under higher penetration RE futures (Section 11.7 and Chapter 10).

A structural shift towards a world energy system that is mainly based on renewable energy might begin with a prominent role for energy efficiency in combination with RE; policies that extend beyond R&D to support technology deployment; the creation of an enabling environment that includes education and awareness raising; and the systematic development of integrative policies with broader sectors, including agriculture, transportation, water management and urban planning (Sections 11.6 and 11.7). The appropriate and reliable mix of instruments is even more important where energy infrastructure is not yet developed and energy demand is expected to increase significantly in the future (Section 11.7).

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Appendix to Chapter 1

Table 1. A.1 | Global technical potential of RE sources (compared to global primary energy supply in 2008 of 492 EJ).[1]

		Technical Potential (EJ/yr)					Notes and Sources for Range of Estimates and Notes on Krewitt et al. (2009) estimates
		Krewitt et al. (2009)[2]			Range of Estimates Summarized in Chapters 2-7[3]		
		2020	2030	2050	Low	High	
Electric Power (EJ/yr)	**Solar PV**[4]	1,126	1,351	1,689	1,338	14,778	Chapter 3 – Hofman et al. (2002); Hoogwijk (2004); de Vries et al. (2007). The methodology used by Krewitt et al. (2009) differs between PV and CSP; details are described in Chapter 3.
	Solar CSP[4]	5,156	6,187	8,043	248	10,791	Chapter 3 – Hofman et al. (2002); Trieb (2005); Trieb et al. (2009). The methodology used by Krewitt et al. (2009) differs between PV and CSP; details are described in Chapter 3.
	Geothermal[5]	4,5	18	45	118	1,109	Hydrothermal and EGS: Chapter 4 – EPRI (1978); Rowley (1982); Stefansson (2005); Tester et al. (2005, 2006).
	Hydropower	48	49	50	50	52	Chapter 5 – Krewitt et al. (2009); International Journal of Hydro & Dams (2010).
	Ocean[6]	66	166	331	7	331	Chapter 6 – Sims et al. (2007); Krewitt et al. (2009); technical potential estimates may not include all ocean energy technologies; Sims et al. (2007) estimate is referred to as 'exploitable estimated available energy resource'.
	Wind On-Shore	362	369	379	70	450	Chapter 7 – low estimate from WEC (1994), high estimate from Archer and Jacobson (2005) and includes 'near-shore', more recent estimates tend towards higher end of range.
	Wind Off-Shore[7]	26	36	57	15	130	Chapter 7 – low estimate from Fellows (2000), high estimate from Leutz et al. (2001), only considering relatively shallow water and near-shore applications; greater technical potential exists if one considers deeper water applications (Lu et al., 2009; Capps and Zender, 2010).
Heat (EJ/yr)	**Solar**	113	117	123	N/A	N/A	Technical potential is mainly limited by the demand for heat. Krewitt et al. (2009) base estimates on available rooftop area and only solar water heating; technical potential considering non-rooftop applications and process heat would far exceed these estimates.
	Geothermal	104	312	1,040	10	312	Hydrothermal: Chapter 4 – Stefansson (2005). Although the estimates from Krewitt et al. (2009) are also based on Stefansson (2005), Krewitt et al. (2009) assume a higher capacity factor than Chapter 4.
Primary Energy (EJ/yr)	**Solar**[8]	N/A	N/A	N/A	1,575	49,837	Total solar energy technical potential: Chapter 3 – Rogner et al. (2000)
	Biomass Energy Crops[9]	43	61	96	small	120	Dedicated biomass production on surplus agriculture and pasture lands: Chapter 2 – Dornburg et al. (2010).
					small	140	Further intensification of agriculture: Chapter 2 – Dornburg et al. (2010).
					small	70	Dedicated biomass production on marginal/degraded lands: Chapter 2 – Dornburg et al. (2010).
					small	100	More intensive forest management: Chapter 2 – Dornburg et al. (2010).
	Biomass Residues[9]	59	68	88	40	100	Agriculture and forestry residues, other organic wastes, dung etc.: Chapter 2 – Dornburg et al. (2010).
	Biomass Total[9]	***102***	***129***	***184***	***50***[10]	***500***[11]	Rounded figures based on Chapter 2 expert review of technical potential assessments.

Notes:

1 Technical potentials reported here represent total worldwide potentials for annual RE supply and do not deduct any potential that is already being utilized for energy production. In 2008, total primary energy supply from RE sources on a direct equivalent basis equalled: bioenergy (50.33 EJ); hydropower (11.55 EJ); wind (0.79 EJ); solar (0.50 EJ); geothermal (0.41 EJ); and ocean (0.002 EJ). According to the definition of technical potential in the Glossary (see Annex I), many of the studies summarized here take into some account broader economic and socio-political considerations. For example, for some technologies, land suitability or other sustainability factors are included, which result in lower technical potential estimates.

2 Technical potential estimates for 2020, 2030 and 2050 are based on a review of studies in Krewitt et al. (2009). Due to differences in methodologies and accounting methods between studies, comparison of these estimates across technologies and regions, as well as to primary energy demand, should be exercised with caution. Data presented in Chapters 2 through 7 may disagree with these figures due to differing methodologies. Krewitt et al. (2009), as well as many of the other studies reported in the table, assume that technical potential increases over time due, in part, to technological advancements.

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3 Range of estimates derives from studies presented in Chapters 2 through 7 (occasionally including some of the studies reported in the Krewitt et al. (2009) review). As a result, ranges do not always encompass the figures presented in Krewitt et al. (2009). Ranges are based on various methods and apply to different future years; consequently, as with Krewitt et al. (2009), the resulting ranges are not strictly comparable across technologies.

4 Estimates for PV and CSP in Krewitt et al. (2009) are based on different data and methodologies, which tend to significantly understate the technical potential for PV relative to CSP. In part as a result, a range for total solar energy technical potential is provided in the primary energy category based on Rogner et al. (2000). Note that this technical potential for total solar primary energy is not the sum of the three listed technologies (PV, CSP and solar heat) due to different studies used. Also note that the technical potentials for PV, CSP and solar heat listed in the table are not strictly additive due to possible competition for land among specific solar technologies.

5 Estimates for geothermal electricity in Krewitt et al. (2009) appear to largely consider only hydrothermal resources. The range of estimates presented in Chapter 4 derives from EPRI (1978), Rowley (1982), Stefansson (2005), and Tester et al. (2005, 2006) and includes both hydrothermal and EGS potential.

6 The absolute range of technical potential for ocean energy is highly uncertain, because few technical potential estimates have been conducted due to the fact that the technologies are still largely in the R&D phase and have not been commercially deployed at scale.

7 Estimates for offshore wind energy in Krewitt et al. (2009) and the range of estimates provided in the literature as presented in the table are both based on relatively shallow water and near-shore applications. Greater technical potential for offshore wind energy is found when considering deeper-water applications that might rely on floating wind turbine designs.

8 The technical potential for total solar primary energy is not the sum of the three listed technologies (PV, CSP and solar heat) due to different studies used; also note that possible competition for land among specific solar technologies makes it inappropriate to add the technical potential estimates for PV, CSP and solar heat to derive a total solar technical potential. The estimates of the total solar energy technical potential provided in the table do not differentiate between the different solar conversion technologies, but just take into account average conversion efficiency, available land area and meteorological conditions. At certain geographical locations all listed solar technologies could be used and users will decide what service they need from which technology.

9 Primary energy from biomass (in direct equivalent terms) could be used to meet electricity, thermal or transportation needs, all with a conversion loss from primary energy ranging from roughly 20 to 80%. As a result, comparisons of the technical potential for biomass in primary energy terms to the technical potentials of other RE sources in delivering secondary energy supply (i.e., electric power and heat) should be made with care.

10 The conditions under the low technical potential estimate could emerge when agricultural productivity increases stall worldwide combined with high food demand and no surplus land for energy crops being available. It is also assumed that marginal and degraded lands are not utilized and a large fraction of biomass residue flows is assumed to be used as feedstock in other sectors rather than for bioenergy. However, low-grade residues, dung and municipal waste will in such a situation likely still remain available for bioenergy.

11 The higher end of the biomass potential is conditional and assumes proper land management and substantial increases in agricultural yields and intensified forestry management. Achieving such a potential will be sustainable only if monitoring and good governance of land use is effective, and sustainability frameworks are in place.

2

Bioenergy

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Table of Contents

Executive Summary

Bioenergy has a significant greenhouse gas (GHG) mitigation potential, provided that the resources are developed sustainably and that efficient bioenergy systems are used. Certain current systems and key future options including perennial cropping systems, use of biomass residues and wastes and advanced conversion systems are able to deliver 80 to 90% emission reductions compared to the fossil energy baseline. However, land use conversion and forest management that lead to a loss of carbon stocks (direct) in addition to indirect land use change (d+iLUC) effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts. Impacts of climate change through temperature increases, rainfall pattern changes and increased frequency of extreme events will influence and interact with biomass resource potential. This interaction is still poorly understood, but it is likely to exhibit strong regional differences. Climate change impacts on biomass feedstock production exist but if global temperature rise is limited to less than 2°C compared with the pre-industrial record, it may pose few constraints. Combining adaptation measures with biomass resource production can offer more sustainable opportunities for bioenergy and perennial cropping systems.

Biomass is a primary source of food, fodder and fibre and as a renewable energy (RE) source provided about 10.2% (50.3 EJ) of global total primary energy supply (TPES) in 2008. Traditional use of wood, straws, charcoal, dung and other manures for cooking, space heating and lighting by generally poorer populations in developing countries accounts for about 30.7 EJ, and another 20 to 40% occurs in unaccounted informal sectors including charcoal production and distribution. TPES from biomass for electricity, heat, combined heat and power (CHP), and transport fuels was 11.3 EJ in 2008 compared to 9.6 EJ in 2005 and the share of modern bioenergy was 22% compared to 20.6%.

From the expert review of available scientific literature, potential deployment levels of biomass for energy by 2050 could be in the range of 100 to 300 EJ. However, there are large uncertainties in this potential such as market and policy conditions, and it strongly depends on the rate of improvement in the production of food and fodder as well as wood and pulp products.

The upper bound of the technical potential of biomass for energy may be as large as 500 EJ/yr by 2050. Reaching a substantial fraction of the technical potential will require sophisticated land and water management, large worldwide plant productivity increases, land optimization and other measures. Realizing this potential will be a major challenge, but it could make a substantial contribution to the world's primary energy supply in 2050. For comparison, the equivalent heat content of the total biomass harvested worldwide for food, fodder and fibre is about 219 EJ/yr today.

A scenario review conducted in Chapter 10 indicates that the contribution of bioenergy in GHG stabilization scenarios of different stringency can be expected to be significantly higher than today. By 2050, in the median case bioenergy contributes 120 to 155 EJ/yr to global primary energy supply, or 150 to 190 EJ/yr for the 75th percentile case, and even up to 265 to 300 EJ/yr in the highest deployment scenarios. This deployment range is roughly in line with the IPCC Special Report on Emission Scenarios (SRES) regionally oriented A2 and B2 and globally oriented A1 and B1 conditions and storylines. Success in implementing sustainability and policy frameworks that ensure good governance of land use and improvements in forestry, agricultural and livestock management could lead to both high (B1) and low (B2) potentials. However, biomass supplies may remain limited to approximately 100 EJ/yr in 2050 if such policy frameworks and enforcing mechanisms are not introduced and if there is strong competition for biomaterials from other (innovative future) sectors. In that environment, further biomass expansion could lead to significant regional conflicts for food supplies, water resources and biodiversity, and could even result in additional GHG emissions, especially due to iLUC and loss of carbon stocks. In another deployment scenario, biomass resources may be constrained to use of residues and organic waste, energy crops cultivated on marginal/degraded and poorly utilized lands, and to supplies in endowed world regions where bioenergy is a cheaper energy option compared to market alternatives (e.g., sugarcane ethanol production in Brazil).

Bioenergy has complex societal and environmental interactions, including climate change feedback, biomass production and land use. The impact of bioenergy on social and environmental issues (e.g., health, poverty, biodiversity) may be positive or negative depending on local conditions and the design and implementation of specific projects. The policy context for bioenergy, and particularly biofuels, has changed rapidly and dramatically in recent years. The food versus fuel debate and growing concerns about other conflicts are driving a strong push for the development and implementation of sustainability criteria and frameworks. Many conflicts can be reduced if not avoided by encouraging synergisms in the management of natural resource, agricultural and livestock sectors as part of good governance of land use that increases rural development and contributes to poverty alleviation and a secure energy supply.

Costs vary by world regions, feedstock types, feedstock supply costs for conversion processes, the scale of bioenergy production and production time during the year. Examples of estimated commercial bioenergy levelized cost ranges are roughly USD_{2005} 2 to 48/GJ for liquid and gaseous biofuels; roughly US $cents_{2005}$ 3.5 to 25/kWh (USD_{2005} 10 to 50/GJ) for electricity or CHP systems larger than about 2 MW (with feedstock costs of USD_{2005} $3/GJ_{feed}$ and a heat value of USD_{2005} 5/GJ for steam or USD_{2005} 12/GJ for hot water); and roughly USD_{2005} 2 to 77/GJ for domestic or district heating systems with feedstock costs in the range of USD_{2005} 0 to 20/GJ (solid waste to wood pellets). These calculations refer to 2005 to 2008 data and are expressed in USD_{2005} at a 7% discount rate.

Recent analyses of lignocellulosic biofuels indicate potential improvements that enable them to compete at oil prices of USD_{2005} 60 to 70/barrel (USD_{2005} 0.38 to 0.44/litre) assuming no revenue from carbon dioxide (CO_2) mitigation. Scenario analyses indicate that strong short-term research and development (R&D) and market support could allow for commercialization around 2020 depending on oil and carbon pricing. In addition to ethanol and biodiesel, a range of hydrocarbons and chemicals/materials similar to those currently derived from oil could provide biofuels for not only vehicles but also for the aviation and maritime sectors. Biomass is the only renewable resource that can currently provide high energy density liquid fuels. A wider variety of bio-based products can also be produced at biorefineries to enhance the economics of the overall conversion process. Short-term options (some of them already competitive) that can deliver long-term synergies include co-firing, CHP, heat generation and sugarcane-based ethanol and bioelectricity co-production. Development of working bioenergy markets and facilitation of international bioenergy trade can help achieve these synergies.

Further improvements in power generation technologies, supply systems of biomass and production of perennial cropping systems can bring bioenergy costs down. There is clear evidence that technological learning and related cost reductions occur in many biomass technologies with learning rates comparable to other RE technologies. This is true for cropping systems where improvements in agricultural management of annual crops, supply systems and logistics, conversion technologies to produce energy carriers such as heat, electricity and ethanol from sugarcane or maize, and biogas have demonstrated significant cost reductions.

Combining biomass conversion with developing carbon capture and storage (CCS) could lead to long-term substantial removal of GHGs from the atmosphere (also referred to as negative emissions). Advanced biomaterials are promising as well from both an economic and a GHG mitigation perspective, though the relative magnitude of their mitigation potential is not well understood. The potential role of aquatic biomass (algae) is highly uncertain but could reduce land use conflict. More experience, research, development and demonstration (RD&D), and detailed analyses of these options are needed.

Multiple drivers for bioenergy systems and their deployment in sustainable directions are emerging. Examples include rapidly changing policy contexts, recent market-based activities, the increasing support for advanced biorefinery and lignocellulosic biofuel options and, in particular, development of sustainability criteria and frameworks. Sustained cost reductions of key technologies in biomass production and conversion, supply infrastructure development, and integrated systems research can lead to the implementation of strategies that facilitate sustainable land and water use and gain public and political acceptance.

2.1 Introduction

Bioenergy is embedded in complex ways in global biomass systems for food, fodder and fibre production and for forest products; in wastes and residue management; and in the everyday living of the developing countries' poor. Bioenergy includes different sets of technologies for applications in various sectors.

2.1.1 Current pattern of biomass and bioenergy use and trends

Biomass provided about 10.2% (50.3 EJ/yr) of the annual global primary energy supply in 2008, from a wide variety of biomass sources feeding numerous sectors of society (see Table 2.1; IEA, 2010a). The biomass feedstocks used for energy are shown in Figure 2.1 (top), and more than 80% are derived from wood (trees, branches, residues) and shrubs. The remaining bioenergy feedstocks came from the agricultural sector (energy crops, residues and by-products) and from various commercial and post-consumer waste and by-product streams (biomass product recycling and processing or the organic biogenic fraction of municipal solid waste[1] (MSW)).

Biomass is used (see Table 2.1) with varying degrees of energy efficiency in various sectors:

- Low-efficiency *traditional biomass*[2] such as wood, straws, dung and other manures are used for cooking, lighting and space heating, generally by the poorer populations in developing countries. This biomass is mostly combusted, creating serious negative impacts on health and living conditions. Increasingly, charcoal is becoming a secondary energy carrier in rural areas. As an indicator of the magnitude of traditional biomass use, Figure 2.1 (bottom) illustrates that the global primary energy supply from traditional biomass parallels the world's industrial roundwood production.

  In the International Energy Agency's (IEA) World Energy Statistics (IEA, 2010a) and World Energy Outlook (WEO: IEA, 2010b) TPES from traditional biomass amounts to 30.7 EJ/yr based on national databases that tend to systematically underestimate fuelwood consumption. Although international forestry and energy data (FAO, 2005) are the main reference sources for policy analyses, they are

Table 2.1 | Examples of traditional and select modern biomass energy flows in 2008 according to the IEA (2010 a,b) and supplemented by Masera et al., 2005, 2006; Drigo et al., 2007, 2009.

Type	Approximate Primary Energy (EJ/yr)	Approximate Average Efficiency (%)	Approximate Secondary Energy (EJ/yr)
Traditional Biomass			
Accounted for in IEA energy statistics	30.7	10–20	3–6
Estimated for informal sectors (e.g., charcoal)	6–12		0.6–2.4
Total Traditional Biomass	37–43		3.6–8.4
Modern Bioenergy			
Electricity and CHP from biomass, MSW, and biogas	4.0	32	1.3
Heat in residential, public/commercial buildings from solid biomass and biogas	4.2	80	3.4
Road transport fuels (ethanol and biodiesel)	3.1	60	1.9
Total Modern Bioenergy	11.3	58	6.6

Notes: According to the IEA (2010a,b), the 2008 TPES from biomass of 50.3 EJ was composed primarily of solid biomass (46.9 EJ); biogenic MSW used for heat and CHP (0.58 EJ); and biogas (secondary energy) for electricity and CHP (0.41 EJ) and heating (0.33 EJ). The contribution of ethanol, biodiesel, and other biofuels (e.g., ethers) used in the transport sector amounted to 1.9 EJ in secondary energy terms. Examples of specific flows: output electricity from biomass was 0.82 EJ (biomass power plants including pulp and paper industry surplus, biogas and MSW) and output heating from CHP was 0.44 EJ. Modern residential heat consumption was calculated by subtracting the IEA estimate of traditional use of biomass (30.7 EJ) from the total residential heat consumption (33.7 EJ).

Some table numbers were taken directly from the IEA global energy statistics, such as secondary biofuels at 1.9 EJ (whereas the derived primary energy input is based on the assumed efficiency of 60% which could be lower) as well as output electricity and heat at 1.3 EJ for all feedstocks. Primary input for MSW and biogas (secondary) and the corresponding output were available and efficiencies are calculated. Solid biomass primary input was calculated from the average efficiency for MSW. Not included in the numbers above are solid biomass (3.4 EJ) used to make charcoal (1.15 EJ) for heating (0.88 EJ, traditional mostly) and industry, such as the iron/steel industry (0.22 EJ), mostly in Brazil. Heat for making charcoal is included in Figure 1.18 in the 5.2 EJ from biomass for electricity, CHP, and heat plants. Not included in Table 2.1 is the industry sector that consumed 7.7 EJ, but the electricity sold by the pulp and paper industry is included.

1 MSW is used throughout the chapter with the same meaning as the term municipal wastes as defined by EUROSTAT.

2 Traditional biomass is defined as biomass consumption in the residential sector in developing countries and refers to the often unsustainable use of wood, charcoal, agricultural residues and animal dung for cooking and heating (IEA, 2010b and Annex I). All other biomass use is defined as modern biomass; this report further differentiates between highly efficient modern bioenergy and industrial bioenergy applications with varying degrees of efficiency (Annex I). The renewability and sustainability of biomass use is primarily discussed in Sections 2.5.4 and 2.5.5, respectively (see also Section 1.2.1 and Annex I).

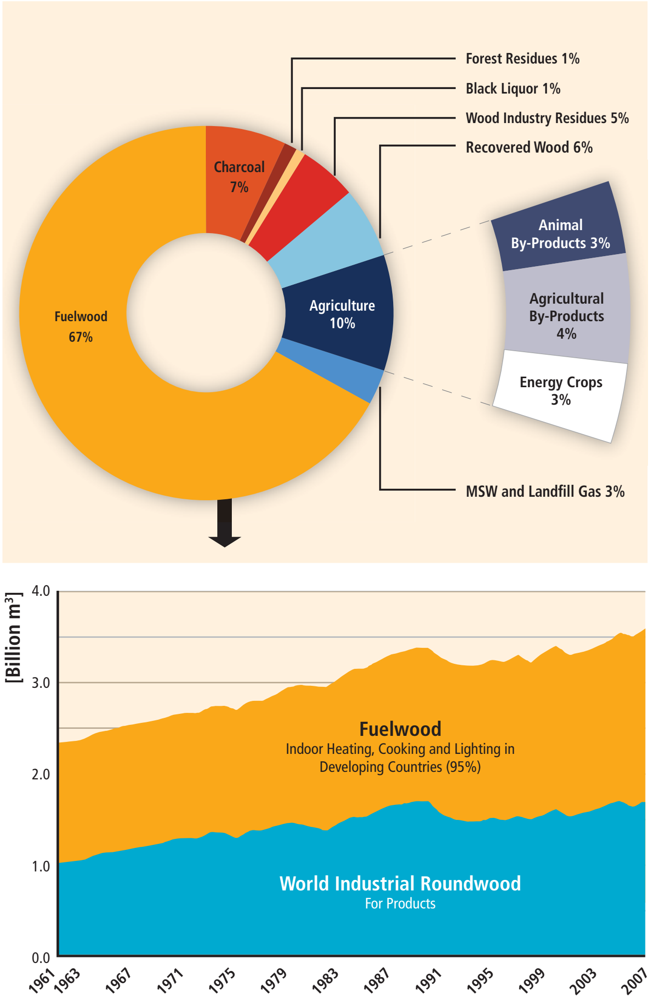

Figure 2.1 | Top: Shares of global primary biomass sources for energy (IPCC, 2007a,d; IEA Bioenergy, 2009); Bottom: Fuelwood used in developing countries parallels world industrial roundwood[1] production levels (UNECE/FAO Timber Database, 2011).

Note: 1. Roundwood products are saw logs and veneer logs for the forest products industry and wood chips that are used for making pulpwood used in paper, newsprint and Kraft paper. In 2009, reflecting the downturn in the economy, there was a decline to 3.25 (total) and 1.25 (industrial) billion m³; the data can be retrieved from a presentation on Global Forest Resources and Market Developments: timber.unece.org/fileadmin/DAM/other/GlobalResMkts300311.pdf.

often in contradiction when it comes to estimates of biomass consumption for energy, because production and trade of these solid biomass fuels are largely informal.[3] A supplement of 20 to 40% to the global TPES of biomass in Table 2.1 is based on detailed, multi-scale, spatially explicit analyses performed in more than 20 countries (e.g., Masera et al., 2005, 2006; Drigo et al., 2007, 2009). Traditional biomass is discussed in later sections on feedstock logistics and supply (Section 2.3.2.2), improved technologies, practices and barriers (Sections 2.4.2.1 and 2.4.2.2), climate change effects (Section 2.5.4) and socioeconomic aspects (Section 2.5.7).

3 See the Glossary in Annex I for a definition of informal sector/economy.

- High-efficiency *modern bioenergy* uses more convenient solids, liquids and gases as secondary energy carriers to generate heat, electricity, combined heat and power (CHP) and transport fuels for various sectors (Figure 2.2). Many entities in the process industry, municipalities, districts and cooperatives generate these energy products, in some cases for their own use, but also for sale to national and international markets in the increasingly global trade. Liquid biofuels, such as ethanol and biodiesel, are used for global road transport and some industrial uses. Biomass-derived gases, primarily methane from anaerobic digestion of agricultural residues and waste treatment streams, are used to generate electricity, heat or CHP for multiple sectors. The most important contribution to these energy services is, however, based on solids, such as chips, pellets, recovered wood previously used etc. Heating includes space and hot water heating such as in district heating systems. The estimated TPES from modern bioenergy is 11.3 EJ/yr and the secondary energy delivered to end-use consumers is roughly 6.6 EJ/yr (IEA, 2010a,b). Modern bioenergy feedstocks such as short-rotation trees (poplars or willows) and herbaceous plants (*Miscanthus* or switchgrass) are discussed in Sections 2.3.1 and 2.6.1. The discussion of modern bioenergy includes biomass logistics and supply chains (Sections 2.3.2 and 2.6.2); conversion of biomass into secondary carriers or energy through existing (Section 2.3.3) or developing (Section 2.6.3) technologies; integration into bioenergy systems and supply chains (Section 2.3.4); and market and industry development (Section 2.4).

- High energy efficiency biomass conversion is found typically in the *industry* sector (with a total consumption of ~7.7 EJ/yr) associated with the pulp and paper industry, forest products, food and chemicals. Examples are fibre products (e.g., paper), energy, wood products, and charcoal for steel manufacture. Industrial heating is primarily steam generation for industrial processes, often in conjunction with power generation. The industry sector's final consumption of biomass is not shown in Table 2.1 since it cannot be unambiguously assigned. Also see Section 8.3.4, which addresses the biomass industry sector.

Global bioenergy use has steadily grown worldwide in absolute terms in the last 40 years, with large differences among countries. In 2006, China led all countries and used 9 EJ of biomass for energy, followed by India (6 EJ), the USA (2.3 EJ) and Brazil (2 EJ) (GBEP, 2008). Bioenergy provides a relatively small but growing share of TPES (1 to 4 % in 2006) in the largest industrialized countries (grouped as the G8 countries: the USA, Canada, Germany, France, Japan, Italy, the UK and Russia). The use of solid biomass for electricity production is particularly important in pulp and paper plants and in sugar mills. Bioenergy's share in total energy consumption is generally increasing in the G8 countries through the use of modern biomass forms (e.g., co-combustion or co-firing for electricity generation, space heating with pellets) especially in Germany, Italy and the UK (see Figure 2.8; GBEP, 2008).

By contrast, in 2006, bioenergy provided 5 to 27% of TPES in the largest developing countries (China, India, Mexico, Brazil and South Africa),

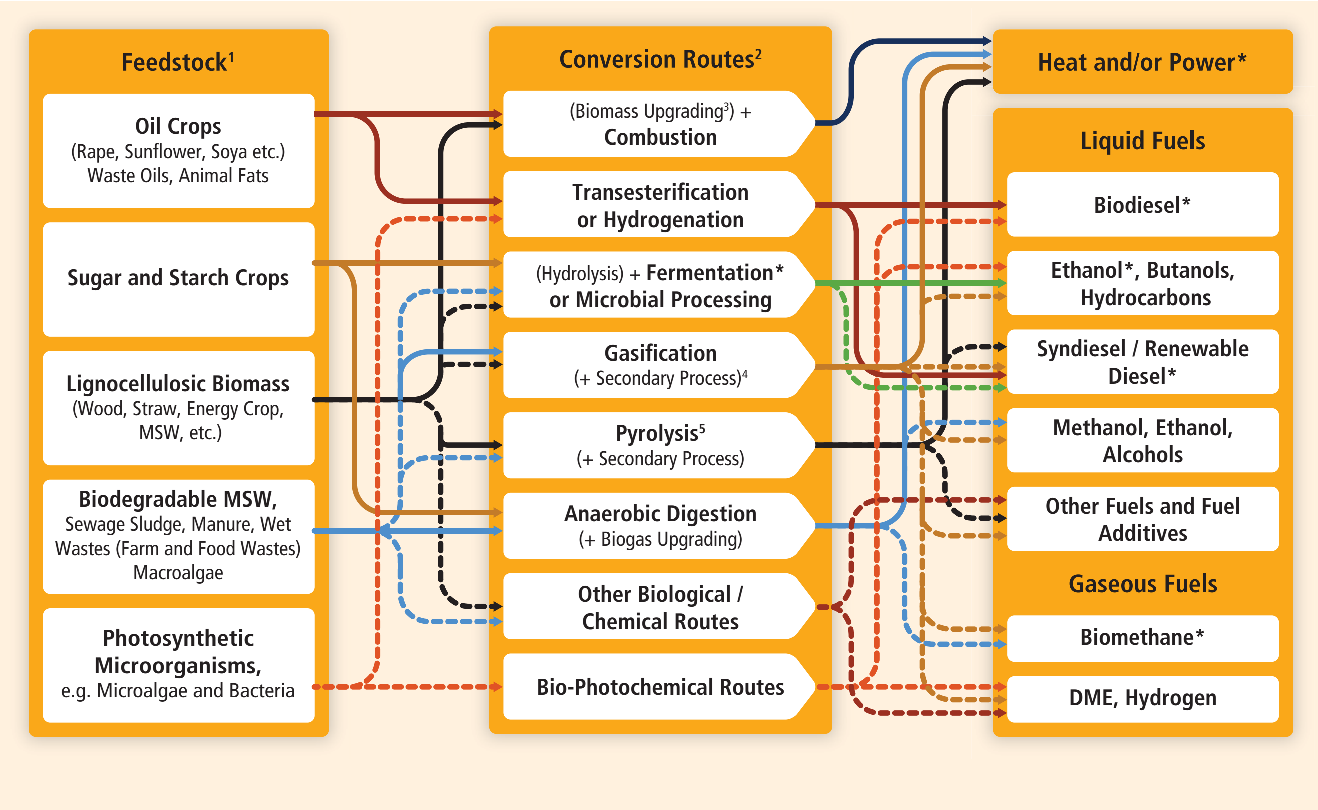

Figure 2.2 | Schematic view of the variety of commercial (solid lines, see Figure 2.6) and developing bioenergy routes (dotted lines) from biomass feedstocks through thermochemical, chemical, biochemical and biological conversion routes to heat, power, CHP and liquid or gaseous fuels (modified from IEA Bioenergy, 2009). Commercial products are marked with an asterisk.

Notes: 1. Parts of each feedstock, for example, crop residues, could also be used in other routes. 2. Each route also gives coproducts. 3. Biomass upgrading includes any one of the densification processes (pelletization, pyrolysis, torrefaction, etc.). 4. Anaerobic digestion processes release methane and CO_2 and removal of CO_2 provides essentially methane, the major component of natural gas; the upgraded gas is called biomethane. 5. Could be other thermal processing routes such as hydrothermal, liquefaction, etc. DME=dimethyl ether.

mainly through the use of traditional forms, and more than 80% of TPES in the poorest countries. The bioenergy share in India, China and Mexico is decreasing, mostly as traditional biomass is substituted by kerosene and liquefied petroleum gas within large cities. However, consumption in absolute terms continues to grow. This trend is also true for most African countries, where demand has been driven by a steady increase in wood fuels, particularly in the use of charcoal in booming urban areas (GBEP, 2008).

Turning from the technological perspectives of bioenergy to environmental and social aspects, the literature assessments in this chapter reveal positive and negative aspects of bioenergy. Sustainably produced and managed, bioenergy can provide a substantial contribution to climate change mitigation through increasing carbon stocks in the biosphere (e.g., in degraded lands), reducing carbon emissions from unsustainable forest use and replacing fossil fuel-based systems in the generation of heat, power and modern fuels. Additionally, bioenergy may provide opportunities for regional economic development (see Sections 9.3.1 and 2.5.4). Advanced bioenergy systems and end-use technologies can also substantially reduce the emissions of black carbon and other short-lived GHGs such as methane and carbon monoxide (CO), which are related to the burning of biomass in traditional open fires and kilns. If improperly designed or implemented, the large-scale expansion of bioenergy systems is likely to have negative consequences for climate and sustainability, for example, by inducing d+iLUC that can alter surface albedo and release carbon from soils and vegetation, reducing biodiversity or negatively impacting local populations in terms of land tenure or reduced food security, among other effects.

The literature on the resource potential of biomass is covered in Section 2.2, which discusses a variety of global modelling studies and the factors that influence the assessments. Section 2.2 also presents examples of resource assessments from countries and specific regions, which provide cost dimensions for these resources. The overall technology portfolio is shown in Figure 2.2 and includes commercial and developing energy carriers from modern biomass. The commercially available energy products and (conversion) technologies are discussed in Section 2.3. These are based on sugar crops (perennial sugarcane and beets), starch crops (maize, wheat, cassava etc.), and oil crops (soy, rapeseed) as feedstocks, and they expand food and fodder processing to bioenergy production. Current bioenergy production is also coupled with forest products industry residues and the pulping industry that has traditionally self generated heat and power; with dry and wet municipal wastes; with sewage sludge; and with a variety of organic wet wastes from various sectors. These wastes and residues, if left untreated, can have a major impact on climate through methane emission releases. The bioenergy market is described in Section 2.4 for traditional and modern forms, as are evolving international trade and sustainability frameworks for bioenergy. The advanced technologies for production of feedstocks and conversion to energy products are discussed in Section 2.6.

In Section 2.5, the environmental and social impacts of biomass use are addressed with emphasis on the climate change effects of bioenergy. Because of the complexity of GHG impacts and of the bioenergy chains, impacts are analyzed without and with LUC separately. These impacts span micro-, meso- and macro- scales and depend on the land cover conversion and water availability, among other factors, in specific regions. Direct land use impacts occur locally by changes in crop use or the dedication of a crop to bioenergy. The iLUC results from a market-mediated shift in land management activities (i.e., dLUC) outside the region of primary production expansion. Both are addressed in Section 2.5. The social impacts of modern and traditional biomass use are presented and related to key issues such as the impact of bioenergy on food production and sustainable development in Section 2.5.7 (also refer to Sections 9.3 and 9.4).

To reach high levels of bioenergy production and minimize environmental and social impacts, it is necessary to develop a variety of lignocellulosic biomass sources and a portfolio of conversion routes for power, heat and gaseous and liquid fuels that satisfy existing and future energy needs (Figure 2.2). With these prospects for technology improvement, innovation and integration, key conversion intermediates derived from biomass such as sugars, syngas, pyrolysis oils (or oils derived from other thermal treatments), biogas and vegetable oils (lipids) can be upgraded in conversion facilities that are capable of making a variety of products including biofuels, power and process heat, alongside other products as discussed in Section 2.6. In Section 2.7, the costs of existing commercial technologies and their trends are discussed, highlighting that over the past 25 years technological learning occurred in a variety of bioenergy systems in specific countries. Finally, Section 2.8 addresses the potential deployment of biomass for energy. It also compares biomass resource assessments from Section 2.2, informed by environmental and social impacts discussions, with the levels of deployment indicated by the scenario literature review described in Chapter 10. The role of biomass and its multiple energy products alongside food, fodder, fibre and forest products is viewed through IPCC scenario storylines (IPCC, 2000a,d) to reach significant penetration levels with and without taking into account sustainable development and climate change mitigation pathways. High and low penetration levels can be reached with (and without) climate change mitigation and sustainable development strategies. Many insights into bioenergy technology developments and integrated systems can be gleaned from these sketches, and they will be useful in further developing bioenergy sustainably with climate mitigation.

2.1.2 Previous Intergovernmental Panel on Climate Change assessments

Bioenergy has not been examined in detail in previous IPCC reports. In the most recent Fourth Assessment Report (AR4), the analysis of GHG mitigation from bioenergy was scattered among seven chapters, making it difficult to obtain an integrated and cohesive picture of the resource and mitigation potential, challenges and opportunities. The main conclusions from the AR4 report (IPCC, 2007b,d) are as follows:

- **Biomass energy demand.** Primary biomass requirements for the production of transportation fuels were largely based on the WEO (IEA, 2006) global projections, with a relatively wide range of about 14 to 40 EJ/yr of primary biomass, or 8 to 25 EJ/yr of biofuels in 2030. However, higher demand estimates of 45 to 85 EJ/yr for primary biomass in 2030 (roughly 30 to 50 EJ/yr of biofuel) were also included. For comparison, the scenario review in Chapter 10 shows biofuel production ranges of 0 to 14 EJ/yr in 2030 and 2 to 50 EJ/yr in 2050 with median values of 5 to 12 EJ/yr and 18 to 20 EJ/yr in the two GHG mitigation scenario categories analyzed. The demand for biomass-generated heat and power was stated to be strongly influenced by the availability and introduction of competing technologies such as CCS, nuclear power, wind energy, solar heating and others. The projected biomass demand in 2030 would be around 28 to 43 EJ according to the data used in the AR4. These estimates focus on electricity generation. Heat was not explicitly modelled or estimated in the WEO (IEA, 2006), on which the AR4 was based, therefore underestimating the total demand for biomass.

  Potential future demand for biomass in industry (especially new uses such as biochemicals, but also expansion of charcoal use for steel production) and the built environment (heating as well as increased use of biomass as a building material) was also highlighted as important, but no quantitative projections were included in the potential demand for biomass at the medium and longer term.

- **Biomass resource potential (supply).** According to the AR4, the largest contribution to technical potential could come from energy crops on arable land, assuming that efficiency improvements in agriculture are fast enough to outpace food demand so as to avoid increased pressure on forests and nature areas. A range of 20 to 400 EJ/yr is presented for 2050, with a best estimate of 250 EJ/yr. Using degraded lands for biomass production (e.g., in reforestation schemes: 8 to 110 EJ/yr) can contribute significantly. Although such low-yielding biomass production generally results in more expensive biomass supplies, competition with food production is almost absent and various co-benefits, such as regeneration of soils (and carbon storage), improved water retention and protection from (further) erosion may also offset part of the establishment costs. A current example of such biomass production schemes is the establishment of *Jatropha* crops (oilseeds) on marginal lands.

The technical potential in residues from forestry is estimated at 12 to 74 EJ/yr, that from agriculture at 15 to 70 EJ/yr and that from waste at 13 EJ/yr. These biomass resource categories are largely available before 2030, but also partly uncertain. The uncertainty comes from possible competing uses (e.g., increased use of biomaterials such as fibreboard production from forest residues and use of agricultural residues for fodder and fertilizer) and differing assumptions about sustainability criteria deployed with respect to forest management and agricultural intensity. The technical potential for biogas fuel from waste, landfill gas and digester gas is much smaller.

- **Carbon mitigation potential.** The mitigation potential for electricity generation from biomass reaches 1,220 Mt CO_2eq for the year 2030, a substantial fraction of it at costs lower than USD_{2005} 19.5/t CO_2. From a top-down assessment, the economic mitigation potential of biomass energy supplied from agriculture is estimated to range from 70 to 1,260 Mt CO_2eq/yr at costs of up to USD_{2005} 19.5/t CO_2eq, and from 560 to 2,320 Mt CO_2eq/yr at costs of up to USD_{2005} 48.5/t CO_2eq. The overall mitigation from biomass energy coming from the forest sector is estimated to reach 400 Mt CO_2/yr up to 2030.

2.2 Resource potential

2.2.1 Introduction

Bioenergy production interacts with food, fodder and fibre production as well as with conventional forest products in complex ways. Bioenergy demand constitutes a benefit to conventional plant production in agriculture and forestry by offering new markets for biomass flows that earlier were considered to be waste products; it can also provide opportunities for cultivating new types of crops and integrating bioenergy production with food and forestry production to improve overall resource management. However, biomass for energy production can intensify competition for land, water and other production factors, and can result in overexploitation and degradation of resources. For example, too-intensive biomass extraction from the land can lead to soil degradation, and water diversion to energy plantations can impact downstream and regional ecological functions and economic services.

As a consequence, the magnitude of the biomass resource potential depends on the priority given to bioenergy products versus other products obtained from the land—notably food, fodder, fibre and conventional forest products such as sawn wood and paper—and on how much total biomass can be mobilized in agriculture and forestry. This in turn depends on natural conditions (climate, soils, topography), on agronomic and forestry practices, and on how societies understand and prioritize nature conservation and soil/water/biodiversity protection and on how production systems are shaped to reflect these priorities (Figure 2.3).

This section focuses on long-term biomass resource potential and how it has been estimated based on considerations of the Earth's biophysical resources (ultimately net primary production: NPP) and restrictions on their energetic use arising from competing requirements, including non-extractive requirements such as soil quality maintenance/improvement and biodiversity protection. Additionally, approaches to assessing biomass resource potentials—and results from selected studies—are presented with an account of the main determining factors. These factors are treated explicitly, including the constraints on their utilization. The section ends by summarizing conclusions about biomass resource assessments, including uncertainties.

2.2.1.1 Methodology assessment

Studies quantifying biomass resource potential have assessed the resource base in a variety of ways. They differ in the extent to which the influence of natural conditions (and how these can change in the future) are considered as well as in the extent to which the types and details of important additional factors are taken into account, such as socioeconomic considerations, the character and development of agriculture and forestry, and factors connected to nature conservation and soil/water/biodiversity preservation (Berndes et al., 2003). Different types of resource potentials are assessed but the following are commonly referred to (see Glossary in Annex I):

- **Theoretical potential** refers to the biomass supply as limited only by biophysical conditions (see discussion below in this same sub-section);

- **Technical potential** considers the limitations of the biomass production practices assumed to be employed and also takes into account concurrent demand for food, fodder, fibre, forest products and area requirements for human infrastructure. Restrictions connected to nature conservation and soil/water/biodiversity preservation can also be considered. In such cases, the term *sustainable potential* is sometimes used (see Section 2.2.2); and

- **Market potential** refers to the part of the technical potential that can be produced given a specified requirement for the level of economic profit in production. This depends not only on the cost of production but also on the price of the biomass feedstock, which is determined by a range of factors such as the characteristics of biomass conversion technologies, the price of competing energy technologies and the prevailing policy regime (see Section 2.2.3).

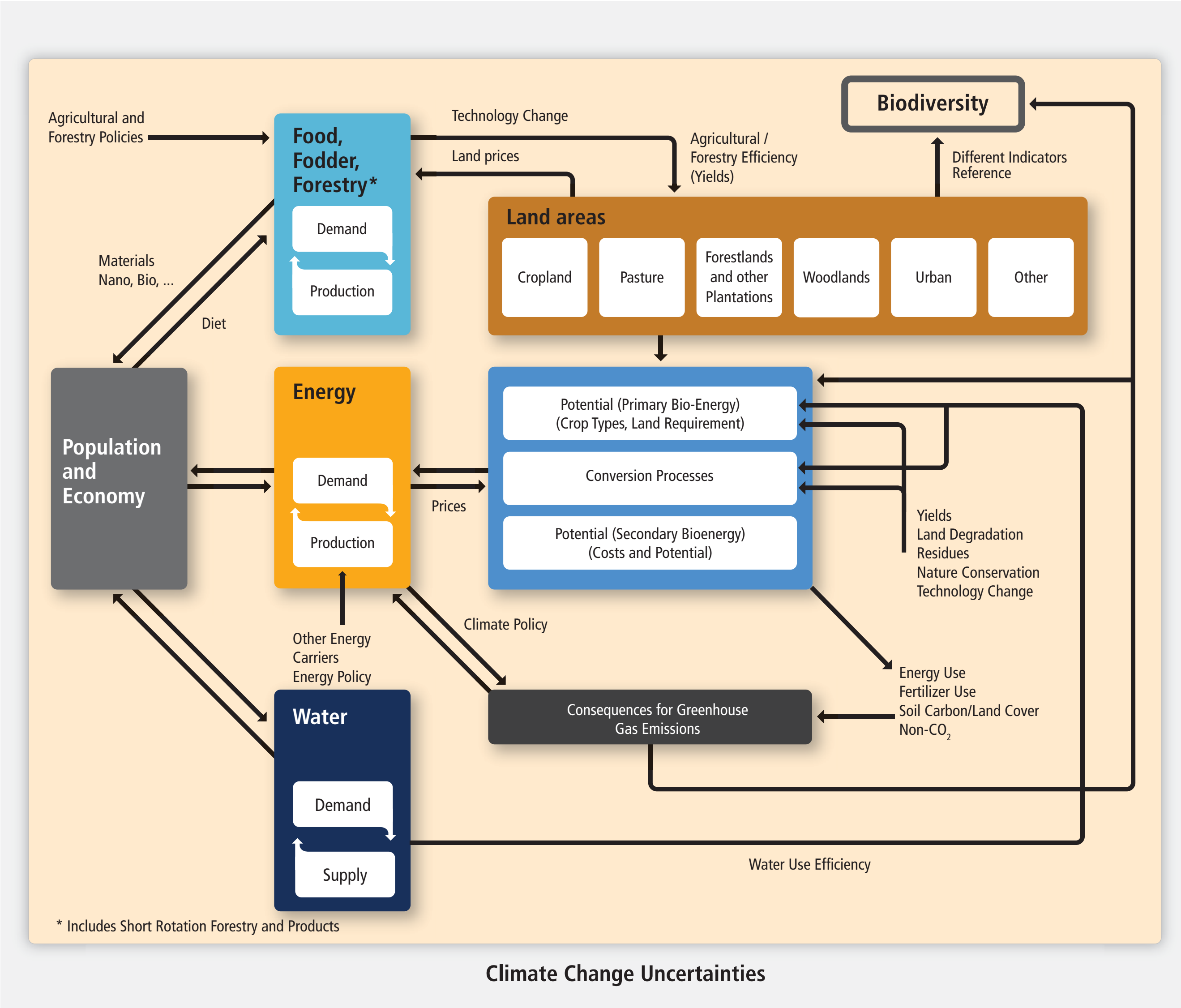

Figure 2.3 | Overview of key relationships relevant to assessment of biomass resource potentials (modified from Dornburg et al., 2010). Indirect land use and social issues are not displayed. Reproduced with permission from the Royal Society of Chemistry.

Three principal categories are—more or less comprehensively—considered in assessments of biomass resource potentials (see also Section 2.3.1.1):

- Primary residues from conventional food and fibre production in agriculture and forestry, such as cereal straw and logging residues;
- Secondary and tertiary residues in the form of organic food/forest industry by-products and retail/post consumer waste; and
- Plants produced for energy supply, including conventional food/fodder/industrial crops, surplus roundwood forestry products, and new agricultural, forestry or aquatic plants.

Given that resource potential assessments quantify the availability of residue flows in the food and forest sectors, the definition of how these sectors develop is central for the outcome. As discussed below, consideration of various environmental and socioeconomic factors as a rule reduces the assessed resource potential to lower levels.

Most assessments of the biomass resource potential considered in this section are variants of technical/market potentials employing a 'food/fibre first principle', applied with the objective of quantifying biomass resource potentials under the condition that global requirements for food and conventional forest products such as sawn wood and paper are met with priority (see, e.g., WBGU, 2009; Smeets and Faaij, 2007).

Studies that start out from such principles should not be understood as providing guarantees that a certain level of biomass can be supplied for energy purposes without competing with food or fibre production. They quantify how much bioenergy could be produced in a certain future year based on using resources not required for meeting food and fibre demands, given a specified development in the world or in a region. But they do not analyze how bioenergy expansion towards such a future level of production would—or should—interact with food and fibre production.

Studies using integrated energy/industry/land use cover models (see, e.g., Leemans et al., 1996; Strengers et al., 2004; Johansson and Azar, 2007; van Vuuren et al., 2007; Fischer et al., 2009; Lotze-Campben, 2009; Melillo et al., 2009; Wise et al., 2009; Figure 2.4) can provide insights into how an expanding bioenergy sector interacts with other sectors in society including land use and the management of biospheric carbon stocks. Studies focused on sectors can contain more detailed information on interactions with other biomass uses. Restricted scope (only selected biofuel/land uses and/or regions covered) or lack of sufficiently detailed empirical data can limit the confidence in results—especially in prospective studies. This is further discussed in Sections 2.5 and 2.8.

By considering the upper level of productivity of biomass plantations on land while assuming theoretical potentials also for worldwide agriculture and fully taking into account conservation of a viable biosphere, global modelling studies by Smeets et al. (2007) derived a maximum global potential of biomass for energy of 1,548 EJ/yr.[4] In this chapter, this figure is considered to be an estimate of theoretical potential.

2.2.1.2 Total aboveground net primary production of biomass

A first qualitative understanding of biomass technical potentials can be gained from considering the total annual aboveground net primary production (NPP: the net amount of carbon assimilated in a time period by vegetation) on the Earth's terrestrial surface. This is estimated to be about 35 Gt carbon, or 1,260 EJ/yr assuming an average carbon content of 50% and 18 GJ/t average heating value (Haberl et al., 2007), which can be compared to the current world primary energy supply of about 500 EJ/yr (IEA, 2010a). This comparison shows that total terrestrial aboveground NPP is larger, but by no more than a factor of around three, than what is required to meet society's energy demand. Establishing bioenergy as a major source of future primary energy requires that a significant part of global terrestrial NPP takes place within production systems that provide bioenergy feedstocks (removing their NPP from the trophic chains of ecosystems). In addition, total terrestrial NPP may have to be increased through fertilizer, irrigation and other inputs on lands managed for food, fodder, fibre, forest products and bioenergy.

2.2.1.3 Human appropriation of terrestrial net primary production

A comparison with biomass production in agriculture and forestry can give a perspective on the potential bioenergy supply in relation to what is presently harvested. Today's global industrial roundwood production corresponds to 15 to 20 EJ/yr, and the global harvest of major crops (cereals, oil crops, sugar crops, roots, tubers and pulses) corresponds to about 60 EJ/yr (FAOSTAT, 2011). One immediate conclusion from this comparison is that biomass extraction by agriculture and forestry will have to increase substantially in order to provide feedstocks for a bioenergy sector large enough to make a significant contribution to the future energy supply.

Studies estimating the overall human appropriation of terrestrial NPP across all human uses of biomass (HANPP, taking into account all NPP gained or lost due to human activities, including harvesting and backflows) suggest that societies already appropriate a substantial share of the world's aboveground terrestrial NPP. This provides a context for prospective future biomass extraction for bioenergy. Estimates of HANPP vary depending on its definition as well as the models and data used for the calculations. A spatially explicit calculation by Haberl et al. (2007) estimated that in the year 2000, aboveground HANPP amounted to nearly 29% of the modelled global aboveground NPP. Total human biomass harvest alone was estimated to amount to about 20% (including utilized residues and grazing), with all harvested biomass used by humans containing an energy of 219 EJ/yr (Krausmann et al., 2008).

Other HANPP estimates range from a similar level down to about half of this level (D. Wright, 1990; Imhoff et al., 2004). The HANPP concept cannot directly be used to define a certain level of biomass use that would be 'safe' or 'sustainable' because the impacts of human land use depend on how agriculture and forestry systems are shaped (Bai et al., 2008). However, it can be used as a measure of the human domination of the biosphere and provide a reference for assessing the comparative magnitude of prospective additional biomass resource potentials.

Besides biophysical factors, socioeconomic conditions also influence the biomass resource potential by defining how—and how much—biomass can be produced without causing socioeconomic impacts that might be considered unacceptable. Socioeconomic restrictions vary around the world, change as society develops and depend on how societies prioritize bioenergy in relation to other socioeconomic objectives (see also Sections 2.5 and 2.8).

4 Smeets et al. (2007) model a scenario with a fully landless animal production system with globally high feed conversion efficiency and a 4.6-fold increase in global agricultural productivity by 2050 due to technological progress and deployment that is considerably faster than has historically ever been achieved (a 1.9-fold increase for Europe and a 7.7-fold increase in sub-Saharan Africa). In that case, 72% of current agricultural area could be used for bioenergy production in 2050 and supply a theoretical potential of 1,548 EJ/yr, which is of the same magnitude as the total energy content of the world's natural aboveground net primary production on land.

2.2.2 Global and regional technical potential

2.2.2.1 Literature assessment

In an assessment of technical potential based on an analysis of the literature available in 2007 and additional modelling, Dornburg et al. (2008, 2010) arrived at the conclusion that the upper bound of the technical potential in 2050 can amount to about 500 EJ. The study assumes policy frameworks that secure good governance of land use and major improvements in agricultural management and takes into account water limitations, biodiversity protection, soil degradation and competition with food. Residues originating from forestry, agriculture and organic wastes (including the organic fraction of MSW, dung, process residues etc.) are estimated to amount to 40 to 170 EJ/yr, with a mean estimate of around 100 EJ/yr. This part of the technical potential is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range. Surplus forestry other than from forestry residues has an additional technical potential of 60 to 100 EJ/yr.

The findings of the Dornburg et al. (2008, 2010) reviews for biomass produced via cropping systems is that a lower estimate for energy crop production on possible surplus, good quality agricultural and pasture lands is 120 EJ/yr. The potential contribution of water-scarce, marginal and degraded lands could amount up to an additional 70 EJ/yr. This would comprise a large area where water scarcity provides limitations and soil degradation is more severe. Assuming strong learning in agricultural technology for improvements in agricultural and livestock management would add 140 EJ/yr. The three categories added together lead to a technical potential from this analysis of up to about 500 EJ/yr (Dornburg et al., 2008, 2010). For example, Hoogwijk et al. (2005, 2009) estimate that the biomass technical potential could expand from 290 to 320 EJ/yr in 2020 to 330 to 400 EJ/yr in 2030. Developing the technical potential would require major policy efforts; therefore, actual deployment is likely to be lower and the biomass resource base will be largely constrained to a share of the biomass residues and organic wastes, some cultivation of bioenergy crops on marginal and degraded lands, and some regions where biomass is a cheaper energy supply option compared to the main reference options (e.g., sugarcane-based ethanol production), amounting to a minimum of about 50 EJ/yr (Dornburg et al., 2008, 2010).

Table 2.2 shows ranges in the assessed global technical potential for the year 2050 explicitly for various biomass categories. The wide ranges shown are due to differences in the studies' approaches to considering important factors, which are in themselves uncertain: population, economic and technology development assumed or computed can vary and evolve at different regional paces; biodiversity, nature conservation and other environmental requirements are difficult to assess and depend on numerous factors and social preferences; and the magnitude and pattern of climate change and land use can strongly influence the biophysical capacity of the environment. Furthermore, technical potentials cannot be determined precisely while uncertainties remain regarding societal preferences with respect to trade-offs in environmental impacts and the implications of increased intensification in food and fibre production, and regarding potential synergies between different forms of land use.

Although assessments employing improved data and modelling capacity have not succeeded in providing narrow distinct estimates of the technical potential of biomass, they do indicate the most influential factors that affect this technical potential. This is further discussed below, where approaches used in the assessments are treated in more detail.

2.2.2.2 The contribution from residues, dung, processing by-products and waste

As can be seen in Table 2.2, biomass resource assessments indicate that retail/post-consumer waste, dung and primary residues/processing by-products in the agriculture and forestry sectors have prospects for providing a substantial share of the total global biomass supply in the longer term. Yet, the sizes of these biomass resources are ultimately determined by the demand for conventional agriculture and forestry products and the sustainability of the land resources.

Assessments of the potential contribution from these sources to the future biomass supply combine data on future production of agriculture and forestry products obtained from food/forest sector scenarios, the possibility of use of degraded lands, and the residue factors that account for the amount of residues generated per unit of primary product produced. For example, harvest residue generation in agricultural crops cultivation is estimated based on harvest index data, that is, the ratio of harvested product to total aboveground biomass (e.g., Wirsenius, 2003; Lal, 2005; Krausmann et al., 2008; Hakala et al., 2009). The generation of logging residues in forestry, and of additional biomass flows such as thinning wood and process by-products, is estimated using similar methods (see Ericsson and Nilsson, 2006; Smeets and Faaij, 2007).

The shares of the biomass flows that are available for energy (i.e., recoverability fractions) are then estimated based on consideration of other extractive uses and requirements (e.g., soil conservation, animal feeding or bedding in agriculture, and fibre board production in the forest sector).

2.2.2.3 The contribution from unutilized forest growth

In addition to the residue flows that are linked to industrial roundwood production and processing into conventional forest products, forest growth currently not harvested is considered in some studies. This biomass resource is quantified based on estimates of the biomass increment in parts of forests that are assessed as being available for wood supply. This increment is compared with the estimated level of forest biomass extraction for conventional industrial roundwood production—and sometimes for traditional biomass, notably heating and cooking—to obtain the unutilized forest growth. Smeets and Faaij (2007) provide illustrative quantifications showing how this technical potential of biomass can vary from being a major source of bioenergy to being practically zero as a consequence of competing demand and economic and ecological considerations. A comparison with the present industrial roundwood production of about 15 to 20 EJ/yr shows that a drastic increase in forest biomass output is required to reach the higher-end technical potential assessed for the forest biomass category in Table 2.2. A special case that can play a role is forest growth that becomes available after extensive tree mortality from insect outbreaks or fires (Dymond et al., 2010).

2.2.2.4 The contribution from biomass plantations

Table 2.2 indicates that substantial supplies from biomass plantations are required for reaching the high end of the technical potential range. Land availability (and its suitability) for dedicated biomass plantations and the biomass yields that can be obtained on the available lands are two critical determinants of the technical potential. Given that surplus agricultural land is commonly identified as the major land resource for the plantations, food sector development is critical. Methods for determining land availability and suitability should consider requirements for maintaining the economic, ecological and social value of ecosystems. There are different approaches for considering such requirements, as described for a selection of studies below.

Most earlier assessments of biomass resource potentials used rather simplistic approaches to estimating the technical potential of biomass plantations (Berndes et al., 2003), but the continuous development of modelling tools that combine databases containing biophysical information (soil, topography, climate) with analytical representations of relevant crops and agronomic systems and the use of economic and full biogeochemical vegetation models has resulted in improvements over time (see, e.g., van Vuuren et al., 2007; Fischer et al., 2008; Lotze-Campen et al., 2009; Melillo et al., 2009; WBGU, 2009; Wise et al., 2009;

Table 2.2 | Global technical potential overview for a number of categories of land-based biomass supply for energy production (primary energy numbers have been rounded). The total assessed technical potential can be lower than the present biomass use of about 50 EJ/yr in the case of high future food and fibre demand in combination with slow productivity development in land use, leading to strong declines in biomass availability for energetic purposes.

Biomass category	Comment	2050 Technical potential (EJ/yr)
Category 1. **Residues from agriculture**	By-products associated with food/fodder production and processing, both primary (e.g., cereal straw from harvesting) and secondary (e.g., rice husks from rice milling) residues.	15 – 70
Category 2. **Dedicated biomass production on surplus agricultural land**	Includes both conventional agriculture crops and dedicated bioenergy plants including oil crops, lignocellulosic grasses, short-rotation coppice and tree plantations. Only land not required for food, fodder or other agricultural commodities production is assumed to be available for bioenergy. However, surplus agriculture land (or abandoned land) need not imply that its development is such that less total land is needed for agriculture: the lands may become excluded from agriculture use in modelling runs due to land degradation processes or climate change (see also 'marginal lands' below). Large technical potential requires global development towards high-yielding agricultural production and low demand for grazing land. Zero technical potential reflects that studies report that food sector development can be such that no surplus agricultural land will be available.	0 – 700
Category 3. **Dedicated biomass production on marginal lands**	Refers to biomass production on deforested or otherwise degraded or marginal land that is judged unsuitable for conventional agriculture but suitable for some bioenergy schemes (e.g., via reforestation). There is no globally established definition of degraded/marginal land and not all studies make a distinction between such land and other land judged as suitable for bioenergy. Adding categories 2 and 3 can therefore lead to double counting if numbers come from different studies. High technical potential numbers for categories 2 and 3 assume biomass production on an area exceeding the present global cropland area (ca. 1.5 billion ha or 15 million km^2). Zero technical potential reflects low potential for this category due to land requirements for, for example, extensive grazing management and/or subsistence agriculture or poor economic performance if using the marginal lands for bioenergy.	0 – 110
Category 4. **Forest biomass**	Forest sector by-products including both primary residues from silvicultural thinning and logging, and secondary residues such as sawdust and bark from wood processing. Dead wood from natural disturbances, such as fires and insect outbreaks, represents a second category. Biomass growth in natural/semi-natural forests that is not required for industrial roundwood production to meet projected biomaterials demand (e.g., sawn wood, paper and board) represents a third category. By-products provide up to about 20 EJ/yr implying that high forest biomass technical potentials correspond to a much larger forest biomass extraction for energy than what is presently achieved in industrial wood production. Zero technical potential indicates that studies report that demand from sectors other than the energy sector can become larger than the estimated forest supply capacity.	0 – 110
Category 5. **Dung**	Animal manure. Population development, diets and character of animal production systems are critical determinants.	5 – 50
Category 6. **Organic wastes**	Biomass associated with materials use, for example, organic waste from households and restaurants and discarded wood products including paper, construction and demolition wood; availability depends on competing uses and implementation of collection systems.	5 – >50
Total		**<50 – >1000**

Notes: Based on Fischer and Schrattenholzer (2001); Hoogwijk et al. (2003, 2005, 2009); Smeets and Faaij (2007); Dornburg et al. (2008, 2010); Field et al. (2008); Hakala et al. (2009); IEA Bioenergy (2009); Metzger and Huttermann (2009); van Vuuren et al. (2009); Haberl et al. (2010); Wirsenius et al. (2010); Beringer et al. (2011).

Beringer et al., 2011). Important conclusions are: a) the effects of LUC associated with bioenergy expansion can considerably influence the climate benefit of bioenergy (see Section 2.5) and b) biofuel yields from crops have frequently been overestimated by neglecting spatial variations in productivity (Johnston et al., 2009).

Figure 2.4—representing one example (Fischer et al., 2009)—shows the modelled global land suitability for selected first-generation biofuel feedstocks and for lignocellulosic plants (see caption to Figure 2.4 for information about plants included). By overlaying spatial data on global land cover derived from the best available remote sensing data combined

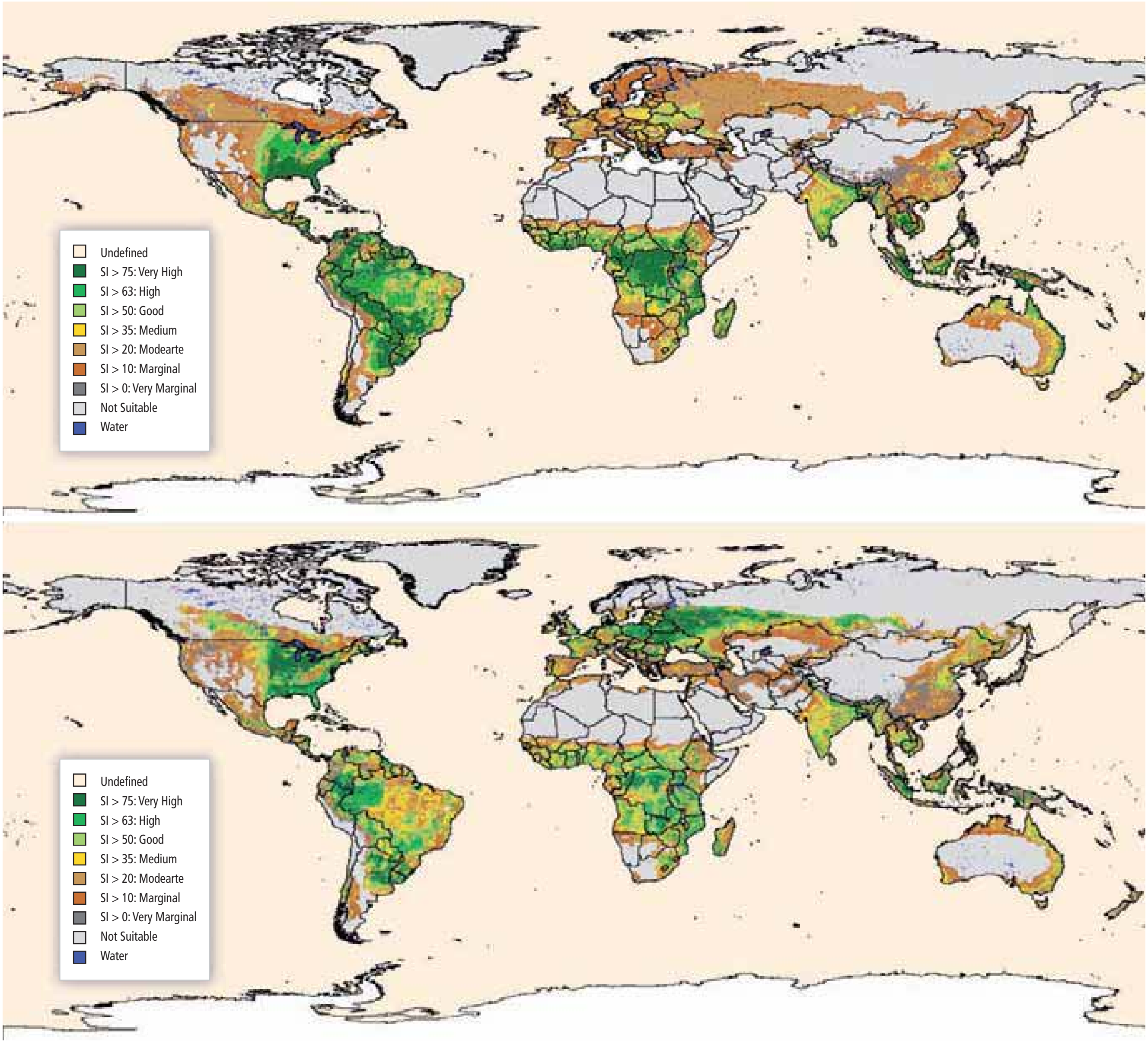

Figure 2.4 | Global land suitability for bioenergy plantations. The upper map shows suitability for herbaceous and woody lignocellulosic plants (*Miscanthus*, switchgrass, reed canary grass, poplar, willow, eucalyptus) and the lower map shows suitability for first-generation biofuel feedstocks (sugarcane, maize, cassava, rapeseed, soybean, palm oil, *Jatropha*). The suitability index (SI)[1] describes the spatial suitability of each pixel and reflects the match between crop requirements and prevailing climate, soil and terrain conditions. The map shows suitability under rain-fed cultivation and advanced management systems that assume availability of sufficient nutrients, adequate pest control and mechanization, and other practices. Results for irrigated conditions or low-input management systems would result in different pictures (Fischer et al., 2009; reproduced with permission from the International Institute for Applied Systems Analysis (IIASA)).

Note: 1. SI: suitability index. The SI used reflects the spatial suitability of each pixel and is calculated as SI = VS*0.9+S*0.7+MS*0.5+mS*0.3, where VS, S, MS and mS correspond to yield levels at 80–100%, 60–80%, 40–60% and 20–40% of the modelled maximum, respectively (Fischer et al., 2009).

with statistical information and data on protected areas, it is possible to quantify suitable lands for different land cover types. A suitability index has been used in order to represent both yield potentials[5] and suitability (see caption to Figure 2.4). For instance, almost 700 Mha (7,000 km^2), or about 20%, of currently unprotected grasslands and woodlands are assessed as suitable for soybean while less than 50 Mha (500 km^2) are assessed as suitable for oil palm (note that these land suitability numbers cannot be added because areas overlap). Considering unprotected forest land, an area roughly 10 times larger (almost 500 Mha or 5,000 km^2) is suitable for oil palm cultivation (Fischer et al., 2009, their Annex 5 and 6). However, converting large areas of forests into biomass plantations would negatively impact biodiversity and might—depending on the carbon density of converted forests—also lead to large initial CO_2 emissions that can drastically reduce the annual accumulated climate benefit of substituting fossil fuels with the bioenergy derived from such plantations. Converting grass- and woodlands with high soil carbon content to intensively cultivated annual crops can similarly lead to large CO_2 emissions, while if degraded and C-depleted pastures are cultivated with herbaceous and woody lignocellulosic plants soil carbon may instead accumulate, enhancing the climate benefit. This is further discussed in Section 2.5.

under a 'food and environment first' paradigm excluding forests and land currently used for food and fodder production. The latter includes estimates of unprotected grassland and woodland required today for ruminant livestock feeding. Calculations are based on FAOSTAT data on fodder utilization of crops, and national livestock numbers, estimated fodder energy requirements of the national herds and derived fodder gaps filled by grassland and pastures. Grassland and woodland with very low productivity or steep sloping conditions were considered unsuitable for lignocellulosic feedstock production. The results, shown in Table 2.3, represent one example of estimates of regional technical potentials of biomass resulting from a specific set of assumptions with respect to nature protection requirements, biofuel feedstock crop choice and agronomic practice determining attainable yield levels and livestock production systems determining grazing requirements. Furthermore, the results represent current agriculture practice and productivity, population, diets, climate etc. Quantifications of the technical potential of the future biomass resource need to consider how such parameters change over time.

A similar analysis (WBGU, 2009; Beringer et al., 2011) reserved current and near-future agricultural land for food and fibre production and also

Table 2.3 | Example of the technical potential of rain-fed lignocellulosic plants on unprotected grassland and woodland (i.e., forests excluded) where land requirements for food production, including grazing, have been considered at 2000 levels. Calculated based on Fischer et al. (2009); reproduced with permission from the International Institute for Applied Systems Analysis (IIASA).

Region	Total grass- and woodland area (Mha) [million km^2]	Protected areas (Mha) [million km^2]	Unproductive or very low productive areas (Mha) [million km^2]	Bioenergy area also excluding grazing land (Mha) [million km^2]	Technical potential (average yield,[1] GJ/ha/yr) [GJ/km^2/yr]	Technical Potential[2] (total, EJ/yr)
North America	659 [6.59]	103 [1.03]	391 [3.91]	111 [1.11]	165 [16,500]	19
Europe and Russia	902 [9.02]	76 [0.76]	618 [6.18]	122 [1.22]	140 [14,000]	17
Pacific OECD	515 [5.15]	7 [0.07]	332 [3.32]	97 [0.97]	175 [17,500]	17
Africa	1,086 [10.68]	146 [1.46]	386 [3.86]	275 [2.75]	250 [2,500]	69
South and East Asia	556 [5.56]	92 [0.92]	335 [3.35]	14 [0.14]	285 [28,500]	4
Latin America	765 [7.65]	54 [0.54]	211 [2.11]	160 [1.6]	280 [28,000]	45
Middle East and North Africa	107 [1.07]	2 [0.02]	93 [0.93]	1 [0.01]	125 [12,500]	0.2
World	**4,605 [46.05]**	**481 [4.81]**	**2,371 [23.71]**	**780 [7.80]**	**220 [22,000]**	**171**

Notes: 1. Calculated based on average yields of rain-fed lignocellulosic feedstocks on grass- and woodland area given in Fischer et al. (2009, p.174) and assuming an energy content of 18 GJ/t dry matter (rounded numbers). 2. If livestock grazing area can be freed up by intensification of agricultural practices and pasture use, these areas could be used for additional bioenergy production. The technical potential in this case could increase from 171 up to 288 EJ/yr.

Technical potentials of biomass plantations can thus be calculated based on assessed land availability and corresponding yield levels. Based on the results as shown in Figure 2.4, Fischer et al. (2009) estimated regional land balances of unprotected grassland and woodland potentially available for rain-fed lignocellulosic biofuel feedstock production

excluded unmanaged land from bioenergy production if its conversion to biomass plantations would lead to large net CO_2 emissions to the atmosphere, or if the land was degraded, a wetland, environmentally protected or rich in biodiversity. If dedicated biomass plantations were established in the available lands, an estimated 26 to 116 EJ/yr could be produced (52 to 174 EJ with irrigation). The spatial variation of technical potential was computed from biogeochemical principles, that is, photosynthesis, transpiration, soil quality and climate. Haberl et

5 Yield potential is the yield obtained when an adapted cultivar (cultivated variety of a plant) is grown with the minimal possible stress that can be achieved with best management practices, a functional definition by Cassman (1999).

al. (2010) considered the land available after meeting prospective future food, fodder and nature conservation targets, also taking into account spatial variation in projected future productivity of bioenergy plantations, and arrived at a technical potential in 2050 in the range of 160 to 270 EJ/yr. Of the 210 EJ/yr average technical potential, 81 EJ/yr are provided by dedicated plantations, 27 EJ/yr by residues in forestry and 100 EJ/yr by crop residues, manure and organic wastes, emphasizing the importance of process optimization and cascading biomass use.

Water constraints are highlighted in the literature for agriculture (UN-Water, 2007) and for bioenergy (Berndes, 2002; Molden, 2007; De Fraiture et al., 2008; Sections 9.3.4.4 and 2.5.5.1). In a number of regions the technical potential can decrease to lower levels than what is assessed based on approaches that do not involve explicit geo-hydrological modelling (Rost et al., 2009). Such modelling can lead to improved quality bioenergy potential assessments. Planting of trees and other perennial vegetation can decrease erosive water run-off and replenish groundwater but may lead to substantial reductions in downstream water availability (Calder et al., 2004; Farley et al., 2005).

Illustrative of this, Zomer et al. (2006) report that large areas deemed suitable for afforestation within the Clean Development Mechanism (CDM) would exhibit evapotranspiration increases and/or decreases in runoff if they become forested, that is, a decrease in water potentially available offsite for other uses. This would be particularly evident in drier areas, the semi-arid tropics, and in conversion from grasslands and subsistence agriculture. Similarly, based on a global analysis of 504 annual catchment observations, Jackson et al. (2005) report that afforestation dramatically decreased stream flow within a few years of planting. Across all plantation ages in the database, afforestation of grasslands, shrublands or croplands decreased stream flow by, on average, 38%. Average losses for 10- to 20-year-old plantations were even greater, reaching 52% of stream flow.

Studies by Hoogwijk et al. (2003), Wolf et al. (2003), Smeets et al. (2007) and van Minnen et al., (2008) also illustrate the importance of biomass plantations for reaching a higher global technical potential, and how different determining parameters greatly influence the technical potential. For instance, in a scenario with rapid population growth and slow technology progress, where agriculture productivity does not increase from its present level and little biomass is traded, Smeets et al. (2007) found that no land would be available for bioenergy plantations. In a contrasting scenario where all critical parameters were instead set to be very favourable, up to 3.5 billion hectares (35 million km^2) of former agricultural land—mainly pastures and with large areas in Latin America and sub-Saharan Africa—were assessed as not required for food in 2050. A substantial part of this area was assessed as technically suitable for bioenergy plantations.

2.2.3 Economic considerations in biomass resource assessments

Some studies exclude areas where attainable yields are below a certain minimum level. Other studies exclude biomass resources judged as being too expensive to mobilize, given a certain biomass price level. These assessments address biomass resource availability and cost for given levels of production so that an owner of a facility for secondary energy production from modern biomass could assess a location and the size of a facility for a cost-effective business with a guaranteed supply of biomass throughout the year. Costs models are based on combining land availability, yield levels and production costs to obtain plant- and region-specific cost-supply curves (Walsh, 2008). These are based on projections or scenarios for the development of cost factors, including opportunity cost of land, and can be produced for different contexts and scales—including feasibility studies of supplying individual bioenergy plants and estimating the future global cost-supply curve. Studies using this approach at different scales include Dornburg et al. (2007), Hoogwijk et al. (2009), de Wit et al. (2010) and van Vuuren et al. (2009). P. Gallagher et al. (2003) exemplify the production of cost-supply curves for the case of crop harvest residues and Gerasimov and Karjalainen (2009) for the case of forest wood.

The biomass production costs can be combined with technological and economic data for related logistic systems and conversion technologies to derive market potentials at the level of secondary energy carriers such as bioelectricity and biofuels for transport (e.g., Gan, 2007; Hoogwijk et al., 2009; van Dam et al., 2009c). Using biomass cost and availability data as exogenously defined input parameters in scenario-based energy system modelling can provide information about levels of implementation in relation to a specific energy system context and possible climate and energy policy targets. Cost trends are discussed further in Section 2.7.

Figure 2.5(a) shows projections of European market potential estimated based on food sector scenarios for 2030, considering also nature protection requirements and infrastructure development (Fischer et al., 2010). Estimated production cost supply curves shown in Figure 2.5(b) were subsequently produced including biomass plantations and forest/agriculture residues (de Wit and Faaij, 2010). The key factor determining the size of the market potential was the development of agricultural land productivity, including animal production.

Figure 2.5(c) data for the USA are based on recent assessments of lignocellulosic feedstock supply cost curves conducted at county-level resolution (Walsh, 2008; Perlack et al., 2005; US DOE, 2011). Figure 2.5(d) illustrates the delivered price of biomass to the conversion facility under the baseline conditions for various production levels of lignocellulosic feedstocks.[6] Total market potential for crop-based ethanol and

6 For instance, at a biomass feedstock price of USD_{2005} 3/GJ delivered to the conversion facility, the three types of feedstocks shown in Figure 2.5(d) would provide 5.5 EJ. At higher prices there is more feedstock up to a point, for example, 1.5 EJ for the forest residues in the figure.

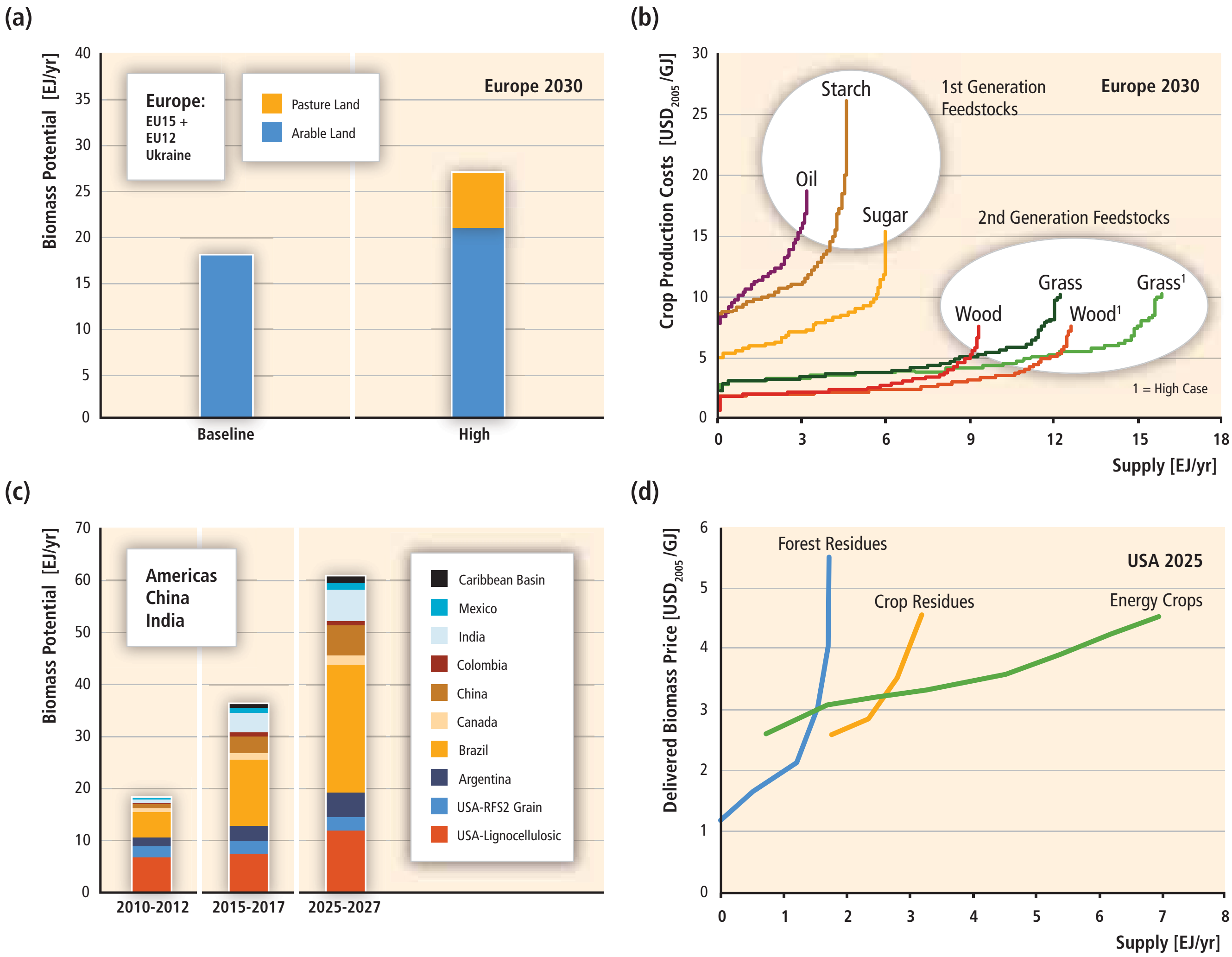

Figure 2.5 | Examples of preliminary market potentials based on feedstock cost supply curves shown in (b) for European countries and (d) for the USA. The feedstock cost supply curves for these assessments are from recent studies conducted at levels of: (a) region; (c) country based on state/province except for the USA, which is performed at a county level. In (c) the US data are for the baseline case and the other countries' cases are for a high-growth scenario (a total of 45 EJ/yr, which would decrease to 25 EJ/yr in the base case and to around 8 EJ/yr in the low case) by 2025. See text for further information. Sources: (a) Fischer et al. (2010); (b) de Wit and Faaij (2010); (c) Kline et al. (2007); Walsh (2008); EPA (2010); (d) Walsh (2008), US DOE (2011).

biodiesel are from EPA (2010) projections. In addition, Figure 2.5(c) includes preliminary estimates of high-growth scenarios of market potentials for the Americas, China and India based on historic production trends and average production costs at the state/province level (Kline et al., 2007), considering multiple crops, residues and perennial biomass crops. Market potentials were estimated based on arable land availability for bioenergy plants and some degree of environmental protection and infrastructure. High-growth market potentials are shown for years 2012, 2017 and 2027 (Kline et al., 2007). The largest supplier, Brazil, is using AgroEcological Zoning (EMBRAPA, 2010) to limit expansion to unrestricted areas with appropriate soil and climate, with no or low irrigation requirements, and low slopes for mechanized harvesting. Similar zoning is available for oil palm.[7] These steps are recommended by several of the organizations developing sustainability criteria (van Dam et al., 2010, and see Section 2.4.5).

2.2.4 Factors influencing biomass resource potentials

As described briefly above, many studies that quantify the biomass resource potential consider a range of factors that reduce it to lower levels than if they are not included. These factors are also connected to impacts arising from the exploitation of biomass resources, which are further discussed in Section 2.5. The most important factors are

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discussed below in relation to how they influence the future biomass resource potential.

2.2.4.1 Residue supply in agriculture and forestry

Soil conservation and biodiversity requirements influence technical potentials for both agriculture and forestry residues. In forestry, the combination of residue harvest and nutrient (including wood ash) input can avoid nutrient depletion and acidification and can in some areas improve environmental conditions due to reduced nutrient leaching from forests (Börjesson, 2000; Eisenbies et al., 2009). Even so, organic matter at different stages of decay plays an important ecological role in conserving soil quality as well as for biodiversity in soils and above ground (Grove and Hanula, 2006). Thresholds for desirable amounts of dead wood in forest stands are difficult to set and the most demanding species require amounts of dead wood that are difficult to reach in managed forests (Ranius and Fahrig, 2006). Dymond et al. (2010) report that estimates from studies taking into account the need for on-site sustainability can be several times lower than those that do not. Large differences were also reported by Gronowska et al. (2009). Titus et al. (2009) report wide ranges (0 to 100%) in allowed residue recovery rates for large-scale logging residue inventories and propose a 50% retention proportion as an appropriate level, noting that besides soil sustainability additional aspects (e.g., biodiversity and water quality) need to be considered.

Development of technologies for stump harvesting after felling increases the availability of residues during logging (Näslund-Eriksson and Gustavsson, 2008). Stump harvesting can also reduce the cost of site preparation for replanting (Saarinen, 2006). It can reduce damage from insects and spreading of root rot fungus, but can also lead to negative effects including reduced forest soil carbon and nutrient stocks, increased soil erosion and soil compaction (Zabowski et al., 2008; Walmsley and Godbold, 2010).

In agriculture, overexploitation of harvest residues is one important cause of soil degradation in many places in the world (Wilhelm et al., 2004; Ball et al., 2005; Blanco-Canqui et al., 2006; Lal, 2008). Fertilizer inputs can compensate for nutrient removals connected to harvest and residue extraction, but maintenance or improvement of soil fertility, structural stability and water-holding capacity requires recirculation of organic matter to the soil (Lal and Pimentel, 2007; Wilhelm et al., 2007; Blanco-Canqui and Lal, 2009). Residue recirculation leading to nutrient replenishment and carbon storage in soils and dead biomass not only contributes positively to climate change mitigation by withdrawing carbon from the atmosphere but also by reducing soil degradation and improving soil productivity. This leads to higher yields and consequently less need to convert land to croplands for meeting future food/fibre/bioenergy demand (i.e., fewer GHG emissions arising from vegetation removal and ploughing of soils). Residue removal can, all other things being equal, be increased when total biomass production per hectare becomes higher and if 'waste' from processing of crop residues that is rich in refractory compounds such as lignin is returned to the field (J. Johnson et al., 2004; Reijnders, 2008; Lal, 2008).

Principles, criteria and indicators are developed to ensure ecological sustainability (e.g., van Dam et al., 2010; Lattimore et al., 2009; Section 2.4.3) but these cannot easily be used to derive sustainable residue extraction rates. Large uncertainties are also linked to the possible future development of several factors determining residue generation rates. Population growth, economic development and dietary changes influence the demand for products from agriculture and forestry, and materials management strategies (including recycling and cascading use of material) influence how this demand translates into demand for basic food commodities and industrial roundwood.

Furthermore, changes in food and forestry sectors influence the residue/waste generation per unit of product output up or down: crop breeding leads to improved harvest index, reducing residue generation rates; implementation of no-till/conservation agriculture requires that harvest residues are left on the fields to maintain soil cover and increase organic matter in soils (Lal, 2004); shifts in livestock production to more confined and intensive systems can increase recoverability of dung but reduce overall dung production at a given level of livestock product output; and increased occurrence of silvicultural treatments such as early thinning to improve stand growth will lead to increased availability of small roundwood suitable for energy uses.

Consequently, the longer-term technical potential connected to residue/waste flows will continue to be uncertain even if more comprehensive assessment approaches are used. It should be noted that it does not necessarily follow that more comprehensive assessments of determining factors will lead to a lower technical potential of residues; earlier studies may have used conservative residue recovery rates as a precaution in the face of uncertainties (S. Kim and Dale, 2004). However, modelling studies indicate that the cost of soil productivity loss may restrict residue removal intensity to much lower levels than the quantity of biomass physically available in forestry (Gan and Smith, 2010).

2.2.4.2 Dedicated biomass production in agriculture and forestry

Studies indicate significant potential for intensifying conventional long-rotation forestry to increase forest growth and total biomass output—for instance, by fertilizing selected stands and using shorter rotations (Nohrstedt, 2001; Saarsalmi and Mälkönen, 2001)—especially in regions of the world with large forest areas that currently practice extensive forest management. Yet, the prospects for intensifying conventional long-rotation forestry to increase forest growth are not thoroughly investigated in the assessed studies of biomass resource potentials. Instead, the major source of increased forest biomass output is assumed to be fast-growing tree plantations. Besides tree plantations, short-rotation coppicing plants such as willow and perennial grasses such as switchgrass and *Miscanthus* are considered candidate bioenergy plants to become established on these lands.

It is commonly assumed that biomass plantations are established on surplus agricultural land. Intensification in agriculture is therefore a key aspect in essentially all of the assessed studies because it influences both land availability for biomass plantations (indirectly by determining the land requirements in the food sector) and the biomass yield levels obtained. High assessed technical potentials for energy plantations rely on high-yielding agricultural systems and international bioenergy trade leading to the result that biomass plantations are established globally where the production conditions are most favourable. Increasing yields from existing agricultural land is also proposed as a key component for agricultural development (Ausubel, 2000; Fischer et al., 2002; Tilman et al., 2002; Cassman et al., 2003; Evans, 2003; Balmford et al., 2005; Green et al., 2005; D. Lee et al., 2006; Bruinsma, 2009). Studies also point to the importance of diets and the food sector's biomass use efficiency in determining land requirements (both cropland and grazing land) for food (Gerbens-Leenes and Nonhebel, 2002; Smil, 2002; Carlsson-Kanyama and Shanahan, 2003; de Boer et al., 2006; Elferink and Nonhebel, 2007; Stehfest et al., 2009; Wirsenius et al., 2010).

Studies of agricultural development (e.g., Koning, 2008; Alexandratos, 2009; IAASTD, 2009) show lower expected yield growth than studies of the biomass resource potential that report very high technical potentials for biomass plantations (Johnston et al., 2009). Some observations indicate that it can be a challenge to maintain yield growth in several main producer countries and that much cropland and grazing land undergoes degradation and productivity loss as a consequence of improper land use (Cassman, 1999; Pingali and Heisey, 1999; Fischer et al., 2002). The possible consequences of climate change for crop yields are not firmly established but indicate net global negative impact, where damages will be concentrated in developing countries that will lose agriculture production potential while developed countries might gain (Fischer et al., 2002; Cline, 2007; Easterling et al., 2007; Schneider et al., 2007; Lobell et al., 2008; Fischer et al., 2009). Water scarcity can limit both intensification possibilities and the prospects for expansion of bioenergy plantations (Berndes, 2008a,b; de Fraiture et al., 2008; de Fraiture and Berndes, 2009; Rost et al., 2009; van Vuuren et al., 2009) but can be partially alleviated through on-site water management (Rost et al., 2009). Biomass resource potential studies that use biophysical data sets and modelling are able to consider water limitations on land productivity. However, assumptions about productivity growth in land use may implicitly presume irrigation development that could lead to problems in regional water availability, use and distribution among users. Empirical data are needed for use in hydrological process models to better understand and predict the hydrological effects of various land use options at the landscape level (Malmer et al., 2010). Water and land use-related aspects are further discussed in Section 2.5.

Conversely, some observations indicate that rates of gain obtained from breeding have increased in recent years after previous stagnation and that yields might increase faster again as newer hybrids are adopted more widely (Edgerton, 2009). Theoretical limits also appear to leave scope for further increasing the genetic yield potential (Fischer et al., 2009). It should be noted that studies finding high technical potential for bioenergy plantations point primarily to tropical developing countries as major contributors. These countries still have substantial yield gaps to exploit and large opportunities for productivity growth—not the least in livestock production (Fischer et al., 2002; Edgerton, 2009; Wirsenius et al., 2010). There is also a large yield growth potential for dedicated bioenergy plants that have not been subject to the same breeding efforts as the major food crops. Selection and development of suitable plant species and genotypes for given locations to match specific soil types, climate and conversion technologies are possible, but are at an early stage of understanding for some energy plants (Bush and Leach, 2007; Chapple et al., 2007; Lawrence and Walbot, 2007; Carpita and McCann, 2008; Karp and Shield, 2008). Traditional plant breeding, selection and hybridization techniques are slow, particularly for woody plants but also for grasses, but new biotechnological routes to produce both genetically modified (GM) and non-GM plants are possible (Brunner et al., 2007). GM energy plant species may be more acceptable to the public than GM food crops, but there are concerns about the potential environmental impacts of such plants, including gene flow from non-native to native plant relatives (Chapotin and Wolt, 2007; Firbank, 2008; Warwick et al., 2009; see Section 2.5.6.1).

There can be limitations on and negative aspects of further intensification aiming at farm yield increases, for example, high crop yields depending on large inputs of nutrients, fresh water and pesticides can contribute to negative ecosystem effects, such as changes in species composition in the surrounding ecosystems, groundwater contamination and eutrophication with harmful algal blooms, oxygen depletion and anoxic 'dead' zones in oceans (Donner and Kucharik, 2008; Simpson et al., 2009; Sections 2.5.5.1 and 2.6.1.2). However, intensification is not necessarily equivalent to an industrialization of agriculture, as agricultural productivity can be increased in many regions and systems with conventional or organic farming methods (Badgley et al., 2007). The potential to increase the currently low productivity of rain-fed agriculture exists in large parts of the world through improved soil and water conservation (Lal, 2003; Rockström et al., 2007, 2010), fertilizer use and crop selection (Cassman, 1999; Keys and McConnell, 2005). Available best practices[8] are not at present applied in many world regions (Godfray et al., 2010), due to a lack of dissemination, capacity building, availability of resources and access to capital and markets, with distinct regional differences (Neumann et al., 2010).

8 For example, mulching, low tillage, contour ploughing, bounds, terraces, rainwater harvesting and supplementary irrigation, drought adapted crops, crop rotation and fallow time reduction.

Conservation agriculture and mixed production systems (double-cropping, crop with livestock and/or crop with forestry) hold potential to sustainably increase land productivity and water use efficiency as well as carbon sequestration and to improve food security and efficiency in the use of limited resources such as phosphorous (Kumar, 2006; Heggenstaller et al., 2008; Herrero et al., 2010). Integration can also be based on integrating feedstock production with conversion—typically producing animal feed that can replace cultivated feed such as soy and corn (Dale et al., 2009, 2010) and also reduce grazing requirements (Sparovek et al., 2007).

Investment in agricultural research, development and deployment could produce a considerable increase in land and water productivity (Rost et al., 2009; Herrero et al., 2010; Sulser et al., 2010) as well as improve robustness of plant varieties (Reynolds and Borlaug, 2006; Ahrens et al., 2010). Multi-functional systems (IAASTD, 2009) providing multiple ecosystem services (Berndes et al., 2004, 2008a,b; Folke et al., 2004, 2009) represent alternative options for the production of bioenergy on agricultural lands that could contribute to development of farming systems and landscape structures that are beneficial for the conservation of biodiversity (Vandermeer and Perfecto, 2006).

2.2.4.3 Use of marginal lands

Biomass resource potential studies also point to marginal/degraded lands—where productive capacity has declined temporarily or permanently—as lands that can be used for biomass production. Advances in plant breeding and genetic modification of plants not only raise the genetic yield potential but also may adapt plants to more challenging environmental conditions (Fischer et al., 2009). Improved drought tolerance can improve average yields in drier areas and in rain-fed systems in general by reducing the effects of sporadic drought (Nelson et al., 2007; Castiglioni et al., 2008) and can also reduce water requirements in irrigated systems. Thus, besides reducing land requirements for meeting food and materials demand by increasing yields, plant breeding and genetic modification could make lands initially considered unsuitable available for rain-fed or irrigated production.

Some studies show a significant technical potential of marginal/degraded land, but it is uncertain how much of this technical potential can be realized. The main challenges in relation to the use of marginal/degraded land for bioenergy include (1) the large efforts and long time periods required for the reclamation and maintenance of more degraded land; (2) the low productivity levels of these soils; and (3) ensuring that the needs of local populations that use degraded lands for their subsistence are carefully addressed. Studies point to the benefits of local stakeholder participation in appraising and selecting appropriate measures (Schwilch et al., 2009) and suggest that land degradation control could benefit from addressing aspects of biodiversity and climate change and that this could pave the way for funding via international financing mechanisms and major donors (Knowler, 2004; Gisladottir and Stocking, 2005). In this context, the production of properly selected plant species for bioenergy can be an opportunity, where additional benefits involve carbon sequestration in soils and aboveground biomass and improved soil quality over time.

2.2.4.4 Biodiversity protection

Considerations regarding biodiversity can limit residue extraction as well as intensification and expansion of agricultural land area. WBGU (2009) shows that the way biodiversity is considered can have a larger impact on technical potential than either irrigation or climate change. The common way of considering biodiversity requirements as a constraint is by including requirements for land reservation for biodiversity protection. Biomass resource potential assessments commonly exclude nature conservation areas from being available for biomass production, but the focus is as a rule on forest ecosystems and takes the present level of protection as a basis. Other natural ecosystems also require protection—not least grassland ecosystems—and the present status of nature protection for biodiversity may not be sufficient for given targets. While many highly productive lands have low natural biodiversity, the opposite is true for some marginal lands and, consequently, the largest impacts on biodiversity could occur with widespread use of marginal lands.

Some studies indirectly consider biodiversity constraints on productivity by assuming a certain expansion of alternative agriculture production (to promote biodiversity) that yields less than conventional agriculture and therefore requires more land for food production (EEA, 2007; Fischer et al., 2009). However, for multi-cropping systems a general assumption of lower yields from alternative cropping systems is not consistent. Biodiversity loss may also occur indirectly, such as when productive land use displaced by energy crops is re-established by converting natural ecosystems into croplands or pastures elsewhere. Integrated energy system and land use/vegetation cover modelling have better prospects for analyzing these risks.

Bioenergy plantations can play a role in promoting biodiversity, particularly when multiple species are planted and mosaic landscapes are established in uniform agricultural landscapes and in some currently poor or degraded areas (Hartley, 2002). Agro-forestry systems combining biomass and food production can support biodiversity conservation in human-dominated landscapes (Bhagwat et al., 2008). Biomass resource potential assessments, however, as a rule assume yield levels corresponding to those achieved in monoculture plantations and therefore provide little insight into how much biomass could be produced if a significant part of the biomass plantation were shaped to contribute to biodiversity preservation.

2.2.5 Possible impact of climate change on resource potential

Technical potentials are influenced by climate change. The magnitude and spatial pattern of climate change remain uncertain[9] despite high scientific confidence that global warming and an intensification of the hydrological cycle will be a consequence of increased GHG concentrations in the atmosphere (IPCC, 2007c). Furthermore, the effect of unhistorical new changes in temperature, irradiation and soil moisture on the growth of agricultural plants is frequently uncertain (Lobell and Burke, 2008), as is the adaptive response of farmers. As a consequence, the overall magnitude and pattern of climate change effects on agricultural production, including bioenergy plantations, remain uncertain. While positive effects on plant growth may occur, detrimental impacts on productivity cannot at present be precluded for many important regions.

Uncertainty also remains about the concurrent ecophysiological effect of elevated atmospheric CO_2 concentration on plant productivity—the CO_2 fertilization effect. Under elevated CO_2 supply, the growth of plants with C_3 photosynthesis is increased unless it is hampered by increased water stress or nutrient depletion (Oliver et al., 2009). The long-term magnitude of the carbon fertilization effect is disputed, with increases in annual NPP of around 25% possible and observed in some field experiments for a doubling of atmospheric CO_2 concentration (the effect levels off at higher CO_2 concentrations), while some expect smaller gains due to co-limitations and eventual adaptations (Ainsworth and Long, 2005; Körner et al., 2007). The magnitude of the effect under agricultural management and breeding conditions may be different and is not well known.

Under climate warming, the increased requirement for transpiration water by vegetation is partially countered by increased water use efficiency (increased stomatal closure) under elevated atmospheric CO_2 concentrations, with variable regional patterns (Gerten et al., 2005). Changes in precipitation patterns and magnitude can increase or decrease plant production depending on the direction of change. Generally, some semi-arid marginal lands are projected to be more productive due to increased water use efficiency under CO_2 fertilization (Lioubimtseva and Adams, 2004). As crop production is projected to mostly decline with warming of more than 2°C (Easterling et al., 2007), particularly in the tropics, biomass for energy production could be similarly affected. Overall, the effects of climate change on biomass technical potential are found to be smaller than the effects of management, breeding and area planted (WBGU, 2009), but in any particular region they can be strong. Which regions will be most affected remains uncertain, but tropical regions are most likely to see the strongest negative impact.

2.2.6 Synthesis

As discussed, narrowing down the technical potential of the biomass resource to precise numbers is not possible. A number of studies show that between less than 50 and several hundred EJ per year can be provided for energy in the future, the latter strongly conditional on favourable developments. From an assessment of the findings, it can be concluded that:

- The size of the future technical potential is dependent on a number of factors that are inherently uncertain and will continue to make long-term technical potentials unclear. Important factors are population and economic/technology development and how these translate into fibre, fodder and food demand (especially share and type of animal food products in diets) and development in agriculture and forestry.

- Additional important factors include (1) climate change impacts on future land use including its adaptation capability; (2) considerations set by biodiversity and nature conservation requirements; and (3) consequences of land degradation and water scarcity.

- Studies point to residue flows in agriculture and forestry and unused (or extensively used) agricultural land as an important basis for expansion of biomass production for energy, both in the near term and in the longer term. Consideration of biodiversity and the need to ensure maintenance of healthy ecosystems and avoid soil degradation set bounds on residue extraction in agriculture and forestry (further discussed in Section 2.5.5).

- Grasslands and marginal/degraded lands are considered to have potential for supporting substantial bioenergy production, but biodiversity considerations and water shortages may limit this potential. The possibility that conversion of such lands to biomass plantations reduces downstream water availability needs to be considered.

- The cultivation of suitable plants can allow for higher technical potentials by making it possible to produce bioenergy on lands less suited for conventional food crops—also when considering that the cultivation of conventional crops on such lands can lead to soil carbon emissions (further discussed in Section 2.5.2).

- Landscape approaches integrating bioenergy production into agriculture and forestry systems to produce multi-functional land use systems could contribute to the development of farming systems and landscape structures that are beneficial for the conservation of biodiversity and help restore/maintain soil productivity and healthy ecosystems.

9 Uncertainties arise because future GHG emission trajectories cannot be known (and are therefore studied using a variety of scenarios), the computed sensitivities of climate models to GHG forcing vary (i.e., the amount of warming that follows from a given emission scenario), and the spatial pattern and seasonality of changes in precipitation vary greatly between models, particularly for some tropical and subtropical regions (Li et al., 2006).

- Water constraints may limit production in regions experiencing water scarcity. But the use of suitable energy crops that are drought tolerant can also help adaptation in water-scarce situations. Assessments of biomass resource potentials need to more carefully consider constraints and opportunities in relation to water availability and competing uses.

Based on this expert review of the available scientific literature, deployment levels of biomass for energy could reach a range of 100 to 300 EJ/yr around 2050 (see Section 2.8.4.1 for more detail). This can be compared with the present biomass use for energy of about 50 EJ/yr. While recent assessments employing improved data and modelling capacity have not succeeded in providing narrow, distinct estimates of the biomass resource potential, they have advanced the understanding of how influential various factors are on the resource potential and that both positive and negative effects may follow from increased biomass use for energy. One important conclusion is that the effects of LUC associated with bioenergy expansion can considerably influence the climate benefit of bioenergy (Section 2.5.5). The insights from the resource assessments can improve the prospects for bioenergy by pointing out the areas where development is most crucial and where research is needed. A summary is given in Section 2.8.4.3.

2.3 Technologies and applications

This section reviews commercial technologies for biomass feedstock production, pretreatment of solid biomass and logistics of supply chains bringing feedstocks to direct users. The users can be individuals (e.g., fuelwood for cooking or heating) or firms (e.g., industrial users or processors). Pretreated and converted energy carriers are more convenient and can be used in more applications than the original biomass and are modern solid (e.g., pellets), liquid (e.g., ethanol) and gaseous (e.g., methane) fuels from which electricity and/or heat or mobility services are produced (see Figure 2.2). The integration of modern biomass with existing and evolving electricity, natural gas, heating (residential and district, commercial and public services), industrial, agriculture/forestry, and fossil liquid fuels systems is discussed thoroughly in Chapter 8.

This section is organized along the supply chain of bioenergy and thus discusses feedstock production and the synergies with related sectors before turning to pretreatment, logistics and supply chains of solid biomass. The section then explains different state-of-the-art conversion technologies for energy carriers from modern biomass before discussing the costs, directly available from relevant literature, of these broader bioenergy systems and supply chains. Section 2.6 provides prospects for technology improvement, innovation and integration before Section 2.7 addresses relevant cost information in terms of levelized cost of production for many world regions.

2.3.1 Feedstocks

2.3.1.1 Feedstock production and harvest

The performance characteristics of major biomass production systems, dedicated plants or primary residues across the world regions are summarized in Table 2.4. The management of energy plants includes the provision of seeds or seedlings, stand establishment and harvest, soil tillage, irrigation, and fertilizer and pesticide inputs. The latter depend on crop requirements, target yields and local pedo-climatic conditions, and may vary across world regions for similar species (Table 2.4). Strategies such as integrated pest management or organic farming may alleviate the need for synthetic inputs for a given output of biomass (Pimentel et al., 2005).

Wood for energy is obtained as fuelwood or as residue. While fuelwood is derived from the logging of natural or planted forests or trees and shrubs grown in agriculture fields, residues are derived from wood waste and by-products. While natural forests are not managed for production per se, problems arise if fuelwood extraction exceeds the regeneration capacity of the forests, which is the case in many parts of the world. The management of planted forests involves silvicultural techniques similar to those used in cropping systems and includes stand establishment and tree felling (Nabuurs et al., 2007).

Biomass may be harvested several times per year (for forage-type feedstocks such as hay or alfalfa), once per year (for annual species such as wheat or perennial grasses), or every 2 to 50 years or more (for short-rotation coppice and conventional forestry, respectively). Sugarcane is harvested annually but planted every 4 to 7 years and grown in ratoons; it is considered a perennial grass. Harvested biomass is typically transported to a collection point on the farm or at the edge of the road before being transported to the bioenergy unit or to an intermediate storage facility. It may be preconditioned and densified to facilitate storage, transport and handling (see Section 2.3.2).

The species listed in Table 2.4 have different possible energy end uses and require diverse conversion technologies (see Figure 2.6). Starch and oil crops are grown and harvested annually as feedstocks for what are called first-generation liquid biofuels (ethanol and biodiesel, see Section 2.3.3). Only a fraction of the total aboveground biomass is used for biofuels, with the rest being processed for animal feed or lignocellulosic residues. Sugarcane plants are feedstocks for the production of sugar and ethanol and, increasingly, sugarcane bagasse and straw, which serve as sources of process heat and extra power in many sugar- and ethanol-producing countries (Macedo et al., 2008; Dantas et al., 2009; Seabra et al., 2010) resulting in favourable environmental footprints for these biorefinery products. Lignocellulosic plants such as perennial grasses or short-rotation coppice may be entirely converted to energy, and feature two to five times higher

Table 2.4 | Typical characteristics of the production technologies for dedicated species and their primary residues. Yields are expressed as GJ of energy content in biomass prior to conversion to energy, or of the ethanol end product for sugar and starch crops. Costs refer to private production costs or market price when costs were unavailable (data from 2005 to 2009). Key to management inputs: +: low; ++: moderate; +++: high requirements.

Feedstock type	Region	Yield	Management			Co-products	Costs	Refs.
		GJ/ha/yr [TJ/km²/yr]	Fertilizer use[1]	Water needs	Pesticides		Examples (2005-2009) USD/GJ	
OIL CROPS		**As oil**						
Oilseed rape	Europe	60–70 [6.7–7.0]	+++	+	+++	Rape cake, straw	7.2–16.0	1,2,3,22
Soybean	North America	16–19 [1.6–1.9]	++	+	+++	Soy cake, straw	11.7	3,12
	Brazil	18–21 [1.8–2.1]	++	+	+++		N/A	
Palm oil	Asia	135–200 [13.5–20.0]	++	+	+++	Fruit bunches, press fibres	N/A	
	Brazil	169 [16.9]	++	+	+++		12.6[2]	3
Jatropha	World	17–88 [1.7–8.8]	+/++	+	+	Seed cake (toxic), wood, shells	3.2	3,4,5,10,11
STARCH CROPS		**As ethanol**						
Wheat	Europe	54–58 [5.4–5.8]	+++	++	+++	Straw, DDGS[3]	5.2	3
Maize	North America	72–79 [7.2–7.9]	+++	+++	+++	Corn stover, DDGS	10.9	3
Cassava	World	43 [4.3]	++	+	++	DDGS	3.3–4	3
SUGAR CROPS		**As ethanol**						
Sugarcane	Brazil	116–149 [11.6–14.9]	++	+	+++	Bagasse, straw	1.0–2.0[2]	3,17
	India	95–112 [9.5–11.2]					N/A	3
Sugar beet	Europe	116–158 [11.6–15.8]	++	++	+++	Molasses, pulp	5.2–9.6	3,13,22
Sorghum (sweet)	China	105–160 [10.5–16.0]	+++	+	++	Bagasse	4.4	2,21
LIGNOCELLULOSIC CROPS		**As ethanol**						
Miscanthus	Europe	190–280 [19.0–28.0]	+/++	++	+		4.8–16	6,8
Switchgrass	Europe	120–225 [12.0–22.5]	++	+	+		2.4–3.2	10,14
	North America	103–150 [10.3–15.0]	++	+	+		4.4	
Short rotation (SR)	Southern Europe	90–225 [9.0–22.5]	+	++	+	Tree bark	2.9–4	10,14
Eucalyptus	South America	150–415 [15.0–41.5]	+/++	+	+		2.7	16,19
SR Willow	Europe	140 [14.0]					4.4	2,7
Fuelwood (chopped)	Europe	110 [11.0]				Forest residues	3.4–13.6	15
Fuelwood (renewable, native forest)	Central America	80–150 [8.0–15.0]					1.8–2.0	23
PRIMARY RESIDUES								
Wheat straw	Europe	60 [6.0]	+			Not Applicable	1.9	2
	USA	7–75 [0.7–7.5]					N/A	14, 20
Sugarcane straw	Brazil	90–126 [9.0–12.6]	+				N/A	17
Corn stover	North America	15–155 [1.5–15.5]	+				N/A	9,14
	India	22–30 [2.2–3.0]	+				0.9	18
Sorghum stover	World	85 [8.5]	+				N/A	9
Forest residues	Europe	2–15 [0.2–1.5]					1–7.7	15

Notes: 1. Nitrogen, phosphorus, and potassium; 2. Market price; 3. DDGS: Dried Distillers Grain with Solubles. These are illustrative cost figures or market prices from the literature. See Annex II for ranges of costs for specific commercial feedstocks over a year period.

References: 1: EEA (2006); 2: Edwards et al. (2007); 3: Bessou et al. (2010); 4: Jongschaap et al. (2007); 5: Openshaw (2000); 6: Clifton-Brown et al. (2004); 7: Ericsson et al. (2009); 8: Fagernäs et al. (2006); 9: Lal (2005); 10: WWI, (2006); 11: Maes et al. (2009); 12: Gerbens-Leenes et al. (2009);13: Berndes (2008a,b); 14: Perlack et al. (2005); 15: Asikainen et al. (2008); 16: Scolforo (2008); 17: Folha (2005); 18: Guille (2007); 19: Diaz-Balteiro and Rodriguez (2006); 20: Lal (2005); 21: Grassi et al. (2006); 22: Faaij (2006); 23: T. Johnson et al. (2009). See Bessou et al. (2010) for specific biofuel volumes per hectare for various countries; see also IEA Renewable Energy Division (2010) for additional country information.

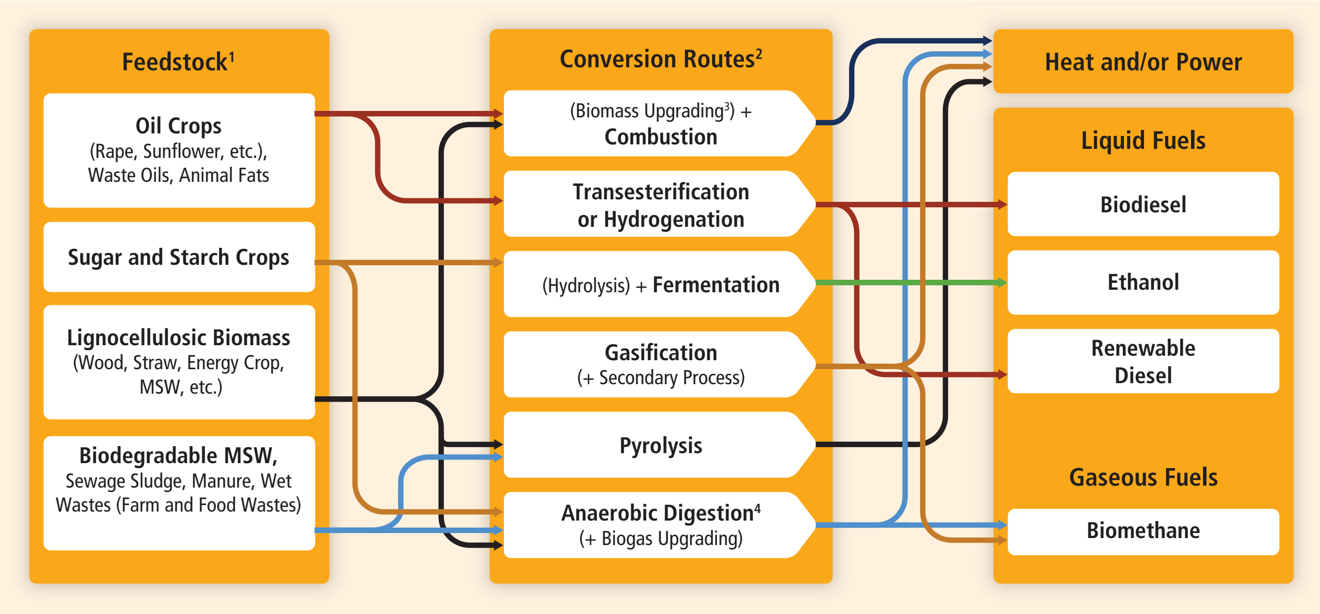

Figure 2.6 | Schematic view of commercial bioenergy routes (modified from IEA, Bioenergy, 2009).

Notes: 1. Parts of each feedstock, for example, crop residues, could also be used in other routes. 2. Each route also gives co-products. 3. Biomass upgrading includes any one of the densification processes (pelletization, pyrolysis, etc.). 4. Anaerobic digestion processes release methane and CO_2 and removal of CO_2 provides essentially methane, the main component of natural gas; the upgraded gas is called biomethane.

yields per hectare than most of the other feedstock types, while requiring far fewer synthetic inputs when managed carefully (Hill, 2007). However, their impact on soil organic matter after the removal of stands is not well understood (Wilhelm et al., 2007; Anderson-Teixeira et al., 2009). Research is underway to assess site-specific removal levels as a function of time and strategies to mitigate weather impacts on residue removal (e.g., Karlen, 2010; Zhang et al., 2010). With technologies that are currently commercial, lignocellulosic feedstocks are only providing heat and power whereas the harvest products of oil, sugar and starch crops are being converted readily to liquid biofuels and in some cases together with heat and power.

Production and harvest costs for dedicated plants vary widely according to the prices of inputs, machinery, labour and land-related costs (Ericsson et al., 2009; Table 2.4). If energy plantations are to compete with land dedicated to food production, the opportunity cost of land (the price that a farmer needs to receive in order to switch from the known annual crop cultivation to an energy crop) could be quite significant and may escalate proportionally with the demand for energy feedstocks (Bureau et al., 2010). Cost-supply curves scaling from farm to the regional level are needed to account for possible large-scale deployment scenario effects (see examples in Figures 2.5(b) and 2.5(d) for feedstock supplies in Europe (cost) and the USA (delivered price), respectively, as a function of feedstock production level, with the unit price per GJ growing several-fold as the total demand for biomass increases).

The cost of forest products depends heavily on harvesting and other logistical practices. In particular labour costs, machinery and the distance from the logging site to the conversion plant are important (Asikainen et al., 2008). This favours local, non-centralized markets especially in developing countries where forests are the dominant fuel source for households (Bravo et al., 2010).

2.3.1.2 Synergies with the agriculture, food and forest sectors

As emphasized in Section 2.2.1, bioenergy feedstock production competes with other uses for resources, chiefly land, with possible negative effects on biodiversity, water availability, soil quality and climate (see Sections 2.2.4 and 2.5). However, synergistic effects may also emerge through the design of integrated production systems, which also provide additional environmental services. Intercropping and mixed cropping are options to maximize the output of biomass per unit area farmed (WWI, 2006). Mixed cropping systems result in increased yields compared to single crops, and may provide both food/fodder and energy feedstocks from the same field (Jensen, 1996; Tilman et al., 2006b). Double-cropping systems have the potential to generate additional feedstocks for bioenergy and livestock utilization and potentially higher yields of biofuel from two crops in the same area in a year (Heggenstaller et al., 2008).

Agro-forestry systems make it possible to use land for food, fodder, timber and energy purposes with mutual benefits for the associated species (R. Bradley et al., 2008). The associated land equivalent ratios may reach up to 1.5, meaning a 50% saving in land area when combining trees with arable crops compared to monocultures (Dupraz and Liagre, 2008) and therefore an equal reduction in indirect LUC effects (see Section

2.5.3). Another option is growing an understory food crop and coppicing the lignocellulosic species to produce residual biomass for energy, similarly to short-rotation coppice (Dupraz and Liagre, 2008). Perennial plants create positive externalities such as erosion control, improved fertilizer use efficiency and reduction in nitrate leaching relative to annual plants (see Section 2.2.4.2). Lastly, the revenues generated from growing bioenergy feedstocks may provide access to technologies or inputs enhancing the yields of food crops, drive additional investments in the agricultural sector and contribute to productivity gains (De La Torre Ugarte and Hellwinckel, 2010), provided feedstock benefits are distributed to local communities (Practical Action Consulting, 2009).

2.3.2 Logistics and supply chains for energy carriers from modern biomass

Because biomass is mostly available in low-density form, it demands more storage space, transport and handling than fossil equivalents, with consequent cost implications. Biomass often needs to be processed (pretreated) to improve handling. For most bioenergy systems and chains, handling and transport of biomass from the source location to the conversion plant is an important contributor to the overall costs of energy production. Crop harvesting, storage, transport, pretreatment and delivery can amount to 20 to 50% of the total costs of energy production (J. Allen et al., 1998).

Use of a single agricultural biomass feedstock for year-round energy generation requires relatively large storage because biomass is only available for a short time following harvest in many places. In addition to such seasonal variations in biomass availability, other characteristics complicate the biomass supply chain and should be taken into account. These include multiple feedstocks with their own complex supply chains, and storage challenges such as space constraints, fire hazards, moisture control and health risks from fungi and spores (Junginger et al., 2001; Rentizelas et al., 2009).

2.3.2.1 Solid biomass supplies and market development for utilization

Over time, several stages may be observed in biomass utilization and market developments in biomass supplies. Different countries seem to follow these stages over time, but clearly differ in their respective stages of development (Faaij, 2006; Sims et al., 2010).

1. Waste treatment (e.g., MSW and use of process residues (paper industry, food industry) onsite at production facilities) is generally the starting phase of a developing bioenergy system. Resources are available and often have a disposal cost (could have a negative value) making utilization profitable and simultaneously solving waste management problems. Large- and small-scale developments are evolving along with integrated resource management.

2. Local utilization of resources from forest management and agriculture. Such resources are more expensive to collect and transport, but usually still economically attractive. Infrastructure development is needed.

3. Biomass market development at regional scale; larger-scale conversion units with increasing fuel flexibility are deployed; increasing average transport distances further improves economies of scale. Increasing costs of biomass supplies make more energy-efficient conversion facilities necessary as well as feasible. Policy support measures such as feed-in tariffs (FITs) are usually needed to develop into this stage.

4. Development of national markets with increasing numbers of suppliers and buyers; creation of a marketplace; increasingly complex logistics. Availability often increases due to improved supply systems and access to markets. Price levels may therefore decrease (see, e.g., Junginger et al., 2005).

5. Increasing scale of markets and transport distances, including cross-border transport of biofuels; international trade in biomass resources (and energy carriers derived from biomass). Biomass is increasingly becoming a globally traded energy commodity (see, e.g., Junginger et al., 2008). Bio-ethanol trade has come closest to that situation (see, e.g., Walter et al., 2008).

6. Growing role for dedicated fuel supply systems (biomass production largely or only for energy purposes). So far, most energy crops are grown because of agricultural interests and support (subsidies for farmers, use of set-aside subsidies), which concentrate on oil crops (such as rapeseed) and surplus food crops (cereals and sugar beets).

Countries that have gained substantial commercial experience with biomass supplies and biomass markets are generally able to obtain substantial cost reductions in biomass supply chains over time. In Finland and Sweden, delivery costs decreased from USD_{2005} 12 to 5/GJ from 1975 to 2003, due to factors such as scale increases, technological innovations or increased competition (Junginger et al., 2005). Similar trends are observed in the corn ethanol industry in the USA and the sugarcane ethanol industry in Brazil (see Table 2.17).

Analyses of regional and international biomass supply chains show that road transport of untreated and bulky biomass becomes uncompetitive and energy-inefficient when crossing distances of 50 to 150 km (Dornburg and Faaij, 2001; McKeough et al., 2005). When long-distance transport is required, early pretreatment and densification in the supply chain (see Sections 2.3.2.3 and 2.6.2) pays off to minimize transport costs. Taking into account energy use and related GHG emissions, well-organized logistic chains can require less than 10% of the initial energy content of the biomass (Hamelinck et al., 2005b; Damen and Faaij, 2006), but this requires substantial scale in transport, efficient pretreatment and minimization of road transport of untreated biomass.

Such organization is observed in the rapidly developing international wood pellet markets (see Sections 2.3.2.3 and 2.4.4). Furthermore, (long distance) transport costs of liquid fuels such as ethanol and vegetable oils contribute only a minor fraction of overall costs and energy use of bioenergy chains (Hamelinck et al., 2005b).

2.3.2.2 Solid biomass and charcoal supplies in developing countries

The majority of poorest households in the developing world depend on solid biomass fuels such as charcoal for cooking, and millions of small industries (such as brick and pottery kilns) generate process heat from these fuels (FAO, 2010a; IEA, 2010b; see Section 1.4.1.2). Despite this pivotal role of biomass, the sector remains largely unregulated, poorly understood, and the supply chains are predominantly in the hands of the informal sector (Sepp, 2008).

When fuelwood is marketed, trees are usually felled and cut into large pieces and transported to local storage facilities where they are collected by merchants and delivered to wholesale and retail facilities, mainly in rural areas. Some of the wood is converted to charcoal in kilns, packed into large bags and transported by hand, animal-drawn carts and small trucks to roadside sites where it is collected by trucks and sent to urban wholesale and retail sites. Thus charcoal making is an enterprise for rural populations to supply urban markets. Crop residues and dung are normally used by animal owners as a seasonal supplement to fuelwood (FAO 2010a).

Shredded biomass residues may be densified by briquetting or pelletizing, typically in screw or piston presses that compress and extrude the biomass (FAO, 1985). Briquettes and pellets can be good substitutes for coal, lignite and fuelwood because they are renewable and have consistent quality and size, better thermal efficiency, and higher density than loose biomass.

There are briquetting plants in operation in India and Thailand, using a range of secondary residues and with different capacities, but none as yet in other Asian countries. There have been numerous, mostly development agency-funded, briquetting projects in Africa, and most have failed technically and/or commercially. The reasons for failure include deployment of new test units that were not proven technically, selection of very expensive machines that did not make economic sense given the location, low local capacity to fabricate components and provide maintenance, and lack of markets for the briquettes due to uncompetitive cost and low acceptance (Erikson and Prior, 1990).

Wood pellets are made of wood waste such as sawdust and grinding dust. Pelletization machines are based on fodder-making technology and produce somewhat lighter and smaller pellets of biomass compared to briquetting. Wood pellets are easy to handle and burn because their shape and characteristics are uniform, transportation efficiency is high and energy density is high. Wood pellets are used as fuel in many countries for cooking and heating applications (Peksa-Blanchard et al., 2007).

Chips are mainly produced from plantations' waste wood and wood residues (branches and presently even spruce stumps) as a by-product of conventional forestry. They require less processing and are cheaper than pellets. Depending on end use, chips may be produced onsite, or the wood may be transported to the chipper. Chips are commonly used in automated heating systems, and can be used directly in coal-fired power stations or for CHP production (Fagernäs et al., 2006).

Charcoal is obtained by heating woody biomass to high temperatures in the absence of oxygen, and has a twice higher calorific value than the original feedstock. It burns without smoke and has a low bulk density, which reduces transport costs. In rural areas in many African countries, charcoal is produced in traditional kilns with efficiencies as low as 10% (Adam, 2009), and typically sold to urban households while rural households use fuelwood. Hardwoods are the most suitable raw material for charcoal, because softwoods incur possibly high losses during handling/transport. Charcoal from granular materials like coffee shells, sawdust and straw is in powder form and needs to be briquetted with or without a binder. Charcoal is also used in large-scale industries, particularly in Brazil from high-yielding eucalyptus plantations (Scolforo, 2008), and in many cases, in conjunction with sustainably produced wood, and also increasingly as a co-firing feedstock in oil-based electric power plants. The projected costs for charcoal production from Brazilian eucalyptus plantations are USD_{2005} 5.7 to 9.8/GJ (Fallot et al., 2009) using industrial carbonizing process.

Charcoal in Africa is predominantly produced in inefficient traditional kilns in the informal sector, often illegally. Current production, packaging and transport of charcoal are characterized by low efficiencies and poor handling, leading to losses. Introducing change to this industry requires that it be recognized and legalized, where it is found to be sustainable and not contradictory to environmental protection goals. Once legalized, it would be possible to regulate it and introduce standards addressing fuel quality, packaging and production kiln standards and better enforcement of which tree species should be used to produce charcoal (Kituyi, 2004).

2.3.2.3 Wood pellet logistics and supplies

Wood pellets are one of the most successful bioenergy-based commodities traded internationally. Wood pellets offer several advantages over other solid biomass fuels: they generally have a low moisture content and a relatively high heating value (about 17 GJ/t), which allow long-distance transport by ship without affecting the energy balance (Junginger et al., 2008). Local transport is carried out by trucks, which sets a feasible upper limit for transportation of 50 km for raw biomass (150 km for pellets) and together with the necessary storage usually represents more than 50% of the final cost. Bulk delivery of pellets is very similar to delivery of home heating oil and is carried out by the lorry driver blowing pellets into the storage space, while a suction pump takes away any dust. Storage solutions include underground tanks, container units, silos or storage within the boiler room. Design of more efficient pellet storage, charging and combustion systems for domestic users is ongoing (Peksa-Blanchard et al., 2007). International trade by ships to ports that are properly equipped for handling pellets is a major logistical barrier.[10] Freight costs are another barrier very sensitive to international trade demand. For instance, in 2004, the average price of pellets at a mill in Canada was USD_{2005} 3.4/GJ; shipped to the Netherlands, USD_{2005} 4.1/GJ (Free on Board); and delivered to the Rotterdam harbour, USD_{2005} 7.5/GJ (Junginger et al., 2008; see also Sikkema et al., 2011).

2.3.3 Conversion technologies to electricity, heat, and liquid and gaseous fuels

Commercial bioenergy routes are shown in Figure 2.6 and start with feedstocks such as forest- or agriculture-based crops or industrial, commercial or municipal waste streams and by-products. These routes deliver electricity or heat from biomass directly or as CHP, biogas and liquid biofuels, including ethanol from sugarcane or corn and biodiesel from oilseed crops. Current biomass-based commercial processes produce a limited range of liquid fuels compared to the variety of petroleum-based fuels and products.

Figure 2.2 presented a complex set of developing technological options based on second- (lignocellulosic herbaceous or woody species) and higher- (aquatic plants) generation feedstocks and a variety of second- (or higher-) generation conversion processes.[11] It also included the commercial (Figure 2.6) first-generation (oil, sugar and starch crops) and solid biomass feedstocks and conversion processes (fermentation, transesterification, combustion, gasification, pyrolysis and anaerobic digestion). Second-generation feedstocks and conversion processes can produce higher-efficiency electricity and heat, as well as a wider range of liquid hydrocarbon fuels, alcohols (including some with higher energy density), ethers, chemical products and polymers (biobased materials) in the developing biorefineries that are discussed in more detail in Section 2.6.3.4. Initial R&D on producing hydrocarbon fuels is starting with sugar and starch crops and covers the range of gasoline, diesel and jet fuel with an increasing focus on chemicals. Both improved first-generation crops (e.g., perennial sugarcane-derived) and second-generation plants suited to specific geographic regions have the potential to provide a variety of energy products, along with high-volume chemicals and materials traditionally derived from the petrochemical industry, maximizing the outputs of end products per unit of feedstock.

10 In most countries with export potential, ports are not yet equipped with storage and modern handling equipment or are poorly managed, which implies high shipping costs.

11 Biofuels produced via new processes are also called advanced or next-genereation biofuels, e.g. from lignocellulosic biomass.

2.3.3.1 Development stages of conversion technologies

The development stages of selected thermochemical, biochemical and chemical routes from solid lignocellulosic biomass, wet waste streams, sugars from sugarcane or starch crops, and vegetable oils are shown in Table 2.5 for the production of heat, power and fuels. For instance, while biomass combustion coupled with electricity generators such as turbines using steam cycles is a commercial system for electricity production (or CHP), coupling with the Stirling engine is still developing, and the Organic Rankine Cycle (ORC) is just starting commercial penetration (van Loo and Koppejan, 2002). Generally, solid wood or waste biomass is processed by thermochemical routes, and wet feedstocks and sugar or starch crops are processed biochemically or chemically and, in the case of the vegetable oils, after a mechanical pressing step (Bauen et al., 2009a). The development stages are roughly divided into R&D, demonstration, early commercial and full commercial products and processes. Precise allocation to these different stages is difficult and somewhat arbitrary, because many developments are taking place in industry and are not often documented in the peer-reviewed literature (Regalbuto, 2009; Bacovsky et al., 2010a,b). Usually, those processes that are deployable throughout the world are fully commercial technologies because their technical risk is small and financing can be obtained (Kirkels and Verbong, 2011).

Synergies between biomass industries and waste management are already established and additional synergies are evolving with the petroleum refining, chemicals, natural gas and coal industries (King et al., 2010; Kirkels and Verbong, 2011). Many bioenergy systems that are moving towards commercialization still have a high technical risk. Section 2.6.3 will describe these additional advancing conversion processes in more detail.

2.3.3.2 Thermochemical processes

Biomass combustion is a process where carbon and hydrogen in the fuel react with excess oxygen to form CO_2 and water and release heat. Direct burning of biomass is popular in rural areas for cooking. Wood and charcoal are also used as a fuel in the industry. Combustion processes are well understood and a wide range of existing commercial technologies are tailored to the characteristics of the biomass and the scale of their applications. Biomass can also be co-combusted with coal in coal-fired plants (van Loo and Koppejan, 2002; Faaij, 2006; Egsgaard et al., 2009).

Pyrolysis is the thermal decomposition of biomass occurring in the absence of oxygen (anaerobic environment) that produces a solid (charcoal), a liquid (pyrolysis oil or bio-oil) and a gas product. The relative amounts of the three co-products depend on the operating temperature and the residence time used in the process. High heating rates of the biomass feedstocks at moderate temperatures (450°C to 550°C) result in oxygenated oils as the major products (70 to 80%), with the remainder split between a biochar and gases. Slow pyrolysis (also known

Table 2.5 | Examples of stages of development of bioenergy: thermochemical (orange), biochemical (blue), and chemical routes (red) for heat, power, and liquid and gaseous fuels from solid lignocellulosic and wet waste biomass streams, sugars from sugarcane or starch crops, and vegetable oils (IEA Bioenergy, 2009; Alper and Stephanopoulos, 2009; Regalbuto, 2009).

Type of Plant	Type of Product	Process	Basic and Applied R&D	Demonstration	Early Commercial	Commercial
			Stage of Development of Process for Product(s) or System(s)			
Low Moisture Lignocellulosic	Densified Biomass		Torrefaction	Hydrothermal Oil (Hy Oil)	Pyrolysis Oil (Py Oil)	Pelletization
Low Moisture Lignocellulosic	Charcoal			Pyrolysis (Biochar)		Carbonization
Low Moisture Lignocellulosic	Heat				Small Scale Gasification	Combustion Stoves
Low Moisture Lignocellulosic	Heat	Combustion			Py/Hy Oil	Home/District/Industrial
Low Moisture Lignocellulosic	Power or CHP	Combustion Coupled with		Stirling Engine	ORC[1]	Steam Cycles
Low Moisture Lignocellulosic	Power or CHP	Co-Combustion or Co-Firing with Coal		Indirect	Parallel	Direct
Low Moisture Lignocellulosic	Power or CHP	Gasification (G) or Integrated Gasification (IG)		IG-Fuel Cell IG-Gas Turbine		
Low Moisture Lignocellulosic	Power or CHP	Gasification (G) or Integrated Gasification (IG)		IG-Combined Cycle	G and Steam Cycle	
Wet Waste	Heat or Power or Fuel	Anaerobic Digestion to Biogas		2-Stage		Landfills (1-Stage)
Wet Waste	Heat or Power or Fuel		Microbial Fuel Cell		Reforming to Hydrogen (H_2)	Small Manure Digesters
Wet Waste	Heat or Power or Fuel				Biogas Upgrading to Methane	
Wet Waste	Heat or Power or Fuel			Hydrothemal Processing to Oils or Gaseous Fuels		
Sugar or Starch Crops	Fuels	Sugar Fermentation		Butanol		Ethanol
Sugar or Starch Crops	Fuels	Microbial Processing[2]	H_2	Gasoline/ Diesel/ Jet Fuel; Biobutanol/Butanols[3]		
Oils Vegetable or Waste	Fuels	Extraction and Esterification				Biodiesel
Oils Vegetable or Waste	Fuels	Extraction and Hydrogenation			Renewable Diesel	
Oils Vegetable or Waste	Fuels	Extraction and Refining		Jet Fuel		

Notes: 1. ORC: Organic Rankine Cycle; 2. genetically engineered yeasts or bacteria to make, for instance, isobutanol (or hydrocarbons) developed either with tools of synthetic biology or through metabolic engineering. 3. Several four-carbon alcohols are possible and isobutanol is a key chemical building block for gasoline, diesel, kerosene and jet fuel and other products.

as carbonization) is practiced throughout the world, for example, in traditional stoves in developing countries, in barbecues in Western countries, and in the Brazilian steel industry (Bridgwater et al., 2003; Laird et al., 2009).

Biomass Gasification occurs when a partial oxidation of biomass happens upon heating. This produces a combustible gas mixture (called producer gas or fuel gas) rich in CO and hydrogen (H_2) that has an energy content of 5 to 20 MJ/Nm^3 (depending on the type of biomass and whether gasification is conducted with air, oxygen or through indirect heating). This energy content is roughly 10 to 45% of the heating value of natural gas. Fuel gas can then be upgraded to a higher-quality gas mixture called biomass synthesis gas or syngas (Faaij, 2006). A gas turbine, a boiler or a steam turbine are options to employ unconverted gas fractions for electricity co-production. Coupled with electricity generators, syngas can be used as a fuel in place of diesel in suitably designed or adapted internal combustion engines. Most commonly available gasifiers use wood or woody biomass and specially designed gasifiers can convert non-woody biomass materials (Yokoyama and Matsumura, 2008). Biomass gasifier stoves are also being used in many rural industries for heating and drying, for instance, in India and China (Yokoyama and Matsumura, 2008; Mukunda et al., 2010). Compared to combustion, gasification is more efficient, providing better controlled heating, higher efficiencies in power production and the possibility for co-producing chemicals and fuels (Kirkels and Verbong, 2011).

2.3.3.3 Chemical processes

Transesterification is the process through which alcohols (often methanol) react in the presence of a catalyst (acid or base) with triglycerides contained in vegetable oils or animal fats to form an alkyl ester of fatty acids and a glycerine by-product. Vegetable oil is extracted from the seeds, usually with mechanical crushing or chemical solvents prior to transesterification. The fatty acid alkyl esters are typically referred to as 'biodiesel' and can be blended with petroleum-based diesel fuel. The protein-rich residue, also known as cake, is typically sold as animal feed or fertilizer, but may also be used to synthesize higher-value chemicals (WWI, 2006; Bauen et al., 2009a; Demirbas, 2009; Balat, 2011).

The **hydrogenation** of vegetable oil, animal fats or recycled oils in the presence of a catalyst yields a renewable diesel fuel—hydrocarbons that can be blended in any proportion with petroleum-based diesel and propane as products. This process involves reacting vegetable oil or animal fats with H_2 (typically sourced from an oil refinery) in the presence of a catalyst (Bauen et al., 2009a). Although at an earlier stage of development and deployment than transesterification, hydrogenation of vegetable oils and animal fats can still be considered a first-generation route as it is demonstrated at a commercial scale.[12] Hydrogenated biofuels have a high cetane number, low sulphur content and high viscosity (Knothe, 2010).

2.3.3.4 Biochemical processes

Biochemical processes use a variety of microorganisms to perform reactions under milder conditions and typically with greater specificity compared to thermochemical processes. These reactions can be part of the organisms' metabolic functions or they can be modified for a specific product through metabolic engineering (Alper and Stephanopoulos, 2009). For instance, *fermentation* is the process by which microorganisms such as yeasts metabolize sugars under low or no oxygen to produce ethanol. Among bacteria, the most commonly employed is *Escherichia (E.) coli*, often used to perform industrial synthesis of biochemical products, including ethanol, lactic acid and others. *Saccharomyces cerevisiae* is the most common yeast used for industrial ethanol production from sugars. The major raw feedstocks for biochemical conversion today are sugarcane, sweet sorghum, sugar beet and starch crops (such as corn, wheat or cassava) and the major commercial product from this process is ethanol, which is predominantly used as a gasoline substitute in light-duty transport.

Anaerobic digestion (AD) involves the breakdown of organic matter in agricultural feedstocks such as animal dung, human excreta, leafy plant materials, urban solid and liquid wastes, or food processing waste streams by a consortium of microorganisms in the absence of oxygen to produce biogas, a mixture of methane (50 to 70%) and CO_2. In this process, the organic fraction of the waste is segregated and fed into a closed container (biogas digester). In the digester, the segregated biomass undergoes biodegradation in the presence of methanogenic bacteria under anaerobic conditions, producing methane-rich biogas and effluent. The biogas can be used either for cooking and heating or for generating motive power or power through dual-fuel or gas engines, low-pressure gas turbines, or steam turbines. The biogas can also be upgraded through enrichment to a higher heat content biomethane (85 to 90% methane) gas and injected in the natural gas grid (Bauen et al., 2009a; Petersson and Wellinger, 2009). The residue from AD, after stabilization, can be used as an organic soil amendment or a fertilizer. The residue can be sold as manure depending upon the composition of the input waste.

Many developing countries, for example India and China, are making use of AD technology extensively in rural areas. Many German and Swedish companies are market leaders in large biogas plant technologies (Faaij, 2006; Petersson and Wellinger, 2009). In Sweden, multiple wastes and manures (co-digestion) are also used and the biogas is upgraded to biomethane, a higher methane content gas, which can be distributed via natural gas pipelines and can also be used directly in vehicles.[13]

2.3.4 Bioenergy systems and chains: Existing state-of-the-art systems

Literature examples of relevant commercial bioenergy systems operating in various countries today by type of energy product(s), feedstock, major process, current and estimated future (2020 to 2030) efficiency, and estimated current and future (2020) production costs are presented in Tables 2.6 and 2.7. Current markets and potential are reviewed in Section 2.4.

Production costs presented in Tables 2.6 and 2.7 are taken directly from the available literature with no attempt to harmonize the literature data because the underlying techno-economic parameters are not always sufficiently transparent to assess the specific conditions under which

12 Many companies throughout the world have patents, demonstration plants, and have tested this technology at a commercial scale for diesel, including Neste Oil's commercial facility in Singapore (Bauen et al., 2009a; Bacovsky et al., 2010b).

13 See, for instance, the Linköping example at www.iea-biogas.net/_download/linkoping_final.pdf (IEA Bioenergy Task 37 success story).

comparable production costs can be achieved, except in cases analyzing multiple products. Section 2.7 presents complementary information on the levelized costs of various bioenergy systems and discusses specific cost determinants based on the methods specified in Annex II and the assumptions summarized in Annex II (note that only a few of the underlying assumptions included in Tables 2.6 and 2.7 were used as inputs to the data presented in Annex III).

2.3.4.1 Bioenergy chains for power, combined heat and power, and heat

Liquid biofuels from biomass have higher production costs than solid biomass (at USD_{2005} ~2 to 5/GJ) used for heat and power. Unprocessed solid biomass is less costly than pre-processed types (via densification, e.g., delivered wood pellets at USD_{2005} 10 to 20/GJ), but entails higher logistic costs and is a reason why both types of solid biomass markets developed (Sections 2.3.2.2 and 2.3.2.3). Because of economies of scale, some of the specific technologies that have proven successful at a large scale (such as combustion for electricity generation) cannot be directly applied to small-scale applications in a cost-effective fashion, making it necessary to identify suitable alternative technologies, usually adapting existing technologies used with carbonaceous fuels. This is the case for ORC technologies, which are entering the commercial stage, and Stirling engine technologies, which are still in developmental phase, or moving from combustion to gasification, coupled to an engine (IEA, 2008a).

An intermediate liquid fuel from pyrolysis is part of evolving heating and power in co-firing applications because it is a transportable fuel (see Table 2.6) and is under investigation for stationary power and for upgrading to transport fuel (see Sections 2.3.3.2 and 2.6.3.1). Pyrolysis oils are a commercial source of low-volume specialty chemicals (see Bridgwater et al., 2003, 2007).

Many bioenergy chains employ cogeneration in their systems where the heat generated as a by-product of power generation is used as steam to meet process heating requirements, with an overall efficiency of 60% or even higher (over 90%) in some cases (IEA, 2008a; Williams et al., 2009). Technologies available for high-temperature/high-pressure steam generation using bagasse as a fuel, for example, make it possible for sugar mills to operate at higher levels of energy efficiency and generate more electricity than what they require. Sugarcane bagasse and now increasingly sugarcane field residues from cane mechanical harvesting are used for process heat and power (Maués, 2007; Macedo et al., 2008; Dantas et al., 2009; Seabra et al., 2010) to such an extent that in 2009, 5% of Brazil's electricity was provided by bagasse cogeneration (EPE, 2010). Similarly, black liquor, an organic pulping product containing pulping chemicals, is produced in the paper and pulp industry and is being burnt efficiently in boilers to produce energy that is then used as process heat (Faaij, 2006). Cogeneration-based district heating in Nordic and European countries is also very popular.

A significant number of electricity generation routes are available, including co-combustion (co-firing) with non-biomass fuels, which is a relatively efficient use of solid biomass compared to direct combustion. Due to economies of scale, small-scale plants usually provide heat and electricity at a higher production cost than do larger systems, although that varies somewhat with location. Heat and power systems are available in a variety of sizes and with high efficiency. Biomass gasification currently provides an annual supply of about 1.4 GW_{th} in industrial applications, CHP and co-firing (Kirkels and Verbong, 2011). Small-scale systems ranging from cooking stoves and anaerobic digestion systems to small gasifiers have been improving in efficiency over time. Several European countries are developing digestion systems using a mixture of solid biomass, municipal waste and manures, producing either electricity or high-quality methane. At the smallest scales, the primary use of biomass is for lighting, heating and cooking (see Table 2.6).

Many region-specific factors determine the production costs of bioenergy carriers, including land and labour costs, biomass distribution density, and seasonal variation. Also, other markets and applications partly determine the value of biomass. For many bioenergy systems, biomass supply costs represent a considerable proportion of total production costs. The scale of biofuel conversion technologies, local legislation and environmental standards can also differ considerably from country to country. Even the operation of conversion systems (e.g., load factor) varies, depending on, for example, climatic conditions (e.g., winter district heating) or crop harvesting cycles (e.g., sugarcane harvest cycles and climate impact). The result is a wide range of production costs that varies not only by technology and resource type, but also by numerous regional and local factors (see examples of such ranges in Section 2.7 and Annex III).

2.3.4.2 Bioenergy chains for liquid transport fuels

Bioenergy chains for liquid transportation fuels are similarly diverse and are described below under three subsections: (1) integrated ethanol, power, and sugar from sugarcane; (2) ethanol and fodder products; and (3) biodiesel. Also covered here are 2008 to 2009 biofuels production costs by feedstock and region. Though liquid biofuels are mainly used in the transport sector, in many developing and in some developed countries they are also used to generate electricity or peak power.

Integrated ethanol, power and sugar from sugarcane
Ethanol from sugarcane is primarily made from pressed juices and molasses or from by-products of sugar mills. The fermentation takes place in single-batch, fed-batch or continuous processes, the latter becoming widespread and being more efficient because yeasts can be recycled. The ethanol content in the fermented liquor is 7 to 10% in Brazil (BNDES/CGEE, 2008), and is subsequently distilled to increase purity to about 93%. To be blended with gasoline in most applications,

Table 2.6 | Current and projected estimated production costs and efficiencies of bioenergy chains at various scales in world regions for power, heat, and biomethane from wastes directly taken from available literature data.

Feedstock/ Country/ Region	Major Process	Efficiency, Application and Production Costs; Eff. = bioenergy/biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ US $cents_{2005}$/kWh	Potential Advances USD_{2005}/GJ US $cents_{2005}$/kWh
Wood log, residues, chips/ Ag. Wastes/ Worldwide	Co-combustion with coal	5 to 100 MW_e, Eff. ~30 to 40%.[1,2] >50 power plants operated or carried on experimental operation using wood logs/ residues, of which 16 are operational and using coal. More than 20 pulverized coal plants in operation.[3] Wood chips (straw) used in at least 5 (10) operating power plants in co-firing with coal.[3]	8.1 – 15 2.9 – 5.3 Inv. Cost (USD/kW): 100 – 1,300[1]	Reduce fuel cost by improved pretreatment, characterization and measurement methods.[4] Torrefied biomass is a solid uniform product with low moisture and high energy content and more suitable for co-firing in pulverized coal plants.[3] Cost reduction and corrosion-resistant materials for coal plant needed.[5]
Wood log, residues, chips/ Ag. Wastes/ Worldwide	Direct combustion	10 to 100 MW_e, Eff. ~20 to 40%.[1,2] Well deployed in Scandinavia and North America; various advanced concepts give high efficiency, low costs and high flexibility.[2] Major variable is biomass supply costs.[2]	20 – 25 7.2 – 9.2 Inv. Cost (USD/kW): 1,600 – 2,500[1]	U.S. 2020 cost projections:[6] 6.3 – 7.8 Stoker fired boilers: 7.5 – 8.1
MSW/ Worldwide	Direct combustion (gasification and co-combustion with coal	50 to 400 MW_e, Eff. ~22%, due to low-temperature steam to avoid corrosion.[7,8] Commercially deployed incineration has higher capital costs and lower (average) efficiency.[2] Four coal-based plants co-fire MSW.[3]	9.1 – 26 3.3 – 9.4[7]	New CHP plant designs using MSW are expected to reach 28 to 30% electrical efficiency, and above 85 to 90% overall efficiency in CHP.[8]
Wood/ Ag. Wastes/ Worldwide	Small scale/gas engine gasification	5 to 10 MW_e, Eff. ~15 to 30%.[1,2] First-generation concepts prove capital intensive.[2]	29 – 38 10 – 14 Inv. Cost (USD/kW): 2,500 – 5,600[1]	Increased efficiency of the gasification and performance of the integrated system. Decrease tars and emissions.[1]
Wood pellets/ EU	Direct coal co-firing or co-gasification	12.5 to 300 MW_e.[9] Used in 2 operating power plants in co-firing with coal.[3] Costs highly dependent on shipment size and distances.[9]	14 – 36 5.0 – 13[9,10]	See PELLETS@LAS Pellet Handbook and www.pelletsatlas.info.
Pyrolysis oil /EU	Coal co-combustion/ gasification	12.5 to 1,200 MW_e.[9] Costs highly dependent on shipment size and distances.[9]	19 – 42 7.0 – 15[9,10]	Develop direct conventional oil refinery integrated and/or upgrading processes allowing for direct use in diesel blends.[1]
Fuelwood/ Mostly in developing countries	Combustion for heat	0.005 to 0.05 MW_{th}, Eff. ~10 to 20%.[2] Traditional devices are inefficient and generate indoor pollution. Improved cook stoves are available that reduce fuel use (up to 60%) and cut 70% of indoor pollution. Residential use (cooking) application.[2]	Inv. Cost (USD/kW): 100[2]	New stoves with 35 to 50% efficiency also reduce indoor air pollution more than 90%.[2] See Section 2.5.7.2.
		1 to 5 MW_{th}, Eff. ~70 to 90% for modern furnaces.[2] Existing industries have highly polluting low-efficiency kilns.[11]	Inv. Cost (USD/kW): 300 – 800[2]	More widespread use of improved kilns to cut consumption by 50 to 60% and reduce pollution.[11]
Organic Waste/MSW/ Worldwide	Landfill with methane recovery	Eff. ~10 to 15% (electricity).[2] Widely applied for electricity and part of waste treatment policies of many countries.[2]	Biogas: 1.3 – 1.7[12]	Continued efficiency increases are expected.
Organic Waste/MSW/ Manures/ Sweden/ EU in expansion	Anaerobic co-digestion, gas clean up, compression, and distribution	Widely applied for homogeneous wet organic waste streams and waste water.[2] To a lesser extent used for heterogeneous wet wastes such as organic domestic wastes.[2]	Fuel: 2.4 – 6.6[13] Elec.: 48 – 59[1] 17 – 21[1]	Improvements in biomass pretreatment, the biogas cleansing processes, the thermophilic process, and biological digestion (already at R&D stage).[1, 17]
		Costs do not include credits for sale of fertilizer by-product.[14]	Fuel: 15 – 16 Inv. Cost (USD/kW): 13,000[14]	In commercial use in Sweden, other EU countries. State of California study shows potential for the augmentation of natural gas distribution.[14]
Manures/ Worldwide	Household digestion	Cooking, heating and electricity applications. By-product liquid fertilizer credit possible.	1 to 2 years payback time	Large reductions in costs by using geomembranes. Improved designs and reduction in digestion times.[15]

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Feedstock/ Country/ Region	Major Process	Efficiency, Application and Production Costs; Eff. = bioenergy/biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ US $cents_{2005}$/kWh	Potential Advances USD_{2005}/GJ US $cents_{2005}$/kWh
Manures/Finland	Farms	Biogas from farms 0.018 to 0.050 MW_e.[16]	Elec.: 77 – 110 Inv. Cost (USD/kW): 14000 – 23000[16]	Improved designs and reduction in digestion times. Improvements in the understanding of anaerobic digestion, metagenomics of complex consortia of microorganisms.[12]
Manures/Food residues	Farms/Food Industry	Biogas from farm animal residues and food processing residues at 0.15 to 0.29 MW_e.[16]	Elec.: 70 – 89 Inv. Cost (USD/kW): 12000 – 15000[16]	

Abbreviations: Inv. = Investment; Elec. = Electricity. References: 1. Bauen et al. (2009a); 2. IEA Bioenergy (2007); 3. Cremers (2009) (see IEA co-firing database at www.ieabcc.nl/database/cofiring.php); 4. Econ Poyry (2008); 5. Egsgaard et al. (2009); 6. NRC (2009b); 7. Koukouzas et al. (2008); 8. IEA (2008a); 9. Hamelinck (2004); 10. Uslu et al. (2008); 11. REN21 (2007); 12. Cirne et al. (2007); 13. Sustainable Transport Solutions (2006); 14. Krich et al. (2005); 15. Müller, (2007); 16. Kuuva and Ruska (2009); 17. Petersson and Wellinger, 2009.

ethanol should be anhydrous and the mixture has to be further dehydrated to reach a grade of 99.8 to 99.9% (WWI, 2006).

Ethanol and fodder products

The dominant dry mill (or dry grind) process (88% of US production) for ethanol fuel manufactured from corn starts with hammer milling the whole grain into a coarse flour, which is cooked into a slurry, then hydrolyzed with alpha amylase enzymes to form dextrins, next hydrolyzed by gluco-amylases to form glucose that is finally fermented by yeasts (the last two processes can be combined). The byproduct is distillers' grains with solubles, an animal feed (McAloon et al., 2000; Rendleman and Shapouri, 2007) that can be sold wet to feedlots near the biorefinery or be dried for stabilization and sold. The most common source of process heat is natural gas. From the early 1980s to 2005, the energy intensity of average dry mill plants in North America has been reduced by 14% for every cumulative doubling of production (learning rate, see Table 2.17; Hettinga et al., 2007, 2009). Since then, 10 cumulative doublings (see also Section 2.7.2) have occurred and the industry continues to improve its energy performance with, for instance, CHP ((S&T)[2] Consultants, 2009). The impacts of this and other process improvements have been estimated to continue such that, by 2022, the projected production cost is USD_{2005} 16/GJ, reduced from USD_{2005} 17.5/GJ in 2009 (EPA, 2010). Table 2.7 presents examples of process improvements from membrane separation for ethanol to enzymes operating at lower temperature, etc. A similar process to corn dry milling is wheat-to-ethanol processing, starting with a malting step, and either enzyme or acid hydrolysis leading to sugars for fermentation.

Biodiesel

Biodiesel is produced from oil seed crops like rapeseed or soybeans, or from trees such as oil seed palms. It is also produced from a variety of greases and wastes from cooking oils or animal fats. This wide range of feedstocks, from low-cost wastes to more expensive vegetable oils, produces biodiesel fuels with more variable properties that follow those of the starting oil seed plant. Fuel standards' harmonization is still under development as are a variety of non-edible oil seed plants (Knothe, 2010; Balat, 2011). Examples of producing regions are shown in Figure 2.7.

Snapshot of 2008 to 2009 biofuels costs from multiple feedstocks and world regions

A snapshot of ranges of biofuels production costs for 2008 to 2009 (primarily 2009) is shown in Figure 2.7 for various world regions based on a variety of feedstocks including wastes and processing streams from the manufacture of sugar (molasses). The snapshot is based on various literature sources such as the recent comparison of costs for Asian Pacific Economic Countries (Milbrandt and Overend, 2008, updated),[14] and data from Table 2.7.[15] For production volumes of these countries see Figure 2.9. For ethanol production, feedstock costs represent about 60 to 80% of the total production cost while, for biodiesel from oil seeds, the proportion is higher (80 to 90%) (data from 2008 to 2009). Latin and Central American sugarcane ethanol is found to have had the lowest production costs over this period, followed by Asian, Pacific and North American starch crops, then by European Union (EU) sugar beet and finally EU grains. Molasses production costs are lower in India and Pacific countries than in Other Asia countries. For biodiesel production, Latin America has the lowest costs, followed by Other Asia countries palm oil, Other Asia rapeseed and soybean, and then North American soybean and EU rapeseed. Biodiesel production costs are generally somewhat higher than for ethanol, but can reach those of ethanol for countries with higher-productivity plants or a lower cost base such as Indonesia/Malaysia and Argentina.

There is significant room for feedstock improvement, mainly its productivity (see also Section 2.6.1), and also for its conversion to products based on the projected increases in efficiency shown in Table 2.7. In an analysis of US biofuel production, the US Environmental Protection Agency (EPA) projected costs based on the Forest and Agricultural Sector Optimization Model (FASOM) and found significant room for improvement (see

14 The study addressed biofuels production, feedstock availability, economics, refuelling infrastructure, use of alternative fuel vehicles, trade, and policies.

15 The ranges of production costs shown here include a variety of waste streams and feedstocks with a broader geographic distribution than those summarized in Section 2.7 and detailed in Annex III. Data in Annex III cover broad ranges of a few feedstocks varying their costs, investment capital, co-products, and financial assumptions. From these transparent techno-economic data, it is possible for the reader to change assumptions and recalculate approximate production costs in specific regions.

Table 2.7 | Current and projected estimated production costs and efficiencies of commercial biofuels in various countries directly taken from available literature data. Also provided is the range of direct reductions of GHG emissions from these routes compared to the fossil fuel replaced (see Section 2.5 for detailed GHG emissions discussion). Parts A and B address ethanol and biodiesel fuels, respectively.

A: Ethanol

Feedstock/ Process	Country/ Region	Efficiency, Application and Production Costs; Eff. = bioenergy/ biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ	Direct GHG Reduction (%) from Fossil Reference (FR)	Potential Advances in Cost Reductions and Efficiency USD_{2005}/GJ
Sugarcane pressed, juice fermented to ethanol, bagasse to process heat and power, and increasingly sale of electricity.	Brazil	Eff. ~38%,[1] ~41% (ethanol only);[2] 170 million l/yr, FC: 11.1; CC*: 3.7 w/o CR.[2]	14.8 w/o CR.[2]	79 to 86% (w/o and w/ CPC); FR: gasoline.[4]	9 – 10.[1] Eff. ~50%.[5] Mechanized harvest and efficient use of sugarcane straw and leaves.[6] Biorefineries with multiple products.[5] Improved yeasts.
	Australia	Eff. ~38%, ~41% (ethanol only), FC: 24.8; CC*: 7 w/o CR.[3]	31.8 w/o CR.[3]		
Corn grain dry milling process for ethanol, fodder (DGS) for animal feed		Eff. ~62%;[2,8] 89% of production.[5] 30% co-product feed DGS sold wet.[5,8] 250 million l/yr plant, FC: 14.1[2] – 29.4[11]; CC*: 6 and CR: 3.8 – 4.4.[2]	20–21 w/ CR[2,15,19] 17.5[5] 31 w/ CR.[11]	35 to 56% for various CPC methods; FR: gasoline 35% (system expansion); Process Heat: NG.[12,13]	Eff. ~64%.[11] Industry Eff. ~65 to 68%. Estimated production cost:16.[5,8] US projected low temperature starch enzyme hydrolysis/fermentation, corn dry fractionation, biodiesel from oil in 90% of mills, membrane ethanol separation, and CHP.[5]
	France	170 million l/yr, FC: 29.3; CC*: 10.5 and CR: 5.[11]	34.8 w/ CR.[11]	60%[9,14]	
Wheat similar to corn to ethanol, fodder (DGS)	EU (UK)	Eff. ~53 to 59%.[11,16] 250 million l/yr plant, FC: 36.2; CC*: 10.5 and CR: 6.[11]	40.7 w/ CR.[11]	40%, DGS to energy.[17] 2 to 80% w/ DGS to energy -8 to 70% w/ DGS to feed.[18]	2020 Eff. ~64%.[11]
	Australia (from waste)	30 million l/yr plant, FC: 14.4; CC*: 8.6 and CR: 0.2.[3]	22.8 w/ CR.[3]	55% wheat starch NG, 27% wheat-coal, 59% wheat w/ straw firing.[3]	
Sugar beet crushing, ferment sugar to ethanol and residue	EU (UK)	Eff. ~12%.[1,16,19] 250 million l/yr plant, FC: 21.6; CC*: 11 and CR: 8.2.[11]	24.4 w/ CR.[11]	28 to 66%, alternate co-product use.[17,18]	2020 Eff. ~15%.[1]
Cassava mashing, cooking, fermentation to ethanol	Thailand/ China	Thailand's process with 38 million l, and feed productivity 20 to 21 t/ha.[16,20,21] China ethanol plant operating at partial capacity.[22]	Thailand: 26[23]	Thailand: 45%.[24] China: 20% with anaerobic digestion energy.[25]	
Molasses by-product of sugar production	Thailand/ Australia	About 3% of molasses could be used for ethanol in Thailand. FC: 10.9 and 10; CC*: 10.1 and CR: 5.7.[23]	Thailand: 21[23] Australia: 16[3]	27 to 59% depending on co-product credit method (Australia).[26,27]	

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Table 2.7; EPA, 2010). The IEA has similarly estimated cost reductions for Organisation for Economic Co-operation and Development (OECD) countries' rapeseed biodiesel by 2030 (IEA Bioenergy, 2007). Further discussions of historical and future cost expectations are provided in Section 2.7.

2.3.5 Synthesis

The key currently commercial technologies are heat production (ranging from home cooking to district heating), power generation from biomass via combustion, CHP, co-firing of biomass and fossil fuels, and first-generation liquid biofuels from oil crops (biodiesel) and sugar and starch crops (ethanol). Several bioenergy systems have been deployed competitively, most notably sugarcane ethanol and heat and power generation from wastes and residues. Other biofuels have also undergone cost and environmental impact reductions and reached significant scales but still require government subsidies.

Modern bioenergy systems involve a wide range of feedstock types, residues from agriculture and forestry, various streams of organic waste, and dedicated crops or perennial systems. Existing bioenergy systems rely mostly on wood, residues and waste for heat and power production, and agricultural crops for liquid biofuels. The economics and yields of feedstocks vary widely across world regions and feedstock types. Energy yields per unit area range from 16 to 200 GJ/ha (1.6 to 20 TJ/km^2) for

B: Biodiesel

Feedstock/ Process	Country	Efficiency, Application and Production Costs; Eff. = bioenergy/biomass energy Component costs in USD_{2005}/GJ	Estimated Production Costs USD_{2005}/GJ	Direct GHG Reduction (%) from Fossil Reference (FR)	Potential Advances in Cost Reductions and Efficiency USD_{2005}/GJ
Rape seed	Germany	Eff. ~29%; for the total system it is assumed that surpluses of straw are used for power production.[27]	31 – 50.[1]	31 to 70%, alternate co-product use.[9,17,28]	25 – 37 for OECD.[1] New methods using bio-catalysts; Supercritical alcohol processing. Heterogeneous catalysts or bio-catalysts. New uses for glycerine. Improved feedstock productivity.[30]
	France	55 GJ/ha/yr (EU), 220 million l/yr plant, FC: 40.5; CC*: 2.7 and CR: 1.7.[11]	41.5 w/ CR.[11]		
	UK	220 million l/yr plant, FC: 35.6; CC*: 4.2 and CR: 11.3.[11]	28.5 w/ CR.[11]		
Oil palm	Indonesia Malaysia Asian countries[20]	163 GJ/ha/yr. 220 million l/yr plant, FC: 25.1; CC*: 2.7 and CR: 1.7.[11]	26.1 w/ CR.[11]	35 to 66%, alternate co-product use.[31] (tropical fallow land, residue to power, good management).[28]	
Vegetable oils	109 countries	Costs neglect some countries with high production costs. FC: 0.6 – 21; CC*: 2.3 – 3.7 and CR: 0 – 6.2.[3,11,29]	4.2 – 17.9.[3,11,31]	N/A	US projected 2020 waste oil ester cost 14.[5] About 50 billion l projected from 119 countries.[29]

Abbreviations: *Conversion costs (CC) include investment costs and operating expenses; CR = Co-product Revenue; CPC = coproduct credit; FC = feedstock cost; FR = fossil reference; N/A = not available.

References: 1. IEA Bioenergy (2007a); 2. Tao and Aden (2009); 3. Beer and Grant 2007; 4. Macedo et al. (2008); 5. EPA (2010); 6. Seabra et al. (2010); 7. UK DfT (2003); 8. Rendleman and Shapouri (2007); 9. Bessou et al. (2010); 10. Wang et al. (2011); 11. Bauen et al. (2009a); 12. Wang et al. (2010); 13. Plevin (2009); 14. Ecobilan (2002); 15. Bain (2007); 16. Fulton et al. (2004); 17. Edwards et al. (2008); 18. Edwards et al. (2007); 19. Hamelinck (2004); 20. Koizumi and Ohga (2008); 21. Milbrandt and Overend (2008); 22. GAIN (2009a; for China); 23. GAIN (2009c; for Thailand); 24. Nguyen and Gheewala et al. (2008); 25. Leng et al. (2008); 26. Beer et al. (2001); 27. Beer et al. (2000); 28. Reinhardt et al. (2006); 29. Johnston and Holloway (2007); 30. Bhojvaid (2007); 31. Wicke et al. (2008).

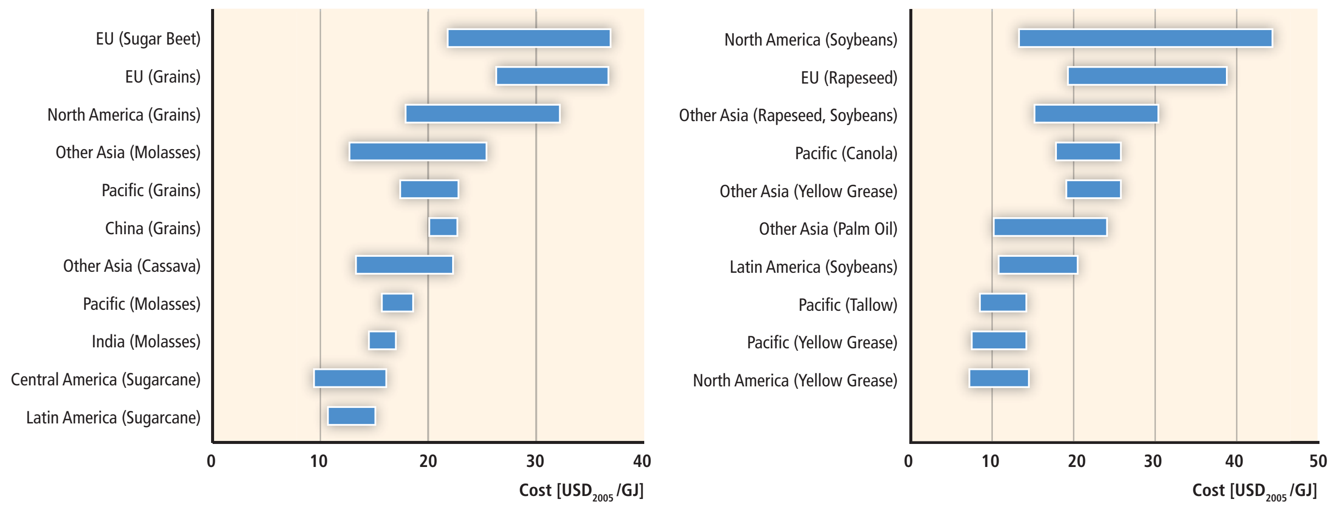


Figure 2.7 | Snapshots of regional ranges of current (2008-2009) estimated production costs for ethanol and biodiesel from various biomass feedstocks and wastes based on Milbrandt and Overend (2008) and Table 2.7.

Notes: The upper value of the range of soybean diesel in North America is due to the single point estimate of Bauen et al. (2009a). Other estimates are in the USD_{2005} 12 to 32/GJ range.

biofuel feedstocks, from 80 to 415 GJ/ha (8 to 41.5 TJ/km^2) for lignocellulosic feedstocks, and from 2 to 155 GJ/ha (0.2 to 15.5 TJ/km^2) for residues, while costs range from USD_{2005} 0.9 to 16/GJ/ha (USD_{2005} 0.09 to 1.6/TJ/km^2). Feedstock production competes with the forestry and food sectors, but the design of integrated production systems such as agro-forestry or mixed cropping may provide synergies along with additional environmental services.

Handling and transport of biomass from production sites to conversion plants may contribute 20 to 50% of the total costs of bioenergy production. Factors such as scale increases, technological innovation and increased competition have contributed to decrease the economic and energy costs of supply chains by more than 50%. Densification via pelletization or briquetting is required for transport distances over 50 km. International costs of delivering densified feedstocks are sensitive to trade and are in the USD_{2005} 10 to 20/GJ range for pellet fuels, and competitive with other market fuels in several regions, thus explaining why such markets are increasing. Charcoal made from biomass is a major fuel in developing countries, and should benefit from the adoption of higher-efficiency kilns and densification technologies.

A significant number of electricity generation routes are available and co-combustion (co-firing) is a relatively efficient way to use solid biomass compared to direct combustion. Small-scale plants usually provide heat and electricity at a higher production cost than larger systems, although this varies somewhat with location. Heat and power systems are available in a variety of sizes and efficiencies. Biomass gasification currently provides about 1.4 GW_{th} of industrial applications, CHP and co-firing. Small-scale systems ranging from cooking stoves and anaerobic digestion systems to small gasifiers have been improving in efficiency over time. Several European countries are developing digestion systems using a mixture of solid biomass, municipal waste and manures, producing either electricity or high-quality methane from upgrading. Many applications, including transport systems, are developing and have the potential to further increase their effectiveness. Technologies at small scales, primarily stoves for heating, continue to improve but diffusion is slow.

Sugarcane-, sugar beet-, and cereal grain-derived ethanol production reached a high level of energy efficiency in major producing countries such as Brazil, the USA, and the EU. The ethanol industry in Center South Brazil significantly increased its cogeneration efficiency and supplied 5% of the country's electricity in 2009. Development of ethanol from waste streams from sugar processing is occurring in India, Pacific and other Asian countries that produce relatively low-cost ethanol but with limited production volumes. Biodiesel production from waste fats and greases has a lower feedstock cost than from rapeseed and soybean but waste fat and grease volumes are limited.

Biofuel production economics is of key importance for future expansion of the biofuels industry. The future development of sustainable biofuels also depends on a balanced scorecard that includes economic, environmental, and social metrics (see Section 2.5). Resolution of technical, economic, social, environmental and regulatory issues remains critical to further development of biofuels. The development of a global market and industry is described in the next section.

2.4 Global and regional status of market and industry development

2.4.1 Current bioenergy production and outlook[16]

Biomass provides about 10% (50.3 EJ in 2008) of the annual global primary energy supply. As presented in Table 2.1, about 60% (IEA accounted) to 70% (including unaccounted informal sector) of this biomass is used in rural areas and relates to charcoal, wood, agricultural residues and manure used for cooking, lighting and space heating, generally by the poorer part of the population in developing countries. Modern bioenergy use (for power generation and CHP, heat or transport fuels) accounted for a primary biomass supply of 11.3 EJ (IEA, 2010a,b; see Table 2.1) in 2008, up from 9.6 EJ[17] in 2004 (IPCC, 2007d), and a rough estimate of 8 EJ in 2000 (IEA Bioenergy, 2007).

The use of solid biomass for energy increased at an average annual growth rate of 1.5%, but secondary energy carriers from modern biomass such as liquid and gaseous fuels increased at 12.1 and 15.4% average annual growth rates, respectively, from 1990 to 2008 (IEA, 2010a). As a result, biofuels' share of global road transport fuel use was 2% in 2008. In 2009, the production of ethanol and biodiesel increased by 10 and 9%, respectively, to 90 billion litres; biofuels provided nearly 3% of global road transport fuel use in 2009, as oil demand decreased for the first time since 1980 (IEA, 2010b). Government policies in various countries led to a five-fold increase in global biofuels production from 2000 to 2008. Biomass and renewable waste power generation was 259 TWh (0.93 EJ) in 2007 and 267 TWh (0.96 EJ) in 2008, representing 1% of the world's electricity, which doubled since 1990 (from 131 TWh or 0.47 EJ). Industrial biomass heating accounts for 8 EJ while space and water heating for building applications account for 3.4 EJ (IEA, 2010b; see Table 2.1).

Most of the increase in the use of biofuels in 2007 and 2008 occurred in the OECD, mainly in North America and Europe. Excess capacity was installed in expectation of increased demand with mandates and subsidies in many countries; however, feedstock and oil price increases and the worsening overall economic conditions during and after the credit crunch made many of these facilities unprofitable. As a result, some are underutilized, more so in biodiesel than in ethanol production. Some plants are not in operation and some businesses failed. Asia Pacific and Latin American markets are growing, primarily

16 This sub-section is largely based on the WEO 2009 (IEA, 2009b) and 2010 (IEA, 2010b) and the Global Biofuels Center assessments, web-based biofuels news, reports, trade, and market information (Hart Energy Publishing, LP, www.globalbiofuelscenter.com/).

17 The 9.6 EJ is an estimated equivalent primary biomass energy deducting the non-biogenic MSW that was included in the AR4 study (IPCC, 2007d), or about 0.4 EJ of plastics (estimated based on subsequent IEA 2005 data).

in developing countries due to economic development. Despite this anticipated short-term downturn, world use of biofuels for road transport is projected to recover in the next few years (IEA, 2010b).

The WEO (IEA, 2010b) projections for 2020 to 2035 are summarized in Table 2.8 (in terms of global TPES from biomass); Table 2.9 (in terms of global biofuel demand, i.e., secondary energy); and Table 2.10 (in terms of global electricity generation)—all of them comparing a baseline case (Current Policies) and a mitigation scenario reaching an atmospheric CO_2 concentration of 450 ppm by 2100.

The overall TPES from biomass in the 450 ppm CO_2 stabilization scenario increases to 83 (95) EJ/yr in 2030 (2035) adding 14 (12) EJ to the Reference (Current Policies) scenario (see Table 2.8).

and many of the technologies needed are at the demonstration to early commercialization stages of development in 2011 (see Tables 2.5 and 2.15; IEA Renewable Energy Division, 2010).

Global biomass and renewable waste electricity generation is also projected to increase in both scenarios, reaching 5.6% of global electricity generation by 2035 in the 450-ppm scenario as shown in Table 2.10. The climate change driver nearly doubles the anticipated penetration levels of biopower compared to the projected levels owing to continuation of current policies.

In the WEO (IEA, 2010b), biomass industrial heating applications for process steam and space and hot water heating for buildings would each double in absolute terms from 2008 levels by 2035, offsetting some of the expected decrease in the major component of the heating category, traditional biomass, as the total heating demand is projected to decrease in 2035. Industrial and building heating is seen as an area for continued biomass growth. In fact, biomass is very efficiently used in CHP plants, supplying a district heating network. Biomass combustion to produce electricity and heat in CHP plants is an efficient and mature technology and is already competitive with fossil fuels in certain locations (IEA, 2008a).

Table 2.8 | IEA WEO scenarios: global TPES from biomass projections (EJ/yr) for 2020 to 2035 (IEA, 2010b).

Year	2007	2008	2020		2030		2035	
Scenario	Actual	Actual	Baseline	450 ppm	Baseline	450 ppm	Baseline	450 ppm
EJ/yr	48	50	60	63	66	83	70	95
Delta, EJ	2		3		17		25	

Table 2.9 | IEA WEO scenarios: global biofuels demand projections (EJ/yr) for 2020 to 2035 reported in secondary energy terms of the delivered product according to IEA data (IEA, 2010b).

Year	2008	2009	2020		2030		2035	
Scenario	Actual	Actual	Baseline	450 ppm	Baseline	450 ppm	Baseline	450 ppm
EJ/yr	1.9	2.1	4.5	5.1	5.9	11.8	6.8	16.2
% Global road transport	2	3	4.4	7	4.4	11 (and air)	5	14 (and air)
% Advanced biofuels			Deployment			60		66

Table 2.10 | IEA WEO scenarios: primary biomass and renewable waste electricity generation projections for 2030 (IEA, 2009, 2010b) and 2035 (IEA, 2010b).

Year	2008	2030		2035	
Scenario	Actual	Baseline, Reference case	450 ppm Scenario	Current Policies	450 ppm Scenario
TWh/yr (EJ/yr)	267 (0.96)	825 (3.0)	1380 (5.0)	1052 (3.8)	1890 (6.8)
% Global electricity	0.96	2.4	4.5	2.7	5.6
TWh/yr (EJ/yr)		840 (3.0)	1450 (5.2)		
% Global electricity		2.4	4.8		

The use of liquid and gaseous energy carriers from modern biomass is growing, in particular biofuels, with a 37% increase from 2006 to 2009 (IEA, 2010c). Regions that currently have strong policy support for biofuels are projected to take the largest share of the eight-fold increase in the market for biofuels that occurs from 2008 to 2035. This is led by the USA (where one-third of the increase occurs), followed by Brazil, the EU and China. To highlight the scale, 7 EJ of advanced biofuels (second generation) is greater than, for example, India's 2007 oil consumption,

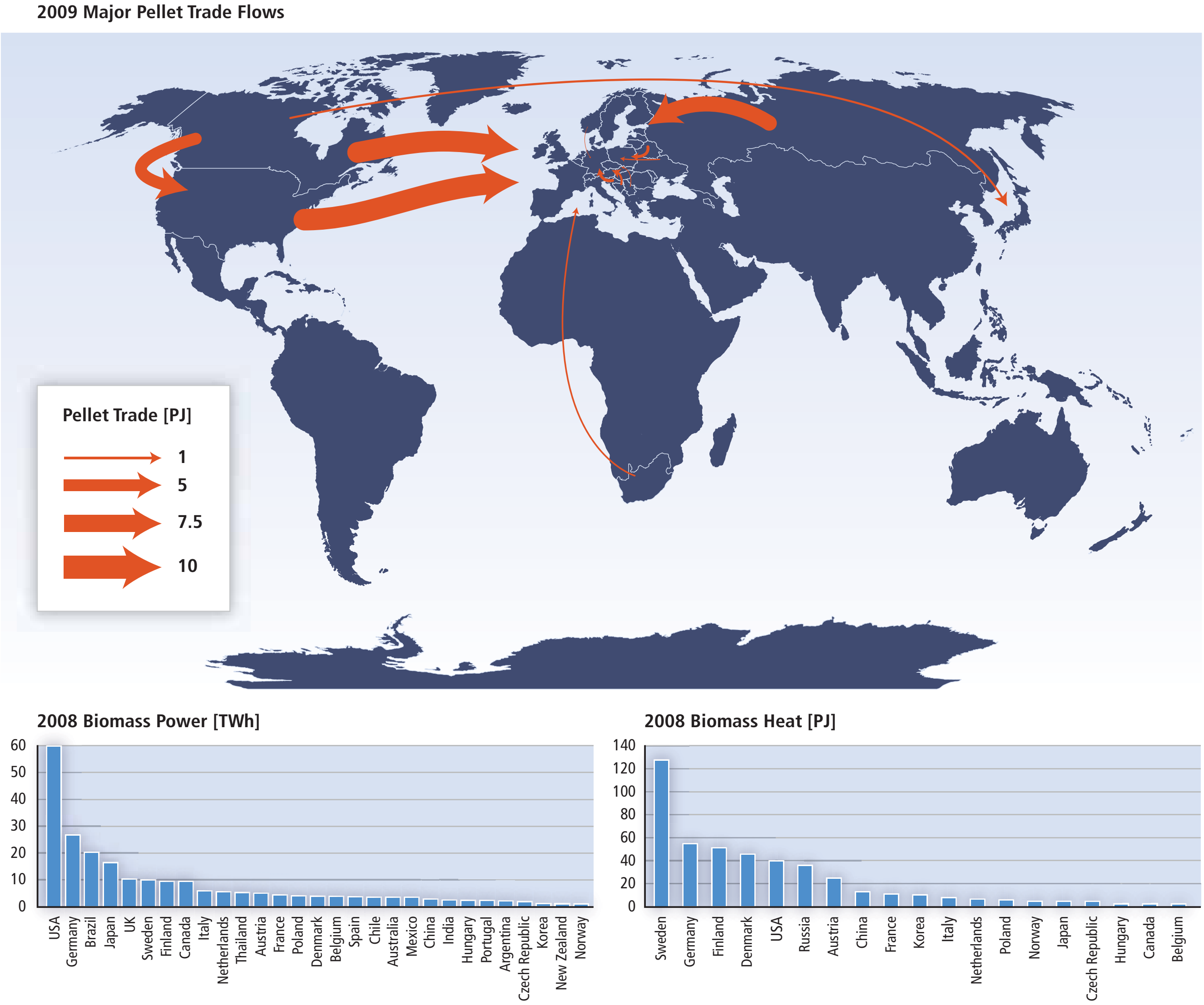


Figure 2.8 | Examples of biomass electricity generation and heating for select countries in 2008 and of the 2009 global trade in wood pellets. Sources: bar chart data from IEA (2010c); trade flow data reproduced from Sikkema et al. (2011) with permission from the Society of Chemical Industry and John Wiley & Sons, Ltd.

The use of solid biomass for electricity production is important, especially from pulp and paper plants and sugar mills. Bioenergy's share of total energy consumption is increasing in the G8 countries (e.g., co-combustion for electricity generation, building heating with pellets), especially in Germany, Italy and the UK (IEA, 2009b). The electricity generation and biomass heating are shown in Figure 2.8. Worldwide biomass heating statistics are uncertain (Sims, 2007) for developed countries. In Europe, biomass heating applications in the building sector are cost competitive and are shown in Figure 2.8. For developing countries, the statistics are less developed, as tools to collect data from informal sectors are lacking (see Table 2.1).

2.4.2 Traditional biomass, improved technologies and practices, and barriers

Biomass is an important traditional fuel in developing countries, where on average it accounts for 22% of the energy mix;[18] in the poorest countries it accounts for more than 80% (see IEA, 2010c). Traditional sources of biomass include mostly wood fuels but also agriculture residues and dung, and they contribute essentially to domestic heating and cooking. The number of people dependent on biomass for cooking is estimated at

18 Average contribution to the energy mix from renewable and waste combustibles was 48, 20, 24, 27, and 10% for Africa, Latin America, India, Non-OECD Asia, and China, respectively, while only 4% for the OECD countries in 2008 (IEA, 2010c).

2.7 billion (for 2008) and is projected to increase to 2.8 billion by 2030 (IEA, 2010b). Many thousand biomass-based small industries—such as brick making, food, charcoal, bakeries and others—provide employment and income to people. Most of these technologies are resource intensive, highly polluting and exhibit low efficiencies (see Tables 2.1 and 2.6; FAO, 2010b). However, there is currently a significant and growing market for improved technologies. Also, several programmes at the global, national and local levels are in place to disseminate more efficient technology options.

2.4.2.1 Improved biomass cook stoves

Most developing countries have initiated some type of improved cook stove (ICS) programme since the 1980s. The World Bank Energy Sector Management Assistance Program (World Bank, 2010) reviewed in depth the international experience on improved stoves and summarized significant lessons learned for developing countries and, in particular, for Bangladesh, the objective of the study. For Eastern African countries, see Karekezi and Turyareeba (1995). Many programmes are in operation, sponsored by development agencies, governments, nongovernmental organizations (NGOs) and the private sector. By the end of 2009, 173 million energy saving stoves were in use in China. Other countries were not very successful in disseminating ICS. Over the past 10 years, a whole new generation of advanced biomass stoves and dissemination approaches have been developed, and the field is now bursting with innovations (World Bank, 2010).

A variety of technologies are used, including direct combustion, small-scale gasification, small-scale anaerobic digestion, direct use of a liquid fuel (ethanol) or combinations of technologies.[19] As a result, combustion efficiency has been greatly improved relative to the alternative open fires. The cost ranges from less than USD 10 for the simpler models to more than USD 100 or more for more sophisticated models and USD 100 to 300 for institutional stoves (e.g., schools, hospitals, and barracks) according to 2007 to 2009 cost range data. Fuel savings are 30 to 60%, measured in field conditions, to more than 90%, measured in pilot testing of the most advanced models (Berrueta et al., 2008; World Bank, 2010). There are also significant reductions in GHG emissions and indoor air pollutants (Section 2.5.4).

By 2008 an estimated 820 million people (around 30% of the 2.7 billion that rely on traditional biomass for cooking, see Section 1.4.1.2) in the world were using some type of improved cook stove for cooking (Legros et al., 2009), and more than 160 stove programmes are in place worldwide, with recently launched large-scale national programmes in India, Mexico and Peru, as well as large donor-based programmes in Africa. The UN Foundation-led Global Alliance for Clean Cookstoves started in 2010 to promote the dissemination and adoption of 100 million advanced cook stoves by 2020.[20]

Two main lines of technology development have been followed. Mass-scale approaches—some of which use state-of-the-art manufacturing facilities—rely on centralized production of stoves or critical components, with distribution channels that can even include different countries. As a result, there are companies that produce more than 100,000 stoves per year (Bairiganjan et al., 2010). A second approach relies more on strengthening regional capabilities, giving more emphasis to local employment creation; sometimes the stoves are built onsite rather than sold on markets, such as the Patsari Stove in Mexico and Groupe Energies Renouvelables, Environnement et Solidarités (GERES) in Cambodia (Bairiganjan et al., 2010). Improved stove designs to appeal to consumers, market segmentation and microfinance mechanisms have also been developed (Hilman et al., 2007).

Incentives and barriers

Cookstove programmes have been successful in countries where proper assessment was made of the local needs in terms of technology, cooking devices, user needs and institutional setting. Financial incentives have helped with the dissemination, while an enabling institutional environment by governments—such as in China—has also helped promote new technologies. Finally, accurate monitoring and evaluation has been critical for successful stove adoption and use (Bairiganjan et al., 2010; Venkataraman et al., 2010). Other drivers for increased adoption of ICS have included: (1) cooking environments where users feel smoke is a health problem and annoyance; (2) a short consumer payback (few months); (3) donor or government support extended over at least five years; and (4) financial support to build local institutions and develop local expertise. Government assistance has been more effective in technical advice and quality control. Carbon offset projects are increasingly providing new financing for these activities, either through the Voluntary Market (Gold Standard) or, increasingly, through the CDM. Successful programmes with low-cost but efficient ICS report that local poor residents purchased cookstoves without support of programmes because of fuel savings (World Bank, 2010).

Several barriers need to be overcome for a rapid diffusion of ICS. There are needs for (1) substantial increases in R&D;[21] (2) more field testing and stove customization for users' needs; and (3) strict product specifications and testing and certification programmes. Finally, it is important to better understand the patterns of stove adoption given the multiple devices and fuels as well as mechanisms to foster their long-term use.

19 These ICS technologies include improvements in the combustion chamber (such as the Rocket 'elbow'), insulation materials, heat transfer ratios, stove geometry and air flow (Still et al., 2003). The most reliable of these use small electric blowers to stabilize the combustion, but there are also designs using natural air flow (World Bank, 2010).

20 See www.cleancookstoves.org.

21 Particularly for new insulating materials as well as robust designs that endure several years of rough use, and small-scale gasification.

2.4.2.2 Biogas systems

Convenient cooking and lighting are also provided by biogas production using household-scale biodigesters.[22] Biodigesters have the distinct co-benefits of enhancing the fertilizer value of the dung in addition to reducing the pathogen risks of human waste. Early stage results have been mixed because of quality control and management problems, which have resulted in a large number of failures. Smaller-scale biogas experience in Africa has been often disappointing at the household level as the capital cost, maintenance and management support required have been higher than expected. The experience gained, new technology developments (such as the use of geo-membranes), better understanding of the resources available to users, such as dung, and better market segmentation are improving the success of new programmes (Kishore et al., 2004).[23]

Incentives and barriers

Key factors for project success include a proper understanding of users' needs and resources.[24] For example, the role of NGOs, networks and associations in transfer, capacity building, extension and adoption of biogas plants in rural India was found to be very important (Myles, 2001). Financial mechanisms, including microfinance schemes and carbon offset projects under the CDM, are also important in the implementation of household biogas programmes. Barriers to increased biogas adoption include lack of proper technical standards; insufficient financial mechanisms to achieve desired profits relative to the digesters' investment, installation and equipment costs; and relatively high costs of technologies and of labour (e.g., geological investigations into proper site installations). Other related barriers include poor reliability and performance of the designs and construction, and limited application of knowledge gained from the operation of existing plants to the design of new plants.

Many other small-scale bioenergy applications are emerging, including systems aimed at transport and productive uses of energy and electricity. The market penetration is still limited, but many of these systems show important benefits in terms of livelihood, new income, revenues and efficiency (Practical Action Consulting, 2009).

22 By the end of 2009, there were 35 million household biodigesters in China and in India (Gerber, 2008; REN21, 2009, 2010). There is also significant experience with commercial biogas use in Nepal. Müller (2007) reviewed existing biogas technologies and case studies with contributions from China, Thailand, India, South Africa, Kenya, Rwanda, and Ghana.

23 For example, the high first cost (which can run up to USD 300 for some systems, including the digestion chamber unit) of traditional systems is being reduced considerably by new designs that reduce the digestion time, increase the specific methane yield and use alternate or multiple feedstocks (such as leafy material and food wastes), substantially reducing the size and cost of the digestion unit (Lehtomäki et al., 2007).

24 The Hedon Household Network provides references to the experience in the field at www.hedon.info. One example is www.hedon.info/docs/20060531_Report_(final)_on_Biogas_Experts_Network_Meeting_Hanoi.pdf.

2.4.3 Modern biomass: Large-scale systems, improved technologies and practices, and barriers

The deployment of large-scale bioenergy systems faces a wide range of barriers. Economic barriers appear most prominent for currently commercial technologies constrained by feedstock availability and by meeting sustainability requirements (Fagernäs et al., 2006; Mayfield et al., 2007), while technical barriers predominate for developing technologies such as second-generation biofuels (Cheng and Timilsina, 2010). Non-technical barriers are related to deployment policies (fiscal incentives, regulations and public finance), market creation, supply chain, infrastructure development, community engagement, collaboration and education (Mayfield et al., 2007; Adams et al., 2011). No single barrier appears to be most critical, but the interactions among different individual barriers seem to impede rapid bioenergy expansion. The relative importance of the barriers hinges on the particular value chain and context considered. In particular, national regulations, such as price-driven FITs for bioelectricity and quantity-driven blending level mandates for biofuels, play a major role in the emergence of large-scale projects, alongside public finance through government loans or guarantee programmes (Table 2.11; Section 11.5.3; Chum and Overend, 2003; Fagernäs et al., 2006). The priorities also depend on the stakeholder groups involved in the value chain and differ from feedstock producers to fuel producers and through to end users (Adams et al., 2011). Scale also matters, because barriers perceived by national governments differ from those perceived by stakeholders and communities in the vicinity of bioenergy projects.[25]

Technical and non-technical barriers may be overcome by appropriate policy frameworks, economic instruments such as government support tied to private investment support for first-of-a kind commercial plants to decrease investment risk,[26] sustained RD&D efforts, and catalysis of coordinated multiple private sector activities[27] (IATA, 2009; Regalbuto, 2009; Sims et al., 2010). In 2009, global public RD&D efforts were USD 0.6 billion and 0.2 billion for biofuels and biomass to energy, respectively, and biofuels public funding increased by 88% from 2008. Corporate RD&D efforts were USD 0.2 billion each for the two areas (UNEP/SEFI/Bloomberg, 2010). Venture capital and private equity investing was

25 For instance, the impacts of bioenergy development on landscapes are a barrier to adoption of new bioenergy conversion plants by some farmers as local acceptance decreases with increased local traffic to supply biomass (van der Horst and Evans, 2010). Some governments are more sensitive to increased efficiencies in GHG abatement and competitiveness of bioenergy with other energy sources, which often means increased scale (Adams et al., 2011) unless technologies succeed in increasing their throughput to accommodate smaller-scale applications without as large of a cost penalty (see Section 2.6.2).

26 See, for instance, the US Department of Energy's integrated biorefinery projects, including first-of-a-kind commercial plants, www1.eere.energy.gov/biomass/integrated_biorefineries.html; see also the IEA Bioenergy Task 39 interactive site with pilot, demonstration and commercial biofuels plants: biofuels.abc-energy.at/demoplants/projects/mapindex.

27 See, for instance, the European Industrial Bioenergy Initiative, a multi-industry partnership across the bioenergy value chains, www.biofuelstp.eu/eibi.html.

Table 2.11 | Key policy instruments in selected countries where E = electricity, H = heat, T = transport, Eth = ethanol and BD = biodiesel (modified after GBEP, 2008; updated with data from the REN21 global interactive map (see note 4 to Figure 2.9); reproduced with permission from GBEP).

Country	Policy Instruments							
	Binding Targets/ Mandates[1]	Voluntary Targets[1]	Direct Incentives[2]	Grants	Feed-in Tariffs	Compulsory grid connection	Sustainability Criteria	Tariffs
Brazil	E, T		T					removed
China		E, T[4]	T	E, T	E, H	E, H		n/a
India	T, (E[3])	T(BD)	E	E, H, T	E			n/a
Mexico	(E[3])	(T)	(E)			(E)		Eth
South Africa	T, E	E, (T)	(E), T					n/a
Canada	E, T, H	E[4], T[4]	T	E, H, T				Eth
France		E[3], H[3], T	E, H, T		E			as EU below
Germany	E[3], T		H	H	E	E	(E, H, T)	as EU below
Italy	E[3]	E[3], T	T	E, H, T	E	E		as EU below
Japan		E, H, T				E		Eth, B-D
Russia		(E, H, T)	(T)					n/a
UK	E[3], T[3]	E[3], T	E, H, T	E, H, T	E		T	as EU below
USA	T, T[4], E[4]	E[4]	E, H, T	E, T	E			Eth
EU	E[3], T	E[3], H[3], T	T	E, H, T		E	(T)	Eth, B-D

Notes: 1. blending or market penetration; 2. fiscal incentives: tax reductions; public finance: loan support/guarantees; 3. target applies to all RE sources; 4. target is set at a sub-national level.

estimated at USD 1.1 billion and 0.4 billion for biofuels and biomass to energy, respectively (UNEP/SEFI/Bloomberg, 2010). A significant fraction of the venture capital investment was in the USA (Curtis, 2010). There was significant first-generation biofuels industry consolidation in the USA and in Brazil. Major global oil company investments occurred in both countries and in the EU (IATA, 2009; Curtis, 2010; IEA, 2010b; UNEP/SEFI/Bloomberg, 2010).

Addressing knowledge gaps in the sustainability of bioenergy systems, as discussed in Section 2.5, is reported as crucial to enable public and private decision making and increase public acceptance. Those gaps are mostly related to feedstock production and the associated impacts on land use, biodiversity, water, and food prices (WWI, 2006; Adams et al., 2011). Other suggested R&D avenues include more sustainable feedstocks and conversion technologies (WWI, 2006), increased conversion efficiency (Cheng and Timilsina, 2010) and overall chain optimization (Fagernäs et al., 2006).

Integrating bioenergy production with other industries/sectors (such as forest, food/fodder, power, or chemical industries) should improve competitiveness and utilize raw materials more efficiently (Fagernäs et al., 2006). For instance, industrial symbiosis evolved over 50 years in the city of Kalundborg, Denmark, as a community of businesses located together on a common property voluntarily entered into several bilateral contracts to enhance environmental, economic and social performance in managing environmental and resource issues by sharing resources in close cooperation with government authorities (Grann, 1997).[28] The Kalundborg experience increased the viability of the businesses involved over the years and developed a community thinking systems approach that could be applied to many other industrial settings (Jacobsen, 2006).

2.4.4 Global trade in biomass and bioenergy

Global trade in biomass feedstocks (e.g., wood chips, raw vegetable oils, agricultural residues) and especially of energy carriers from modern

28 The latest addition is a wheat straw-to-ethanol demonstration plant to the complex of a coal power plant, an oil refinery, biotechnology companies, district heating, fish aquaculture, landfill plant with gas collection, fertilizer production, gypsum (plaster), soil remediation and water treatment facilities, and others. Waste products (e.g., heat, gas and sulphur, ash, hot water, yeasts, fertilizers, waste slurries, solid wastes) from one company become a resource for use by one or more companies, and a nearby town, in a well-functioning industrial ecosystem. (See, for instance, www.kalundborg.dk/Erhvervsliv/The_Green_Industrial_Municipality/Cluster_Biofuels_Denmark_(CBD).aspx and www.inbicon.com/Biomass Refinery/Pages/Inbicon_Biomass_Refinery_at_Kalundborg.aspx.)

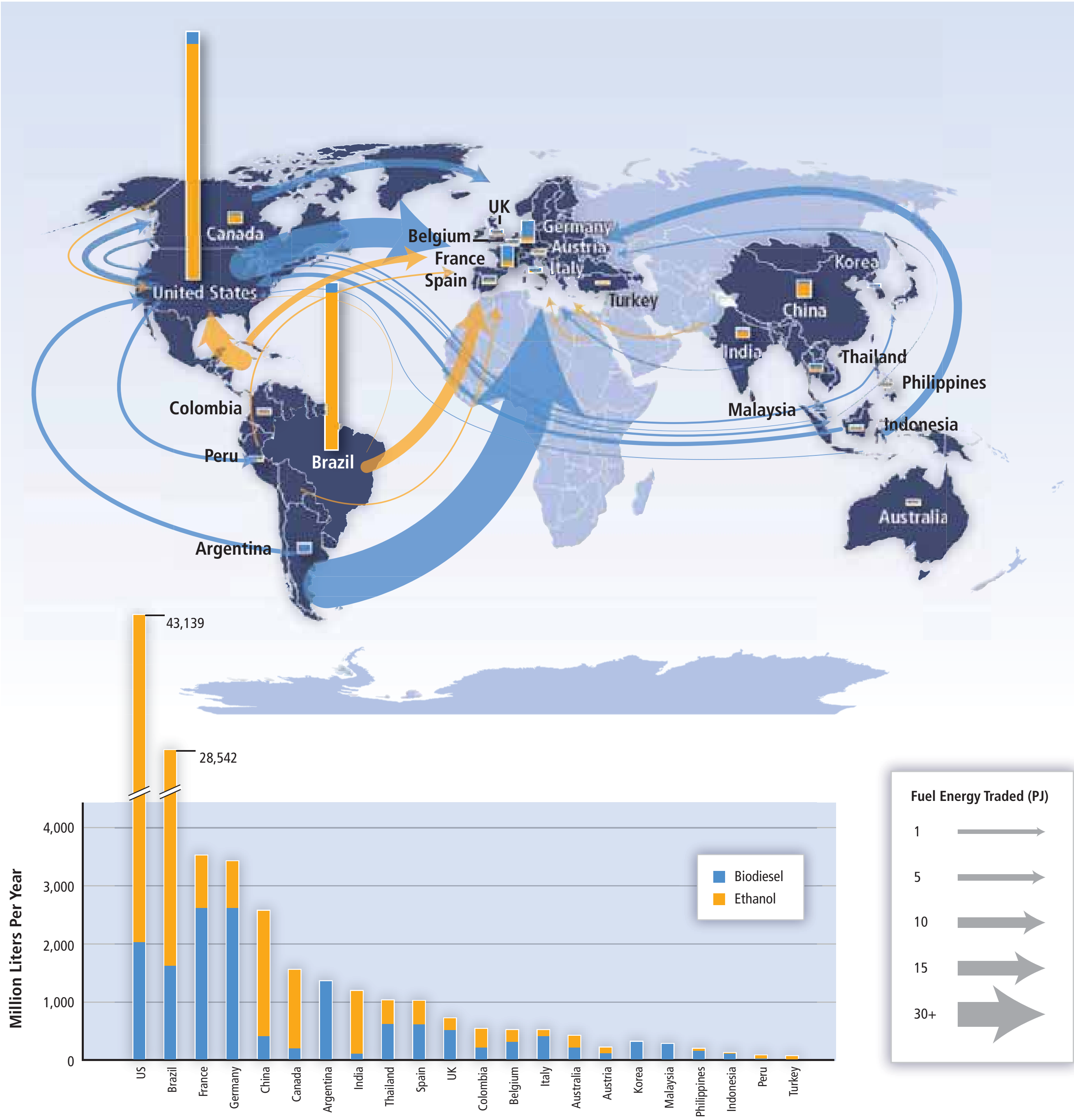


Figure 2.9 | Global biofuels production and main international trade, 2009. Biofuel volume sources: GAIN (2009a,b,[1] 2010a-j[2]); EIA (2010a); EurObserv'ER (2010); RFA (2010);[3] REN21 (2010).[4] Trade flows: Lamers et al. (2010).[5] The total intra-EU biodiesel and ethanol trade corresponds to 78 and 116 PJ, respectively (Lamers et al., 2011).

Notes: 1. Data for China and Indonesia. 2. Data for Argentina, Australia, Brazil, Canada, India, Korea, Malaysia, Peru, The Philippines, Thailand and Turkey. 3. www.ethanolrfa.org/pages/statistics. 4. See www.ren21.net/REN21Activities/ for updated information on biofuels volumes and targets for the various countries and other policy information and interactive tools (www.map.ren21.net). 5. For trade flows used in Figure 2.9 see www.chem.uu.nl/nws; for detailed data see Lamers et al. (2011).

bioenergy (e.g., ethanol, biodiesel, wood pellets) is growing rapidly. While practically no liquid biofuels or wood pellets were traded in 2000, the world net trade of liquid biofuels amounted to 120 to 130 PJ in 2009 (Figure 2.9), compared to about 75 PJ for wood pellets (Figure 2.8). Larger quantities of these products are expected to be traded internationally in the future, with Latin America and sub-Saharan Africa as potential net exporters and North America, Europe and Asia expected as net importers (Heinimö and Junginger, 2009). Trade can therefore become an important component of the sustained growth of the bioenergy sector. Figure 2.9 shows 2009 biofuels production in many countries along with the net global trade streams of bioethanol and biodiesel (see also Table 2.9). In 2008, around 9% of global biofuel production was traded internationally (Junginger et al., 2010). Production and trade of these three commodities are discussed in more detail below.

Global fuel *ethanol production* grew from around 0.375 EJ in 2000 to more than 1.6 EJ in 2009 (Lamers et al., 2011). The USA and Brazil, the two leading ethanol producers and consumers, accounted for about 85% of the world's production. In the EU, total consumption of ethanol for transport in 2009 was 94 PJ (3.6 Mt), with the largest users being France, Germany, Sweden and Spain (Lamers et al., 2011; EurObserv'ER, 2010). Data related to fuel *bioethanol trade* are imprecise on account of the various potential end uses of ethanol (i.e., fuel, industrial and beverage use) and also because of the lack of proper codes for biofuels in global trade statistics. As an estimate, a net amount of 40 to 51 PJ of fuel ethanol was traded in 2009 (Lamers et al., 2011).

World *biodiesel production* started below 20 PJ in 2000 and reached about 565 PJ in 2009 (Lamers et al., 2011). The EU produced 334 PJ (roughly two-thirds of the global production), with Germany, France, Spain and Italy being the top EU producers (EurObserv'ER, 2010). EU27 biodiesel production rates levelled off towards 2008 (FAPRI, 2009).[29] The intra-European biodiesel market has become more competitive, and the 2009 overcapacity has already led to the closure of (smaller, less vertically integrated, less efficient, remote, etc.) biodiesel plants in Germany, Austria and the UK. As shown in Figure 2.9, other main biodiesel producers include the USA, Argentina and Brazil. Biodiesel consumption in the EU amounted to about 403 PJ (8.5 Mt) (EurObserv'ER, 2010), with Germany and France consuming almost half of this amount. Net international *biodiesel trade* was below 1 PJ before 2005 but grew very fast from this small base to more than 80 PJ in 2009, as shown in Figure 2.9 (Lamers et al., 2011).

Production, consumption and trade of *wood pellets* have grown strongly within the last decade and are comparable to ethanol and biodiesel in terms of global trade volumes. As a rough estimate, in 2009, more than 13 Mt (230 PJ) of *wood pellets* were produced primarily in 30 European countries, the USA and Canada (Figure 2.8). Consumption was high in many EU countries and the USA. The largest EU consumers were Sweden (1.8 Mt or 32 PJ), Denmark, the Netherlands, Belgium, Germany and Italy (roughly 1 Mt or 18 PJ each). Main *wood pellet trade* routes lead from Canada and the USA to Europe (especially Sweden, the Netherlands and Belgium) and to the USA. In 2009, other minor trade flows were also reported, for example, from Australia, Argentina and South Africa to the EU. Canadian producers also started to export small quantities to Japan. Total imports of wood pellets by European countries in 2009 were estimated to be about 3.9 Mt (69 PJ), of which about half can be assumed to be intra-EU trade (Sikkema et al., 2010, 2011).

2.4.5 Overview of support policies for biomass and bioenergy[30]

Typical examples of support policies are shown in Table 2.11. For instance, *liquid biofuels* policies include the (former) Brazilian Proálcool programme, regulations in the form of mandates in many EU countries and the USA fiscal incentives such as tax exemptions, production tax credits and accelerated depreciation (WWI, 2007). The majority of successful policies for *heat* from biomass in recent decades have focused on more centralized applications for heat or CHP in district heating and industry (Bauen et al., 2009a). For these sectors, a combination of direct support schemes with indirect incentives has been successful in several countries, such as Sweden (Junginger, 2007). Both quota systems and FITs have been implemented in support of bioenergy *electricity* generation, though FITs have gradually become the more popular incentive. The effectiveness and efficiency of FITs and quota systems for promoting RE generation (including for bioenergy) has been thoroughly debated. A full discussion of these instruments can be found in Section 11.5.3. Next to FITs or quotas, almost all countries that have successfully stimulated bioenergy development have applied additional public finance relating to investment support and soft loans along with fiscal measures (GBEP, 2008). Additionally, grid access for renewable power is an important issue that needs to be addressed. Priority grid access for renewable sources is applied in most countries where bioenergy technologies have been successfully deployed (Sawin, 2004).

Support policies (see Table 2.11) have strongly contributed in past decades to the growth of bioenergy for electricity, heat and transport fuels. However, several reports also point out the costs and risks associated with support policies for biofuels. According to the WEO (IEA, 2010b), the annual global government support for biofuels in 2009, 2008 and 2007 was USD_{2009} 20 billion, 17.5 billion and 14 billion, respectively, with corresponding EU spending of USD_{2009} 7.9 billion, 8.0 billion and 6.3 billion and corresponding US spending of USD_{2009} 8.1 billion, 6.6 billion and 4.9 billion. The US spending was driven by energy security and fossil fuel import reduction goals. Concerns about food prices, GHG emissions and environmental impacts have also led to many countries rethinking biofuels blending targets. For example, Germany revised its blending target for 2009 downward from 6.25 to 5.25%.[31] Addressing these concerns led also to the incorporation of environmental and social

29 While most EU Member States (MS) increased their production volumes, the German biodiesel market shrunk both in supply and demand due to a change in the policy framework phasing out tax exemptions for neat biodiesel at the pump. At the same time biodiesel export to other EU MS became less and less feasible for German (and other) producers due to increasing shares of competitively priced biodiesel imports, mainly from the USA in the period from 2006 to 2008 and also from Argentina in the years 2008 and 2009 (Lamers et al., 2011).

30 Non-technology-specific policy issues are covered in Chapter 11 of this report.

31 Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit decision published on 22.10.2008 and available at www.bmu.de/pressearchiv/16_legislaturperiode/pm/42433.php.

sustainability criteria for biofuels in the EU Renewable Energy Directive. Although seemingly effective in supporting domestic farmers, the effectiveness of biofuel policies in reaching the climate change and secure energy supply objectives is coming under increasing scrutiny. It has been argued that these policies have been costly and have tended to introduce new distortions to already severely distorted and protected agricultural markets—at both domestic and global levels. This has not tended to favour an efficient international production pattern for biofuels and their feedstocks (FAO, 2008a; Bringezu et al., 2009). An overall biomass strategy would have to consider all types of use of food and non-food biomass (Bringezu et al., 2009).

The main drivers behind government support for the sector have been concerns over climate change and energy security as well as the desire to support the agricultural sector through increased demand for agricultural products (FAO, 2008a). According to the REN21 global interactive map (see note 4 to Figure 2.9) a total of 69 countries had one or several biomass support policies in place in 2009 (REN21, 2010; Section 11.2).

2.4.5.1 Intergovernmental platforms for exchange on bioenergy policies and standardization

Several multi-stakeholder initiatives exist in which policymakers can find advice, support and the possibility of exchanging experiences on policymaking for bioenergy. Examples of such international organizations and forums supporting the further development of sustainability criteria and methodological frameworks for assessing GHG mitigation benefits of bioenergy include the Global Bioenergy Partnership (GBEP from the G8+5),[32] the IEA Bioenergy Agreement,[33] the International Bioenergy Platform at the Food and Agriculture Organization (FAO),[34] the OECD Roundtable on Sustainable Development,[35] and standardization organizations such as the European Committee for Standardization[36] and the International Organization for Standardization[37] (ISO) that are actively working toward the development of sustainability standards.

32 The GBEP provides a forum to inform policy development frameworks, promote sustainable biomass and bioenergy development, facilitate investments in bioenergy, promote project development and implementation, and foster R&D and commercial bioenergy activities. Membership includes individual countries, multilateral organizations, and associations.

33 The IEA Bioenergy Agreement provides an umbrella organization and structure for a collective effort in the field of bioenergy including non-OECD countries interested in the topics from RD&D to policies. It brings together policy and decision makers and national experts from research, government and industry across the member countries.

34 See ftp.fao.org/docrep/fao/009/A0469E/A0469E00.pdf.

35 See www.oecd.org/dataoecd/14/3/46063741.pdf.

36 See www.cen.eu/cen/Sectors/TechnicalCommitteesWorkshops/CENTechnicalCommittees/Pages/default.aspx TC335 for solid biofuels standards, TC19 for liquid biofuels, and TC 383 for sustainability criteria for biofuels.

37 See www.iso.org/iso/standards_development/technical_committees/list_of_iso_technical_committees.htm TC 248 for sustainability criteria for biofuels, TC 238 for solid biofuels, TC255 for biogas, and TC 28/SC 7 for liquid biofuels.

2.4.5.2 Sustainability frameworks and standards

Governments are stressing the importance of ensuring sufficient climate change mitigation and avoiding unacceptable negative effects of bioenergy as they implement regulating instruments. For example, the Renewable Energy Directive (European Commission, 2009) provides mandatory sustainability requirements for liquid transport fuels.[38] Also, in the USA, the Renewable Fuel Standard—included in the 2007 Energy Independence and Security Act (EISA, 2007)—mandates minimum GHG reductions from renewable fuels, discourages use of food and fodder crops as feedstocks, permits use of cultivated land and estimates (indirect) LUC effects to set thresholds of GHG emission reductions for categories of fuels (EPA, 2010; see also Section 2.5). The California Low Carbon Fuel Standard set an absolute carbon intensity reduction standard and periodic evaluation of new information, for instance, on indirect land use impacts.[39] Other examples are the UK Renewable Transport Fuel Obligation, the German Biofuel Sustainability Ordinance, and the Cramer Report (The Netherlands). With the exception of Belgium, no mandatory sustainability criteria for solid biomass (e.g., wood pellets) have been implemented—the European Commission will review this at the end of 2011 (European Commission, 2010).

The development of impact assessment frameworks and sustainability criteria involves significant challenges in relation to methodology, process development and harmonization. As of a 2010 review, nearly 70 ongoing certification initiatives exist to safeguard the sustainability of agriculture and forestry products, including those used as feedstock for the production of bioenergy (van Dam et al., 2010). Within the EU, a number of initiatives started or have already set up certification schemes in order to guarantee a more sustainable cultivation of energy crops and production of energy carriers from modern biomass (e.g., ISCC[40]; REDCert[41] 2010 in Germany; or the NTA8080/8081 (NEN[42]) in the Netherlands). Many initiatives focus on the sustainability of liquid biofuels including primarily environmental principles, although some of them, such as the Council for Sustainable Biomass Production and the Better Sugarcane Initiative, the Roundtable for Sustainable Biofuels (RSB) and the Roundtable for Responsible Soy, include explicit socioeconomic impacts of bioenergy production. Principles such as those from the RSB have already led to a Biofuels Sustainability Scorecard used by the Inter-American Development Bank for the development of projects.

38 These requirements are: specific GHG emission reductions must be achieved, and the biofuels in question must not be produced from raw materials being derived from land of high value in terms of biological diversity or high carbon stocks.

39 The California Air Resources Board requires 10% absolute emissions reductions from fossil energy sources by 2020 and considers direct lifecycle emissions of the biofuels and also indirect LUC as required by legislation (CARB, 2009).

40 International Sustainability and Carbon Certification, Koeln, Germany, www.iscc-system.org/index_eng.html

41 REDcert Certification System, www.redcert.org

42 NTA 8080 - Sustainabley Produced Biomass. Dutch Normalization Institute (NEN), Delft, The Netherlands, www.sustainable-biomass.org/publicaties/3950

The proliferation of standards that has taken place over the past four years, and continues, shows that certification has the potential to influence local impacts related to the environmental and social effects of direct bioenergy production. Many of the bodies involved conclude that for an efficient certification system there is a need for further harmonization, availability of reliable data, and linking indicators at micro, meso and macro levels (see Figure 2.15). Considering the multiple spatial scales, certification should be combined with additional measurements and tools at regional, national and international levels.

The role of bioenergy production in iLUC is still uncertain; current initiatives have rarely captured impacts from iLUC in their standards, and the time scale becomes another important variable in assessing such changes (see Section 2.5.3). Addressing unwanted LUC requires overall sustainable agricultural production and good governance first of all, regardless of the end use of the product or of the feedstocks.

2.4.6 Main opportunities and barriers for the market penetration and international trade of bioenergy

2.4.6.1 Opportunities[43]

The prospects for biofuels for road transport depend on developments in competing low-carbon and oil-reducing technologies for road transport (e.g., electric vehicles). Biofuels may in the longer term be increasingly used within the aviation industry, for which high energy density carbon fuels are necessary (see Section 2.6.3), and also in marine shipping.

The development of international markets for bioenergy has become an essential driver to develop available biomass resources and market potential, which are currently underutilized in many world regions. This is true for both (available) residues as well as possibilities for dedicated biomass production (through energy crops or multifunctional systems such as agro-forestry). Export of biomass-derived commodities for the world's energy market can provide a stable and reliable income for rural communities in many (developing) countries, thus creating an important incentive and market access.[44]

Also on the demand side, large biomass users that rely on a stable supply of biomass can benefit from international bioenergy trade, as this enables (often very large) investments in infrastructure and conversion capacity.[45]

Introduction of incentives based on political decisions is a driving force and has triggered an expansion of bioenergy trade. For example, wood pellet imports in the Netherlands and Belgium have been driven respectively through a feed-in premium system and a Green Certificate system. However, the success of policies has varied, due partly to the nature of the design and implementation of the given policy but also to the fact that the institutions related to the incentives are different. For a full discussion of influencing factors outside of policies (e.g., institutions, network access), see Section 11.6.

Another driver is the utilization of established logistics for existing commodities. Taking again the example of wood pellet co-firing in large power plants, the existing infrastructure at ports and storage facilities used to supply coal and other dry bulk goods can (partially, and after adaptations) also be used for wood pellets, making cost-efficient transport and handling possible. Another form of integrated supply chain is bark, sawdust and other residues from imported roundwood, which is common in, for example, Northern Europe. Finally, the concept of regional biomass processing centres has been proposed to deal with supply side challenges and also to help address social sustainability concerns (Carolan et al., 2007).

2.4.6.2 Barriers

Major risks and barriers to deployment are found all along the bioenergy value chain and concern all final energy products (bioheat, biopower, and biofuel for transport).[46] On the supply side, there are challenges related to securing quantity, quality and price of biomass feedstock, irrespective of the origin of the feedstock (energy crops, wastes or residues). There are also technology challenges related to the varied physical properties and chemical composition of the biomass feedstock and challenges associated with the poor economics of current power and biofuel technologies at small scales. On the demand side, the main challenges are the stability and supportiveness of policy frameworks and investors' confidence in the sector and its technologies, in particular to overcome financing challenges associated with demonstrating the reliable operation of new technologies at commercial scale.[47] In the power and heat sectors, competition with other RE sources may also be an issue. Public acceptance and public perception are also critical factors in gaining support for energy crop production and bioenergy facilities.

Specifically for the bioenergy trade, Junginger et al. (2010) identified a number of (potential) barriers:

Tariffs. As of January 2007, import tariffs apply in many countries, especially for ethanol and biodiesel. Tariffs (expressed in local currency and year) are applied on bioethanol imports by both the EU (€ 0.192 per litre) and the USA (USD 0.1427 per litre and an additional 2.5%

43 This sub-section is largely based on Junginger et al. (2008).

44 Exports of ethanol from Brazil and wood pellets from Canada are examples where export opportunities (at least partially) were drivers to further develop the supply side.

45 Utilities in the Netherlands and Belgium import large amounts of wood pellets to co-fire with coal, as domestic biomass resources are very limited and of varying quality.

46 Most of the remainder of this paragraph is based on Bauen et al. (2009a).

47 Some governments have jointly financed first-of-a-kind commercial technological development with the private sector in the past five years, but the financial crisis is making it difficult to complete the private financing needed to continue to obtain government financing.

ad valorem subsidy). In general, the most-favoured nation tariffs range from roughly 6 to 50% on an ad valorem equivalent basis in the OECD, and up to 186% in the case of India (Steenblik, 2007). Biodiesel used to be subject to lower import tariffs than bioethanol, ranging from 0% in Switzerland to 6.5% in the EU and the USA (Steenblik, 2007). However, in July 2009, the European Commission confirmed a five-year temporary imposition of anti-dumping and anti-subsidy rights on American biodiesel imports, with fees standing between € 213 and 409 per tonne (local currency and year) (EurObserv'ER, 2010). These trade tariffs were a reaction to the so-called 'splash-and-dash' practice, in which biodiesel blended with a 'splash' of fossil diesel was eligible for a USD 1 per gallon subsidy (equivalent to USD 300/t) in 2008-2009; see Lamers et al. (2011) for detailed information on the various tariffs, trade regimes, and policies worldwide.

Technical standards describe in detail the physical and chemical properties of fuels. Regulations pertaining to the technical characteristics of liquid transport fuels (including biofuels) exist in all countries. These have been established in large part to ensure the safety of the fuels and to protect consumers from buying fuels that could damage their vehicles' engines. Regulations include maximum percentages of biofuels that can be blended with petroleum fuels and regulations pertaining to the technical characteristics of the biofuels themselves. In the case of biodiesel, the latter may depend on the vegetable oils used for the production, and thus regulations might be used to favour biodiesel from domestic feedstocks over biodiesel from imported feedstocks. Technical barriers for the bioethanol trade also exist. For example, the different demands for maximum water content have negative impacts on trade. However, in practice, most market actors have indicated that they see technical standards as an opportunity enabling international trade rather than as a barrier (Junginger et al., 2010).

Sustainability criteria and biomass and biofuels certification have been developed in increasing numbers in recent years as voluntary or mandatory systems (see Section 2.4.5.2); such criteria, so far, do not apply to conventional fossil fuels. Three major concerns in relation to the international bioenergy trade are:

1. Criteria, especially those related to environmental and social issues, could be too stringent or inappropriate to local environmental and technological conditions in producing developing countries (van Dam et al., 2010). The fear of many developing countries is that if the selected criteria are too strict or are based on the prevailing conditions in the countries setting up the certification schemes, only producers from those countries may be able to meet the criteria, and thus these criteria may act as trade barriers. As the criteria are extremely diverse, ranging from purely commercial aims to rainforest protection, there is a danger that a compromise could result in overly detailed rules that lead to compliance difficulties, or, on the other hand, in standards so general that they become meaningless. Implementing binding requirements is also limited by World Trade Organization rules.

2. With current developments by the European Commission, different European governments, several private sector initiatives, and initiatives of round tables and NGOs, there is a risk that in the short term a multitude of different and partially incompatible systems will arise, creating trade barriers (van Dam et al., 2010). If they are not developed globally or with clear rules for mutual recognition, such a multitude of systems could potentially become a major barrier for international bioenergy trade instead of promoting the use of sustainable biofuels production. A lack of transparency in the development of some methodologies, for example, in the EU legislation, is an issue. Also, the eventual existence of different demands for proving compliance with the criteria for locally produced biomass sources and imported ones is a potential barrier. Finally, lack of international systems may cause market distortions.

   Production of 'uncertified' biofuel feedstocks will continue and enter other markets in countries with lower standards or for non-biofuel applications that may not have the same standards. The existence of a 'two-tier' system would result in failure to achieve the safeguards envisaged (particularly for LUC and socioeconomic impacts).

3. Finally, note that to ensure that biomass commodities are being produced in a sustainable manner, some chain of custody (CoC) method must be used to track biomass and biofuels from production to end use. Generally, the three types of CoC methods are segregation (also known as track-and-trace), book-and-claim and mass-balance. While this is not necessarily a major barrier, it may cause additional cost and administrative burdens.

Logistics are a pivotal part of the system and essential to set up biomass fuel supply chains for large-scale biomass systems. Various studies have shown that long-distance international transport by ship is feasible in terms of energy use and transportation costs (e.g., Sikkema et al., 2010, 2011), but availability of suitable vessels and meteorological conditions (e.g., winter in Scandinavia and Russia) need to be considered. One logistical barrier is a general lack of technically mature technologies to densify biomass at low cost to facilitate transport, although technologies are being developed (Sections 2.3.2 and 2.6.2).

Sanitary and phytosanitary (SPS) measures may be faced by feedstocks for liquid biofuels or technical regulations applied at borders. SPS measures mainly affect feedstocks that, because of their biological origin, can carry pests or pathogens. One of the most common SPS measures is a limit on pesticide residues. Meeting pesticide residue limits is usually not difficult but on occasion has led to the rejection of imported shipments of crop products, especially from developing countries (Steenblik, 2007).

2.4.7 Synthesis

The review of developments in biomass use, markets and policy shows that bioenergy has seen rapid developments over the past years. The use of modern biomass for liquid and gaseous energy carriers is growing, in particular biofuels (with a 37% increase from 2006 to 2009). Projections from the IEA, among others, but also many national targets, count on biomass delivering a substantial increase in the share of RE. International trade in biomass and biofuels has also become much more important over recent years, with roughly 6% (reaching levels of up to 9% in 2008) of biofuels (ethanol and biodiesel only), and one-third of all pellet production for energy use, traded internationally in 2009. Pellets have proven to be an important facilitating factor in both increasing utilization of biomass in regions where supplies are constrained as well as mobilizing resources from areas where demand is lacking. Nevertheless, many barriers remain to developing well-working commodity trading of biomass and biofuels that at the same time meets sustainability criteria.

The policy context for bioenergy, and in particular biofuels, in many countries has changed rapidly and dramatically in recent years. The debate on food versus fuel competition and the growing concerns about other conflicts have resulted in a strong push for the development and implementation of sustainability criteria and frameworks as well as changes in temporization of targets for bioenergy and biofuels. Furthermore, the support for advanced biorefinery and second-generation biofuel options is driving bioenergy in more sustainable directions.

Persistent policy and stable policy support has been a key factor in building biomass production capacity and working markets, required infrastructure and conversion capacity that gets more competitive over time. These conditions have led to the success of the Brazilian programme to the point that ethanol production costs are lower than those of gasoline. Brazil achieved an energy portfolio mix that is substantially renewable and that minimized foreign oil imports. Sweden, Finland, and Denmark also have shown significant growth in renewable electricity and in management of integrated resources, which steadily resulted in innovations such as industrial symbiosis of collocated industries. The USA has been able to quickly ramp up production with the alignment of national and sub-national policies for power in the 1980s and for biofuels in the 1990s to present, as petroleum prices and instability in key producing countries increased; however, as oil prices decreased, policy support and bioenergy production decreased for biopower and is increasing again with environmental policies and sub-national targets.

Countries differ in their priorities, approaches, technology choices and support schemes for further development of bioenergy. Although this means increased complexity of the bioenergy market, this also reflects the many aspects that affect bioenergy deployment—agriculture and land use, energy policy and security, rural development and environmental policies. Priorities, stage of development and geographic access to the resources, and their availability and costs differ widely from country to country.

As policies surrounding bioenergy and biofuels become more holistic, using sustainability demands as a starting point is becoming an overall trend. This is true for the EU, the USA and China, but also for many developing countries such as Mozambique and Tanzania. This is a positive development but is by no means settled (see also Section 2.5). The 70 initiatives registered worldwide by 2009 to develop and implement sustainability frameworks and certification systems for bioenergy and biofuels, as well as agriculture and forestry, can lead to a fragmentation of efforts (van Dam et al., 2010). The needs for harmonization and for international and multilateral collaboration and dialogue are widely stressed at present.

2.5 Environmental and social impacts[48]

Recent studies have highlighted both positive and negative environmental and socioeconomic effects of bioenergy and the associated agriculture and forestry LUC (IPCC, 2000b; Millennium Ecosystem Assessment, 2005). Like conventional agriculture and forestry systems, bioenergy can exacerbate soil and vegetation degradation associated with overexploitation of forests, too intensive crop and forest residue removal, and water overuse (Koh and Ghazoul, 2008; Robertson et al., 2008). Diversion of crops or land into bioenergy production can influence food commodity prices and food security (Headey and Fan, 2008). With proper operational management, the positive effects can include enhanced biodiversity (C. Baum et al., 2009; Schulz et al., 2009), soil carbon increases and improved soil productivity (Tilman et al., 2006a; S. Baum et al., 2009), reduced shallow landslides and local flash floods, reduced wind and water erosion and reduced sediment volume and nutrients transported into river systems (Börjesson and Berndes, 2006). For forests, bioenergy can improve growth and productivity, improve site conditions for replanting and reduce wildfire risk (Dymond et al., 2010). However, forest residue harvesting can have negative impacts such as the loss of coarse woody debris that provides essential habitat for forest species.

Biofuels derived from purpose-grown agricultural feedstocks are water intensive (see Section 9.3.4.4 for comparisons of renewable and non-renewable power sources; Berndes, 2002; King and Weber, 2008; Chiu et al., 2009; Dominguez-Faus et al., 2009; Gerbens-Leenes et al., 2009; Wu et al., 2009; Fingerman et al., 2010). Their influence on water resources and the wider hydrologic cycle depends on where, when and how the biofuel feedstock is produced. Among different bioenergy supply chains, across the spectrum of feedstocks, cultivation systems and conversion technologies, water demand varies greatly (Wu et al., 2009; Fingerman et al., 2010, De La Torre Ugarte, et al., 2010). While biofuel made from irrigated crops requires extraction of large volumes of water from lakes, rivers and aquifers, use of agricultural or forestry residues as bioenergy feedstocks does not generally require much additional land or water. Rain-fed feedstock production does not require water extraction from

48 A comprehensive assessment of social and environmental impacts of all RE sources covered in this report can be found in Chapter 9.

water bodies, but it can still reduce downstream water availability by redirecting precipitation from runoff and groundwater recharge to crop evapotranspiration. Using water for bioenergy has very different social and ecological consequences depending upon the state of the resource base from which that water was drawn.

Few universal conclusions about the socioeconomic and environmental implications of bioenergy can currently be drawn, given the multitude of rapidly evolving bioenergy sources, the complexities of physical, chemical and biological conversion processes, the multiple energy products, and the variability in environmental conditions. Thus, the positive and negative effects of bioenergy are a function of the socioeconomic and institutional context, the types of lands and feedstocks used, the scale of bioenergy programmes and production practices, the conversion processes, and the rate of implementation (e.g., Kartha et al., 2006; Firbank, 2008; E. Gallagher, 2008; OECD-FAO, 2008; Royal Society, 2008; UNEP, 2008b; Howarth et al., 2009; Pacca and Moreira, 2009; Purdon et al., 2009; Rowe et al., 2008).

Bioenergy system impact assessments (IAs) must be compared to the IAs of replaced systems.[49] The methodologies and underlying assumptions for assessing environmental (Sections 2.5.1 through 2.5.6) and socioeconomic (Section 2.5.7) effects (see Table 2.12 for examples of these impacts) differ greatly and therefore the conclusions reached by these studies are inconsistent (H. Kim et al., 2009). One particular challenge for socioeconomic IAs is that their boundaries are difficult to quantify and are a complex composite of numerous interrelated factors, many of which are poorly understood or unknown. Social processes have feedbacks that are difficult to clearly define with an acceptable level of confidence. Environmental IAs include many quantifiable impact categories but still lack data and are uncertain in many areas. The outcome of an environmental IA depends on methodological choices, which are not yet standardized or uniformly applied throughout the world.

2.5.1 Environmental effects

Studies of environmental effects, including those focused on energy balances and GHG emission balances, usually employ methodologies in line with the principles, framework, requirements and guidelines in the ISO 14040:2006 and 14044:2006 standards for Life Cycle Assessment (LCA) discussed in Section 9.3.4.1. An earlier specific method for assessing GHG balances of biomass and bioenergy systems was developed by Schlamadinger et al. (1997).

Key issues for bioenergy LCAs are system definition including spatial and dynamic boundaries, functional units, reference system, and the selection of methods for considering energy and material flows across system boundaries (Soimakallio et al., 2009a; Cherubini and Strømman, 2010). As part of cascading cycles, many processes create multiple products; for example, biomass is used to produce biomaterials while co-products and the biomaterial itself are used for energy after their useful life (Dornburg and Faaij, 2005). Such cascading results in significant data and methodological challenges because environmental effects can be distributed over several decades and in different geographical locations (Cherubini et al., 2009b).

Most of the assumptions and data used in LCA studies of existing bioenergy systems are related to first-generation biofuels and to conditions and practices in Europe or the USA, although studies are becoming available for Brazil, China and other countries (see examples in Tables 2.7, 2.13, and 2.15). Ongoing development of biomass production and conversion technologies makes many of these studies of commercial technologies outdated.[50] LCA studies of prospective bioenergy options involve projections of technology performance and have relatively greater uncertainties (see, e.g., Figure 9.9). The way that uncertainties

Table 2.12 | Environmental and socioeconomic impacts of bioenergy: example areas of concern with selected impact categories (synthesized from the literature review by van Dam et al., 2010).

Example areas of concern	Examples of impact categories
Global, regional, off-site environmental effects	GHGs; albedo; acidification; eutrophication; water availability and quality; regional air quality
Local/onsite environmental effects	Soil quality; local air quality; water availability and quality; biodiversity and habitat loss
Technology	Hazards; emissions; congestion; safety; genetically modified organisms/plants
Human rights and working conditions	Freedom of association; access to social security; job creation and average wages; freedom from discrimination; no child labour and minimum age of workers; freedom of labour (no forced labour); rights of indigenous people; acknowledgment of gender issues
Health and safety	Impacts on workers and users; safety conditions at work
Food security	Replacement of staple crops; safeguarding local food security
Land and property rights	Acknowledgment of customary and legal rights of land owners; proof of ownership; compensation systems available; agreements by consent
Participation and well-being of local communities	Cultural and religious values; contribution to local economy and activities; compensation for use of traditional knowledge; support to local education; local procurement of services and inputs; special measures to target vulnerable groups

49 A 'rebound effect' could be included, usually fossil fuels, but also other primary energy sources (Barker et al., 2009).

50 For instance, using a 2006 reference that analyzed an industrial system in 2002 will not represent the industry in 2010 because learning occurred in commercial technologies that exhibited a significant accumulation of production volume such as in the USA and in Brazil; an example of wide-spread adoption of a different technology in this industry is the USA where dry milling has become the major route to ethanol production (see Sections 2.3.4 and 2.7.2).

and parameter sensitivities are handled across the supply chain to fuel production significantly impacts the results (Sections 2.5.2 through 2.5.6). Studies combining several LCA models and/or Monte Carlo analysis provide bioenergy system uncertainties and levels of confidence for some bioenergy options (e.g., Soimakallio et al., 2009b; Hsu et al., 2010; Spatari and MacLean, 2010).

Most bioenergy system LCAs are designated as attributional to the defined process system boundaries. Consequential LCAs analyze bioenergy systems beyond these boundaries, in the context of the economic interactions, chains of cause and effect in bioenergy production and use, and effects of policies or other initiatives that increase bioenergy production and use. Consequential LCAs can investigate systemic responses to bioenergy expansion (e.g., how the food system changes if increasing volumes of cereals are used as biofuel feedstock or how petroleum markets respond if increased biofuels production results in reduced petroleum demand—see Section 2.5.3 and Figure 2.13). The outcome of *any* measure to reduce a certain use can be affected by a rebound effect—in the case of bioenergy, if increased production of solid, liquid and gaseous biofuels leads to lower demand for fossil fuels, this in turn could lead to lower fossil fuel prices and increased fossil fuel demand (Rajagopal et al., 2011; Stoft, 2010).[51] Similarly, when considering co-products, LCAs should ideally model displacement of alternative products as a dynamic result of market interactions. Consequential LCAs therefore require auxiliary tools such as economic equilibrium models.

2.5.2 Modern bioenergy: Climate change excluding land use change effects

The ranges of GHG emissions for bioenergy systems and their fossil alternatives per unit energy output are shown in Figure 2.10 for several uses (transport, power, heat) calculated based on LCA methodologies (land use-related net changes in carbon stocks and land management impacts

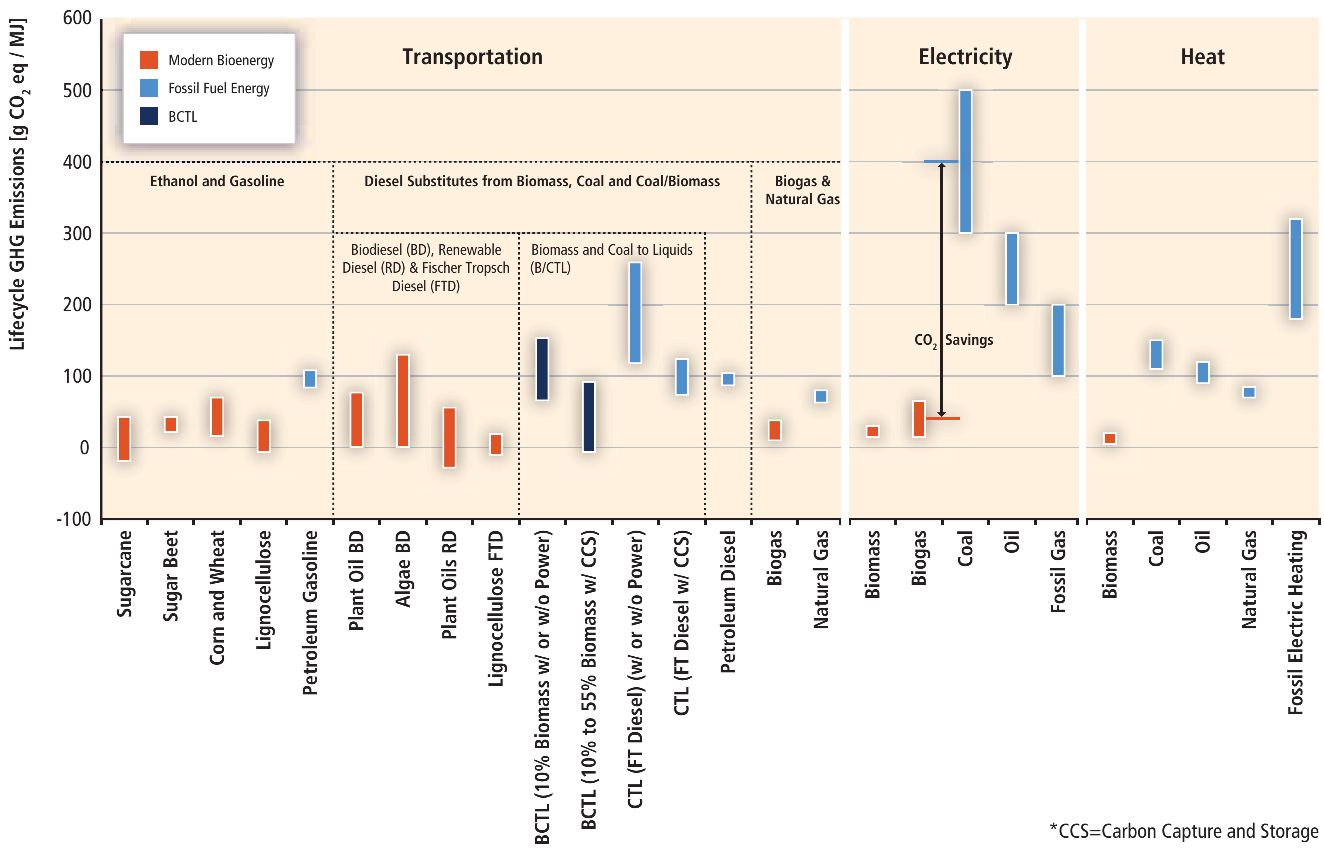


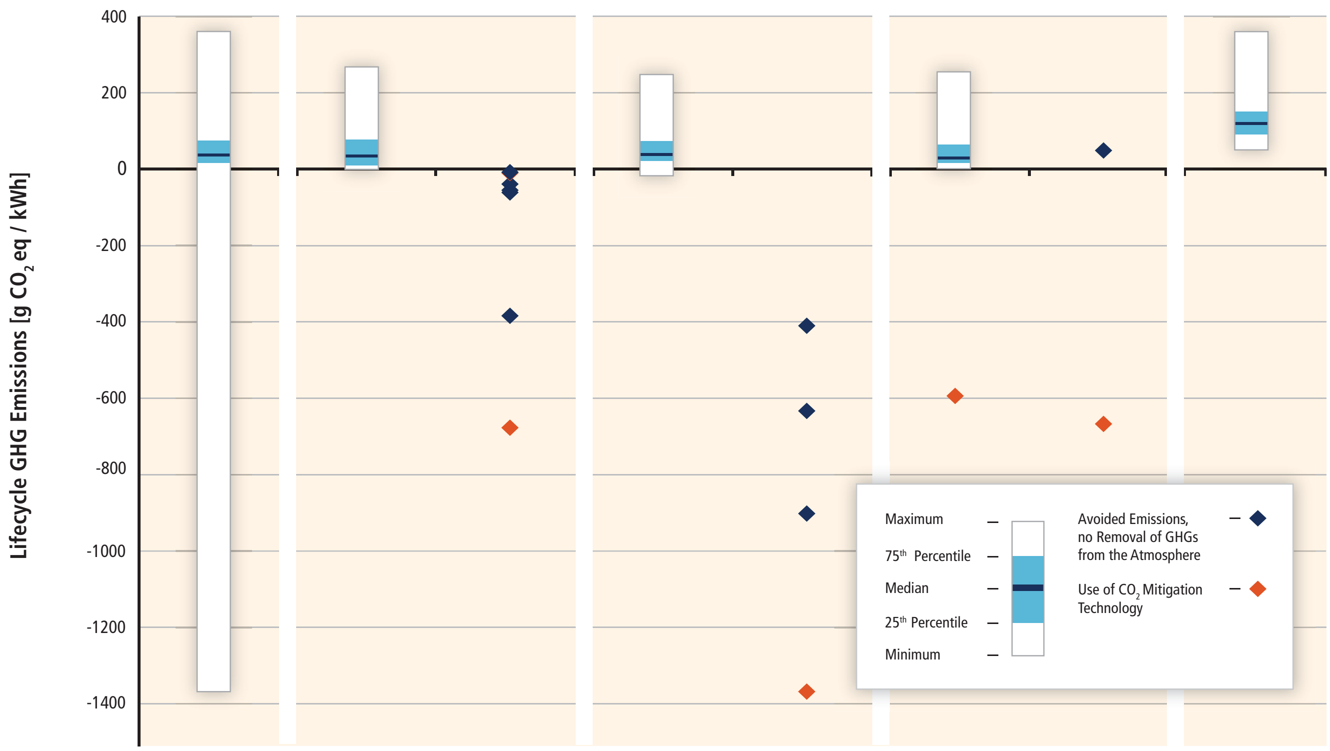
Figure 2.10 | Ranges of GHG emissions per unit energy output (MJ) from major modern bioenergy chains compared to conventional and selected advanced fossil fuel energy systems (land use-related net changes in carbon stocks and land management impacts are excluded). Commercial and developing (e.g., algae biofuels, Fischer-Tropsch) systems for biomass and fossil technologies are illustrated.

Data sources: Wu et al. (2005); Fleming et al. (2006); Hill et al. (2006, 2009); Beer and Grant (2007); Wang et al. (2007, 2010); Edwards et al. (2008); Kreutz et al. (2008); Macedo and Seabra (2008); Macedo et al. (2008); NETL (2008, 2009a,b); CARB (2009); Cherubini et al. (2009a); Huo et al. (2009); Kalnes et al. (2009); van Vliet et al. (2009); EPA (2010); Hoefnagels et al. (2010); Kaliyan et al. (2010); Larson et al. (2010); 25th to 75th percentile of all values from Figure 2.11.

51 The same rebound effect applies to other RE technologies displacing incumbent fossil technologies.

are excluded). Meta-analyses to quantify the influence of bioenergy systems on climate are complicated because of the multitude of existing and rapidly evolving bioenergy sources, the complexities of physical, chemical and biological conversion processes, and feedstock diversity and variability in site-specific environmental conditions—together with differences between studies in method interpretation, assumptions and data. Due to this, review studies report varying estimates of GHG emissions and a wide range of results have been reported for the same bioenergy options, even when temporal and spatial considerations are constant (see, e.g., S. Kim and Dale, 2002; Fava, 2005; Farrell et al., 2006; Fleming et al., 2006; Larson, 2006; von Blottnitz and Curran, 2007; Rowe et al., 2008; Börjesson, 2009; Cherubini et al., 2009a; Menichetti and Otto, 2009; Soimakallio et al., 2009b; Hoefnagels et al., 2010; Wang et al., 2010, 2011).

For electricity generated by various technologies, GHG emissions per kWh generated are detailed in Figure 2.11, based on published estimates from lifecycle GHG emissions (land use-related net changes in carbon stocks and land management impacts are excluded) of an extensive review of biopower LCAs.[52] Figure 2.11 shows that the majority of lifecycle GHG emission estimates cluster between about 16 and 74 g CO_2eq/kWh (4.4 and 21 g CO_2eq/MJ), with one estimate reaching



	All Values	Co-Firing w/o Avoided Emissions	Co-Firing w/ Avoided Emissions	Direct Combustion w/o Avoided Emissions	Direct Combustion w/ Avoided Emissions	Gasification w/o Avoided Emissions	Gasification w/ Avoided Emissions	Pyrolysis w/o Avoided Emissions
Estimates:	228	54	7	102	4	45	2	14
References:	53	19	4	26	3	20	1	3

Figure 2.11 | Lifecycle GHG emissions of biopower technologies per unit of electricity generation, including supply chain emissions (land use-related net changes in carbon stocks and land management impacts are excluded). Co-firing is shown for the biomass portion only (without GHG emissions and electricity output associated with coal). Included in the avoided GHG emissions category are only estimates in which the use of the feedstock itself (e.g. residues and wastes) leads to avoided emissions, for example, in the form of avoided methane emissions from landfills (most common in the literature).[1] Estimates that include avoided emissions from the production of co-products are not included in the avoided GHG emissions category. Individual data points were used instead of box plots for estimates with avoided emissions because of high variability. Red diamonds indicate that a carbon mitigation technology (CCS or carbonate formation by absorption) was considered. Along the bottom of the figure and aligned with each column are the number of estimates and the number of references (CCS estimates in parentheses) producing the distributions.

Note: 1. 'Negative estimates' within the terminology of lifecycle assessments presented in this report refer to avoided emissions. Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHGs from the atmosphere. Due to the inclusion of a non-CCS carbon sequestration technology and non-landfilling related reference cases of avoided emissions credits, estimates displayed here vary slightly from the aggregated values in Figure 9.8.

52 See Annex II for the complete list of references providing estimates for this figure and description of the literature review method.

360 g CO_2eq/kWh (100 g CO_2eq/MJ).[53] Again, variability is caused by differences in study methods, agricultural practice, technology performance and maturity of development (see Section 2.3.3). While the range and central tendency of each evaluated technology are similar to each other, the figure shows that depending on business-as-usual assumptions, avoided GHG emissions (here, mostly methane from landfills) from non-harvest wastes and residues can more than outweigh the GHG emissions associated with the biomass supply chains. Technologies with high conversion efficiency reach lower GHG emissions per kWh generated than less efficient technologies do. Though not displayed here, CHP and other integrated systems with many products could also be an effective way to minimize GHG emissions per unit of primary energy (e.g., in terms of primary energy), though the way co-products are considered in the quantification and allocation of GHG emissions can lead to different results. In the end, the economic value of outputs plays a decisive role, but climate policies that influence the cost of GHG emissions may alter the balance of products.

LCA aspects found to be especially important for GHG results are: (1) assumptions regarding GHG emissions from biomass production where LUC emissions (see Section 2.5.3) and nitrous oxide (N_2O) emissions are especially important; (2) methods used for considering co-products; (3) assumptions about conversion process design, process integration and the type of process fuel used in the conversion of biomass to solid or fluid fuels; (4) the performance of end-use technology, that is, vehicle technology or power/heat plant performance; and (5) the reference system.

N_2O emissions can have an important impact on the overall GHG balance of biofuels (Smeets et al., 2009; Soimakallio et al., 2009b). N_2O emissions vary considerably with environmental and management conditions, including soil water content, temperature, texture, carbon availability, and, most importantly, nitrogen fertilizer input (Bouwman et al., 2002; Stehfest and Bouwman, 2006). Emission factors are used to quantify N_2O emissions as a function of nitrogen fertilizer input. Crutzen et al. (2007) proposed that N_2O emissions from fresh anthropogenic nitrogen are considerably higher than results based on the IPCC's recommended tier 1 method and that N_2O emissions from biofuels consequently have been underestimated by a factor of two to three. IPCC tier 1 and Crutzen et al. (2007) estimates use different accounting approaches. About one-third of agricultural N_2O emissions are due to newly-fixed nitrogen fertilizer (A. Mosier et al., 1998) and two-thirds occur as nitrogen is recycled internally in animal production or by using plant residues as fertilizers. Recent modelling efforts by Davidson (2009) support the conclusion that emission factors based on Crutzen et al. (2007) overestimate the emissions. Using N_2O emissions factors from Crutzen et al. (2007) makes a specific bioenergy plantation responsible for all N_2O emissions taking place subsequently, even for the part of the applied nitrogen that is recirculated into other agriculture systems and substituted for other nitrogen input. See Bessou et al. (2010) for an overview of reactive nitrogen emissions impacts on LCAs.

Process fuel choice is critical and the use of coal especially can drastically reduce the climate benefit of bioenergy. Process integration and the use of biomass fuels or surplus heat from nearby energy/industrial plants can lower net GHG emissions from the biomass conversion process. For example, Wang et al. (2007) showed that GHG emissions for US corn ethanol can vary significantly—from a 3% increase if coal is the process fuel to a 52% reduction if wood chips are used or if improved dry milling processes are used (Wang et al., 2011). Similarly, the low fossil GHG emissions reported for Swedish cereal ethanol plants are explained by their use of biomass-based process energy (Börjesson, 2009). Sugarcane ethanol plants that use the fibrous by-product bagasse as process fuel can provide their own heat, steam and electricity and export surplus electricity to the grid (Macedo et al., 2008). Further improvements are possible as mechanical harvesting becomes established practice, because harvest residues can also be used for energy (Seabra et al., 2010).

However, the marginal benefit of using surplus heat or biomass for the conversion process depends on local economic circumstances and on alternative uses for the surplus heat and biomass (e.g., it could displace coal-based heat or power generation elsewhere). GHG reductions per unit weight of total biomass could be small when biomass is used both as a feedstock and as a process fuel for conversion to biofuels. This underscores the importance of using several indicators in bioenergy option evaluations (see also Section 9.3.4).

Practical uses of indicators to design and establish projects

As shown above, climate change effects can be evaluated based on indicators such as g CO_2eq per MJ (Figure 2.10) or per kWh (Figure 2.11), for which the reference system matters greatly (cf. bioenergy GHG emissions with those from coal and natural gas). Other indicators include mileage per hectare or per unit weight of biomass or per vehicle-km (see Section 8.3.1.3).[54] Limiting resources may define the extent to which land management and biomass-derived fuels can contribute to climate change mitigation, making the following indicators relevant in different contexts (Schlamadinger et al., 2005).

The *displacement factor* indicator describes the reduction in GHG emissions from the displaced energy system per unit of biomass used (e.g., tonne of carbon equivalent per tonne of carbon contained in the biomass that generated the reduction). This indicator does not discourage fossil inputs in the bioenergy chain if these inputs increase the displacement efficiency but it does not consider costs.

The indicator *relative GHG savings* describes the percentage emissions reduction with respect to the fossil alternative for a specific biomass

53 Note that the distributions in Figure 2.11 do not represent an assessment of likelihood; the figure simply reports the distribution of currently published literature estimates that passed screens for quality and relevance.

54 For example, the higher land use efficiency of electric vehicles using bioelectricity compared to ethanol cars reported by Campbell et al. (2009) is partly due to the assumed availability of advanced future drive trains for the bioelectricity option but not for the ethanol option.

use.[55] GHG savings favour biomass options with low GHG emissions. However, this indicator alone cannot distinguish between different biomass uses, such as transport fuel, heat, electricity or CHP, to determine which use reduces emissions more. It ignores the amount of biomass, land or money required, and it can be distorted as each use can have different reference systems.

The indicator *GHG savings per ha (or m^2 or km^2) of land* favours biomass yield and conversion efficiency but ignores costs.[56] Intensified land use that increases the associated GHG emissions (e.g., due to higher fertilizer input) can still improve the indicator value if the amount of biomass produced increases sufficiently.

The indicator *GHG savings per monetary unit input* tends to favour the lowest cost, commercially available bioenergy options. Prioritization based on monetary indicators can lock in current technologies and delay (or preclude) future, more cost-effective or GHG reduction-efficient bioenergy options because their near-term costs are higher.

The usefulness of two indicators for considering local and regional bioenergy options is shown in Table 2.13. In the Finnish study, the use of logging residues in modern CHP plants receives a high ranking in relative GHG savings whether the displaced fossil source is coal or natural gas. However, the displacement factor indicator is only high when coal is displaced and is medium for natural gas displacement. The biodiesel from annual crops option receives the lowest ranking (<1) for both indicators, while the Fischer-Tropsch diesel, with or without electricity from wood residues, receives different rankings depending on indicator and plant configuration but is in all cases higher than crop-derived biodiesel. The standalone plant is the best option from the perspective of relative GHG savings. But if the displacement factor is used the integrated plant is preferable. From the plant owner's perspective, local monetary indicators enable assessment of additional costs of the integrated plant, the relative prices for biomass versus electricity, relative prices for fossil diesel versus CO_2 emissions, as well as existing policy support (and its duration). The differences between the two indicators highlight the need to consider the biomass system when planning bioenergy projects at specific locations. For example, in cases where the displacement factor is less than 1, using biomass to displace fossil fuels would increase net emissions (with respect to the global carbon sink baseline) at least within the next decades. The use of such biomass resources could be sustainable; but is not climate or emissions neutral during that period. Additional fossil carbon reductions may then be needed to achieve low GHG concentration stabilization levels.

For North American corn ethanol, technology improvements from 1995 to 2005 are reflected in both indicators. Implementation of improvements in plant efficiency with existing cogeneration systems brings

Table 2.13 | Two indicators of GHG performance facilitate ranking of new technologies using forest residues and comparison with current agricultural biofuel. Two indicators show improvement of technology performance with time for commercial ethanol systems and project the impact of technology improvements. Ranking: High >70; Low <30.

		Fossil energy reference	Displacement factor[1]	Relative GHG savings[2] (%)
Finnish modern CHP plant (from logging residues)		Coal	78	86[e]
		Natural gas	30	86[e]
Finnish Fischer-Tropsch diesel[3] as a stand-alone plant or integrated with a pulp and paper mill plant; with/without electricity	Standalone plant	Fossil diesel	39[a]	78[f]
	Integrated plant, minimize biomass	Fossil diesel	50[b]	55[g]
	Integrated plant, minimize electricity	Fossil diesel	50[c]	78[h]
Finnish biodiesel (rapeseed oil)		Fossil diesel	-9[d]	-15[i]
North American ethanol (corn) powered by natural gas (NG) dry mill				
1995		Fossil gasoline	18	26
2005		Fossil gasoline	24	39
2015 with CHP[3]		Fossil gasoline	31	55
2015 with CHP and CCS[3]		Fossil gasoline	51	72
Brazilian ethanol (sugarcane)				
2005–2006 (average 44 mills)		Fossil gasoline/ electricity marginal NG	29	79
2020 CHP[3] (mechanical harvest)		Fossil gasoline/ electricity marginal NG	36	120
2020 CHP and CCS[3]		Fossil gasoline/ electricity marginal NG	51	160

Notes: 1. Tonne of carbon equivalent displaced per tonne of biomass carbon in the feedstock. 2. With respect to the fossil alternative and excluding LUC. 3. Projected performance
Uncertainty ranges: For displacement factors a. 35–46; b. 21–61; c. 45–57; d. -107–7. For relative GHG savings e. 60–94; f. 67–90; g. 31–86; h. 69–89; i. -150–5
References: Finland, Soimakallio et al. (2009b); North America, (S&T)2 Consultants (2009); and Brazil, Möllersten et al. (2003) and Macedo et al. (2008).

55 Relative GHG savings are used, for instance, in the EU Directive on Renewable Energy (European Commission, 2009).

56 See Bessou et al. (2010) for examples of LCA emissions as a function of area needed for a variety of feedstocks and biofuels in specific countries.

both indicators to medium range but improves the GHG reduction more than the displacement factor indicator. Application of developing CCS is projected to improve both indicators significantly and bring the GHG reduction indicator to high. In all Brazilian sugarcane ethanol cases, the GHG reduction indicator is high while the displacement factor is low to medium, which is expected because marginal natural gas, not coal, is the displaced fossil fuel and this is a site characteristic (EPE, 2010). The land use indicator differentiates the corn and sugarcane ethanol systems as producing 3,500 and 7,500 litres/ha, respectively. By 2020, biomass productivity increases and also CHP are projected to increase the land use indicator for corn and sugarcane ethanol systems to 4,500 and 12,000 litres/ha, respectively (Möllersten et al., 2003; Macedo et al., 2008; (S&T)[2] Consultants, 2009). See also Wang et al. (2011) for more recent data confirming these trends.

2.5.3 Modern bioenergy: Climate change including land use change effects

Bioenergy is different from the other RE technologies in that it is a part of the terrestrial carbon cycle. The CO_2 emitted due to bioenergy use was earlier sequestered from the atmosphere and will be sequestered again if the bioenergy system is managed sustainably, although emissions and sequestration are not necessarily in temporal balance with each other (e.g., due to long rotation periods of forest stands). In addition to changes in atmospheric carbon, bioenergy use may cause changes in terrestrial carbon stocks. The significance of land use and LUC (e.g., Leemans et al., 1996) and forest rotation (Marland and Schlamadinger, 1997) was demonstrated in the 1990s when dLUC effects were also considered in LCA studies (e.g., Reinhardt, 1991; DeLuchi, 1993). DeLuchi (1993) also called for consideration of indirect effects and iLUC. These effects were first considered about 10 years later (Jungk and Reinhardt, 2000), but most LCA studies have not considered iLUC. LUC can affect GHG emissions in a number of ways, including when biomass is burned in the field during land clearing; when the land management practice changes so that the carbon stocks in soils and vegetation change and/or non-CO_2 emissions (N_2O, ammonium (NH_4^+)) change; and when LUC results in changes in rates of carbon sequestration, that is, CO_2 assimilation by the land increases or decreases relative to the case in which LUC is absent.

Schlamadinger et al. (2001) proposed that bioenergy can have direct/indirect, positive/negative effects on biospheric carbon stocks and that crediting under the CDM could stimulate development of systems that function as a positive carbon sink. Recently, negative effects have been re-emphasized, and studies have estimated LUC emissions associated with, primarily, biofuels for transport. Other bioenergy systems and impact categories (e.g., biodiversity, eutrophication; see Section 2.2.4) have received less attention (see Section 9.3.4). There has been little connection with earlier research in the area of land use, LUC and forestry that partly addressed similar concerns, for example, direct environmental and socioeconomic impacts and leakage (Watson, 2000b).

The quantification of the net GHG effects of dLUC occurring on the site used for bioenergy feedstock production requires definition of reference land use and carbon stock data for relevant land types. Carbon stock data can be uncertain but still appear to allow quantification of dLUC emissions with sufficient confidence for guiding policy (see, e.g., Gibbs et al., 2008).

The quantification of the GHG effects of iLUC is more uncertain. Existing methods for studying iLUC effects employ either (1) a deterministic approach where global LUC is allocated to specific biofuels/feedstocks grown on specified land types (Fritsche et al., 2010); or (2) economic equilibrium models integrating biophysical information and/or biophysical models (Edwards et al., 2010; EPA, 2010; Hertel et al., 2010a,b; Plevin et al., 2010). In the second approach, the amount (and approximate location) of additional land required to produce a specified amount of bioenergy is typically projected. This land is then distributed over land cover categories in line with historic LUC patterns, and iLUC emissions are calculated in the same way as dLUC emissions are. There are inherent uncertainties in this approach because models are calibrated against historic data and are best suited for studying existing production systems and land use regimes. Difficult aspects to model include innovation and paradigm shifts in land use including the presently little-used biomass and mixed production systems described in Sections 2.3 and 2.6. There are also studies that compare scenarios with and without increases in bioenergy to derive LUC associated with the bioenergy expansion (e.g., Fischer et al., 2009). Despite the uncertainties, important conclusions can be drawn from these studies.

Production and use of bioenergy influences climate change through:

- Emissions from the bioenergy chain including non-CO_2 GHG and fossil CO_2 emissions from auxiliary energy use in the biofuel chain.
- GHG emissions related to changes in biospheric carbon stocks often caused by associated LUC.
- Other non-GHG related climatic forcers including particulate and black carbon emissions from small-scale bioenergy use (Ramanathan and Carmichael, 2008), aerosol emissions associated with forests (Carslaw et al., 2010) and changes in surface albedo. Reduction in albedo due to the introduction of perennial green vegetative cover can counteract the climate change mitigation benefit of bioenergy in regions with seasonal snow cover or a seasonal dry period (e.g., savannas). Conversely, albedo increases associated with the conversion of forests to energy crops (e.g., annual crops and grasses) may reduce the net climate change effect from the deforestation (Schwaiger and Bird, 2010).
- Effects due to the bioenergy use, such as price effects on petroleum that impact consumption levels. The net effect is the difference between the influence of the bioenergy system and of the energy system (often fossil-based) that is displaced. Current fossil energy

chains and evolving non-conventional sources have land use impacts (Gorissen et al., 2010; Liska and Perrin, 2010; Yeh et al., 2010), but LUC has a tighter link to bioenergy because of its close association with agriculture and forestry.

- Other factors include the extent and timing of the reversion of cultivated land when the use for bioenergy production ends and how future climate change impacts relative to present impacts are treated (DeLucchi, 2010).

Mitigation efforts over the next two to three decades will influence prospects for achieving lower stabilization levels (van Vuuren et al., 2007; den Elzen et al., 2010). For instance, the dynamics of terrestrial carbon stocks in LUC and long-rotation forestry lead to GHG mitigation trade-offs between biomass extraction for energy use and the alternative to leave the biomass as a carbon store that could further sequester more carbon over time (Marland and Schlamadinger, 1997; Marland et al., 2007; Righelato and Spracklen, 2007). Observations indicate that old forests can be net carbon sinks (Luyssaert et al., 2008; Lewis et al., 2009) but fires, insect outbreaks and other natural disturbances can quickly convert a forest from a net sink to an emitter (Kurz et al., 2008a,b; Lindner et al., 2010).

Short- and long-term indicators

Indicators such as *carbon debt* (Fargione et al., 2008) and *ecosystem carbon payback time* (Gibbs et al., 2008) focus on upfront LUC emissions arising from the conversion of land to bioenergy production. The balance between short- and long-term emissions and the climate benefits of bioenergy projects are reflected in indicators that describe the dynamic effect of GHG emissions (see also Section 9.3.4), for example, *cumulative warming impacts* or *global warming potential* (Kirschbaum, 2003, 2006; Dornburg and Marland, 2008; Fearnside, 2008). These indicators have been used, to a limited extent, to describe bioenergy dynamic climate effects (Kendall et al., 2009; Kirkinen et al., 2009; Levasseur et al., 2010; O'Hare et al., 2009).

Figure 2.12 shows dLUC effects on GHG balances for liquid biofuels using the ecosystem carbon payback time indicator. The left diagram shows payback times with current yields and conversion efficiencies and the right diagram shows the effect of higher yields (set to equal the top 10% of area-weighted yields). The payback times in Figure 2.12 neglect the GHG emissions associated with production and distribution of the transport fuels. Because these emissions currently tend to be higher for biofuels than for gasoline and diesel, the payback times are underestimated. The payback times in Figure 2.12 are calculated assuming constant GHG savings from the gasoline/diesel displacement. Higher GHG savings, that is, reducing the payback times, would be achieved if the biofuels conversion efficiency improved, if more carbon intensive transport fuels were replaced, or if the produced biomass displaced carbon-intensive fossil options for heat/power (Figure 2.10). Further biomass yield increases would reduce payback times but may require higher agronomic inputs that lead to increased GHG emissions, notably N_2O. The payback times would increase if the feedstock production resulted in land degradation over time, impacting yield levels or requiring increased input to maintain yield levels.

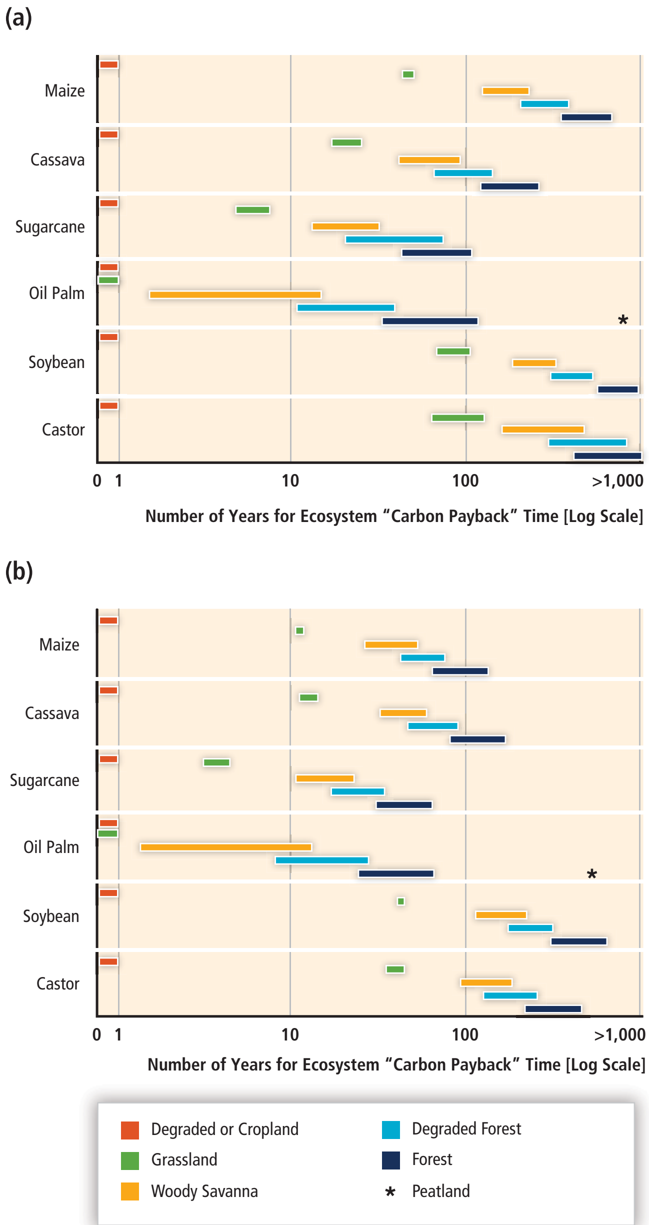


Figure 2.12 | The ecosystem carbon payback time for potential biofuel crop expansion pathways across the tropics comparing the year 2000 agricultural system shown in (a) with a future higher yield scenario (b) which was set to equal the top 10% of area-weighted yields. The asterisk represents oil palm crops grown in peatlands with payback times greater than 900 years in the year 2000 compared to 600 years for a 10% increase in crop productivity. Based on Gibbs et al. (2008) and reproduced with permission from IOP Publishing Ltd.

As shown, all biofuel options have significant payback times when dense forests are converted into bioenergy plantations. The starred points represent very long payback times for oil palm establishment on tropical peat swamp forests because drainage leads to peat oxidation and causes CO_2 emissions that occur over several decades and that can be several times higher than the displaced emissions of fossil diesel (Hooijer et al., 2006; Edwards et al., 2008, 2010). Under natural conditions, these tropical peat swamp forests have negligible CO_2 emissions and small methane emissions (Jauhiainen et al., 2008). Payback times are practically zero when degraded land or cropland is used, and they are relatively low for the most productive systems when grasslands and woody savannas are used (not considering the iLUC that can arise if these lands were originally used, for example, for grazing).

Targeting unused marginal and degraded lands for bioenergy production can thus mitigate dLUC emissions. For some options (e.g., perennial grasses, woody plants, mechanically harvested sugarcane), net gains of soil and aboveground carbon can be obtained (Tilman et al., 2006b; Liebig et al., 2008; Robertson et al., 2008; Anderson-Teixeira et al., 2009; Dondini et al., 2009; Hillier et al., 2009; Galdos et al., 2010). In this context, land application of biochar produced via pyrolysis could be an option to sequester carbon in a more stable form and improve the structure and fertility of soils (Laird et al., 2009; Woolf et al., 2010).

Bioenergy does not always result in LUC. Bioenergy feedstocks can be produced in combination with food and fibre, avoiding land use displacement and improving the productive use of land (Section 2.2). These possibilities may be available for bioenergy options that can use lignocellulosic biomass but also for some other options that use waste oil and oil seeds such as *Jatropha* (Section 2.3). The use of post-consumer organic waste and by-products from the agricultural and forest industries does not cause LUC if these biomass sources are wastes, that is, they were not utilized for alternative purposes. On the other hand, if not utilized for bioenergy, some biomass sources (e.g., harvest residues left in the forest) would retain organic carbon for a longer time than if used for energy. Such delayed GHG emissions can be considered a benefit in relation to near-term GHG mitigation, and this is an especially relevant factor in longer-term accounting for regions where biomass degradation is slow (e.g., boreal forests). However, as noted above, natural disturbances can convert forests from net sinks to net sources of GHGs, and dead wood left in forests can be lost in fires. In forest lands susceptible to periodic fires, good silviculture practices can lead to less frequent, lower intensity fires that accelerate forest growth rates and soil carbon storage. Using biomass removed in such practices for bioenergy can provide GHG and particulate emission reductions.

For different world regions, Edwards et al. (2010) describe the comparison of six equilibrium models to quantify LUC associated with a standard biofuel shock defined as a marginal increase in demand for first-generation ethanol or biodiesel from a base year.[57] All models showed significant LUC (dLUC and iLUC were not considered separable) with variations between models in terms of the extent of LUC and its distribution over regions and crops. A follow-on study by Hiederer et al. (2010) compared the ranges of LUC emissions shown in Figure 2.13 for common biofuel crops as a function of the 'biofuel shock' (0.2 to 1.5 EJ) for select studies. Figure 2.13 also shows the 2010 EPA model results with a relatively high resolution of land use distribution[58] for Brazil resulting in mid-range LUC emissions for sugarcane ethanol (5 to 10 g CO_2eq/MJ), similar to the European study (Al-Riffai et al., 2010) estimate of 12 g CO_2eq/MJ. The Brazilian study with measured LUC dynamics for common crops and native vegetation between 2005 and 2008 by Nassar et al. (2010) obtained 8 g CO_2eq/MJ for iLUC and dLUC, with the latter being nearly zero. Fischer et al. (2010) obtained 28 g CO_2eq/MJ using a deterministic methodology and assuming a high risk of deforestation. Model results from Figure 2.13 show all other crops as having higher LUC values than sugarcane ethanol. In the US maize ethanol case, Plevin et al. (2010) report a plausible range of 25 to 150 g CO_2eq/MJ based on uncertainty analysis of various model parameters and assumptions.

The utility of these models to study scenarios is illustrated with an analysis of the relative contributions of changes in yield and land area to increased crop output along with assumptions about trade-critical factors in model-based LUC estimates (D. Keeney and Hertel, 2009). Subsequent model improvements incorporate crop yields, by-product markets interactions, and trade and policy assumptions, and analyze past and project future usage with existing (2010) EU and US policies, finding LUC in other countries such as Latin America and Oceania to be primarily at the expense of pastureland followed by commercial forests (Hertel et al., 2010a,b).

Lywood et al. (2009b) report that the extent to which output change comes from increased crop yield or land area changes varies between crops and regions. They estimate that yield growth contributed 80 and 60% of the incremental output growth for EU cereals and US maize, respectively, between 1961 and 2007. Conversely, area expansion

57 Biofuel shock (Hertel et al., 2010a,b) is introduced in general equilibrium models by changing some economic parameters (e.g., subsidies to ethanol production) to reach predetermined volume levels (i.e., sum of government mandates for a certain year). The comparison of new and previously determined equilibrium enables estimates of land area changes impacted directly to meet mandates and those indirectly involved to compensate for that agricultural production no longer available, its co-products and its impact throughout the global economic chain. These studies have high uncertainties. Partial equilibrium models were also included in Edwards et al. (2010).

58 Based on the Nassar et al. (2009) Brazilian Land Use Model, which shows a lower share of LUC due to deforestation. More recently, Nassar et al. (2010) obtained elasticities for models from direct data (statistical and satellite-based) of land use substitution over time. The matrix elasticity results for major crops in various regions provide a deterministic estimate for the d+iLUC of sugarcane ethanol of about 8 g CO^2eq/MJ. Higher substitution coefficients are found for soy into native vegetation.

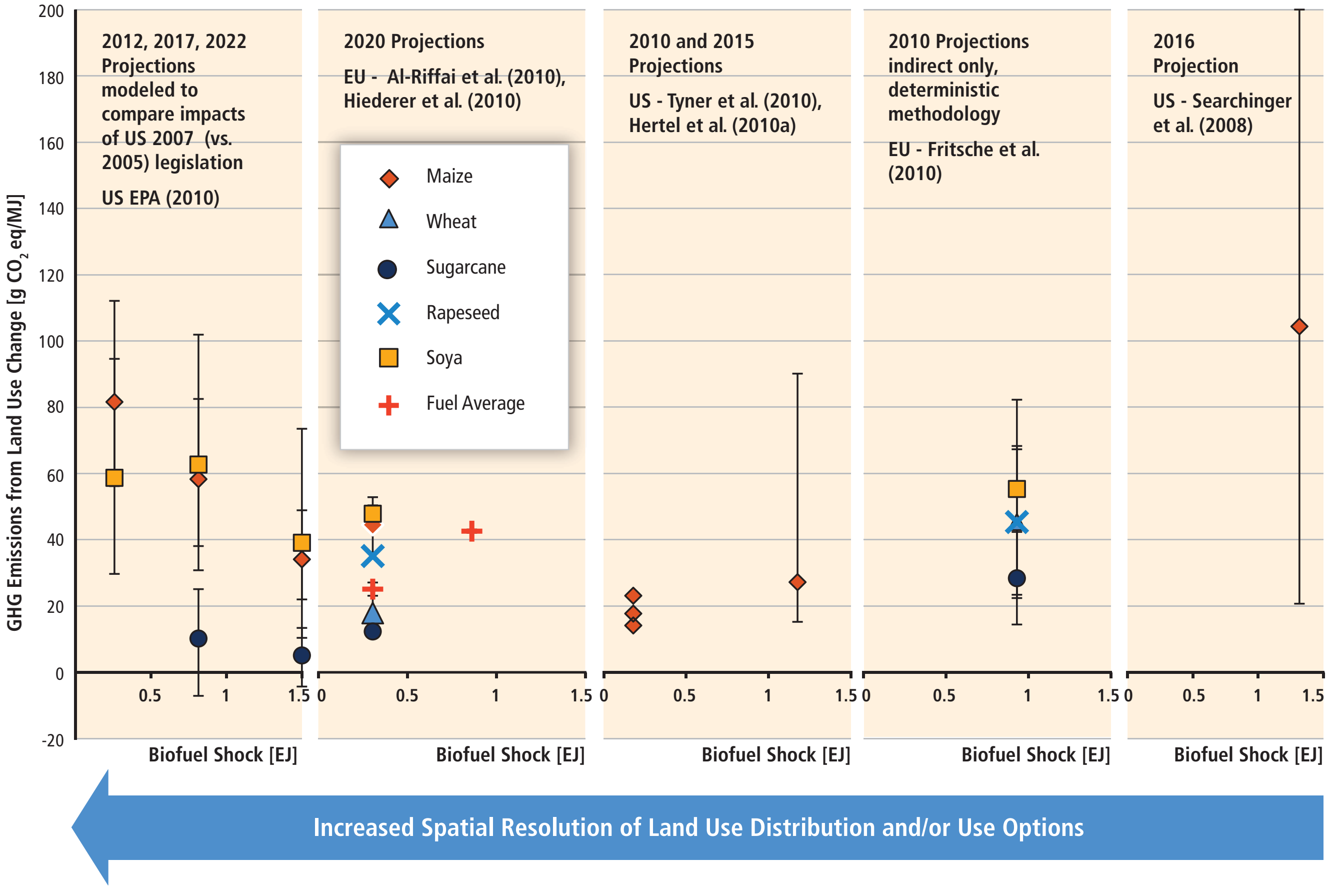


Figure 2.13 | Select model-based estimates of LUC emissions for major biofuel crops given a certain level of demand, a biofuel shock, expressed in EJ (30-year accounting framework). Mid-range values of multiple studies (g CO_2eq/MJ): 14 to 82 for US maize ethanol with high-resolution models and 100 for earlier models; 5 to 28 for sugarcane ethanol; 18 to 45 for European wheat ethanol; 40 to 63 for soy biodiesel (uncertain); and 35 to 45 for rapeseed biodiesel. Points for Tyner et al. (2010) and Hertel et al. (2010a) represent model improvements with the lowest value including feedstock yield and population increases (baseline 2006). Fritsche et al. (2010) value ranges derive from a deterministic methodology representing risk values of 25 and 75% of the theoretical worst case of LUC scenarios, such as high deforestation, to calculate iLUC.

contributed to more than 60% of output growth for EU rapeseed, Brazilian sugarcane, South American soy, and Southeast Asia oil palm. Studies report price-yield relationships; there is a weak basis for deriving these relationships (D. Keeney and Hertel, 2008) although rising oil prices and fuel tax exemptions show strong correlations for the USA and EU, respectively. Edwards et al. (2010) state that the marginal area requirement per additional unit output of a particular biofuel should increase due to decreasing productivity of additional land converted to biofuel feedstock production (also reflected in, e.g., R. Keeney and Hertel, 2005; Tabeau et al., 2006). Lywood et al. (2009b), however, state that in the case of EU cereals and US corn, there is no evidence that average yields decline as more land is used. The assumed or modelled displacement effect of process co-products used as feed can also have a strong influence on LUC values.

For European biofuels, if soy meal and cereals for feed are displaced, the net land area required to produce biofuel from EU cereal, rapeseed and sugar beet is much lower than the gross land requirement (e.g., only 6% for ethanol from feed wheat in northwestern Europe (Lywood et al., 2009a). Lywood et al. (2008) obtained large improvements in net GHG savings for European cereal ethanol and rapeseed biodiesel based on co-products displacing imported soy as animal feed, which reduces deforestation and other LUC for soy cultivation in Brazil. Conversely, increased corn cultivation at the cost of soy cultivation, in response to increasing ethanol demand in the USA, has been reported to increase soy cultivation in other countries such as Brazil (Laurance, 2007). Trade assumptions are critical and differ in the various models. In addition, marginal displacement effects of co-products may have a saturation level (McCoy, 2006; Edwards et al., 2010), although new uses may be developed, for example, to produce more biofuels (Yazdani and Gonzalez, 2007).

Bioenergy options that use lignocellulosic feedstocks are projected to have lower LUC values than those of first-generation biofuels (see, e.g., EPA, 2010; Hoefnagels et al., 2010; see Figure 9.9). As noted above, some of these feedstock sources can be used without causing LUC. Lower LUC values might be expected because of high biomass productivity, multiple products (e.g., animal feed) or avoided competition for prime cropland by using more marginal lands (Sections 2.2 and 2.3). The lower productivity of marginal lands, however, results in higher land requirements per given biomass output and presents particular challenges as discussed in Section 2.2. Also, as many lignocellulosic plants are grown under longer rotations, they should be less responsive to price increases because the average yield over a plantation lifetime can only be influenced through agronomic means (notably increased fertilizer input) and by variety selection at the time of replanting. Thus, output growth in response to increasing demand is more readily obtained by area expansion.

Depending on the atmospheric lifetime of specific GHGs, the trade-off between emitting more now and less in the future is not one-to-one in general. But the relationship for CO_2 is practically one-to-one, so that one additional (less) tonne CO_2 emitted today requires a future reduction (allows a future increase) by one tonne. This relationship is due to the close to irreversible climate effect of CO_2 emissions (Matthews and Caldeira, 2008; M. Allen et al., 2009; Matthews et al., 2009; Solomon et al., 2009).

Integrated energy-industry-land use/cover models can give insights into how an expanding bioenergy sector interacts with other sectors in society, influencing longer-term energy sector development, land use, management of biospheric carbon stocks, and global cumulative GHG emissions. In an example of early studies, Leemans et al. (1996) implemented in the IMAGE model (Integrated Model to Assess the Global Environment) the LESS (low CO_2-emitting energy supply system) scenario, which was developed for the IPCC Second Assessment Report (IPCC, 1996). This study showed that the required land use expansion to provide biomass feedstock can cause significant food-bioenergy competition and influence deforestation rates with significant consequences for environmental issues such as biodiversity, and that the outcome is sensitive to regional emissions and feedback in the carbon cycle. More recently, using linked economic and terrestrial biogeochemistry models, Melillo et al. (2009) found a similar level of cumulative CO_2 emissions associated with LUC from an expanded global cellulosic biofuels programme over the 21st century. The study concluded that iLUC was a larger source of carbon loss than dLUC; fertilizer N_2O emissions were a substantial source of global warming; and forest protection and best practices for nitrogen fertilizer use could dramatically reduce emissions associated with biofuels production.

Wise et al. (2009) also stressed the importance of limiting terrestrial carbon emissions and showed how the design of mitigation regimes can strongly influence the nature of bioenergy development and associated environmental consequences, including the net GHG savings from bioenergy. Including both fossil and LUC emissions in a carbon tax regime, instead of taxing only fossil emissions, was found to lower the cost of meeting environmental goals. However, this tax regime was also found to induce rising food crop and livestock prices and expansion of unmanaged ecosystems and forests. Improved crop productivity was proposed as a potentially important means for GHG emissions reduction, with the caution that non-CO_2 emissions (not modelled) need to be considered.

Biospheric carbon pricing as a sufficient mechanism to protect forests was proposed by Wise et al. (2009) and supported by Venter et al. (2009) and others. Persson and Azar (2010) acknowledge that pricing LUC carbon emissions could potentially make many of the current proximate causes of deforestation unprofitable (e.g., extensive cattle ranching, small-scale slash-and-burn agriculture and fuelwood use) but they question whether it will suffice to make deforestation for bioenergy production unprofitable because these bioenergy systems are highly productive according to the Wise et al. (2009) assumptions of generic feedstock productivity and biofuel conversion efficiency. A higher carbon price will increase not only the cost of forest clearing but also the revenues from certain bioenergy production systems. The upfront cost of land conversion may also be reduced if the bioenergy industry partners with the timber and pulp industries that seek access to timber revenues from clear felling forests as the first step in plantation development (Fitzherbert et al., 2008).

Three tentative conclusions are:

1. Additional, and stronger, protection measures may be needed to meet the objective of tropical forest preservation. A strict focus on the climate benefits of ecosystem preservation may put undue pressure on valuable ecosystems that have a relatively low carbon density. While this may have a small impact in terms of climate change mitigation, it may negatively impact other parts of the ecosystem, for example, biodiversity and water tables.

2. From a strict climate and cost efficiency perspective, in some places a certain level of upfront LUC emissions may be acceptable in converting forest to highly productive bioenergy plantations due to the climate benefits of subsequent continued biofuel production and fossil fuel displacement. The balance between bioenergy expansion benefits and LUC impacts on biodiversity, water and soil conservation is delicate. Climate change mitigation is just one of many rationales for ecosystem protection.

3. iLUC effects strongly (up to fully) depend on the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. Subsequently, implementation of bioenergy production and energy cropping schemes that follow effective sustainability frameworks and start from simultaneous improvements in agricultural management could mitigate conflicts and allow realization of positive outcomes, for example, in rural development, land amelioration and climate change mitigation including opportunities to combine adaptation measures.

2.5.4 Traditional biomass: Climate change effects

Traditional open fires and simple low-efficiency stoves have low combustion efficiency, producing large amounts of incomplete combustion products (CO, methane, particle matter, non-methane volatile organic compounds, and others) that have negative consequences for climate change and local air pollution (Smith et al., 2000; see also Box 9.4 in Section 9.3.4.2). When biomass is harvested renewably—for example, from standing trees or agricultural residues—CO_2 already emitted to the atmosphere is sequestered as biomass re-grows. Because the products of incomplete combustion also include important short-lived greenhouse pollutants and black carbon, even sustainable harvesting does not make such fuel cycles GHG neutral. Worldwide, it is estimated that household fuel combustion causes approximately 30% of the warming due to black carbon and CO emissions from human sources, about 15% of ozone-forming chemicals, and a few percent of methane and CO_2 emissions (Wilkinson et al., 2009).

Improved cookstoves (ICS) and other advanced biomass systems for cooking are cost-effective for achieving large benefits in energy use reduction and climate change mitigation. Fuel savings of 30 to 60% are reported (Berrueta et al., 2008; Jetter and Kariher, 2009). The savings in GHG emissions associated with these efficient stoves are difficult to derive because of the wide range of fuel types, stove designs, cooking practices and environmental conditions across the world. However, advanced biomass systems, such as small-scale gasifier stoves and biogas stoves, have had design improvements that increase combustion efficiency and dramatically reduce the production of short-lived GHGs by up to 90% relative to traditional stoves. Some of these new stoves even reach performance levels similar to liquid propane gas (Jetter and Kariher, 2009). Patsari improved stoves in rural Mexico save between 3 and 9 t CO_2eq/stove/yr relative to open fires, with renewable or non-renewable harvesting of biomass, respectively (M. Johnson et al., 2009).

Venkataraman et al. (2010) estimate that the dissemination of 160 million advanced ICS in India may result in the mitigation of 80 Mt CO_2eq/yr, or more than 4% of India's total estimated GHG emissions, plus a 30% reduction in India's human-caused black carbon emissions. Worldwide, with GHG mitigation per unit at 1 to 4 t CO_2eq/stove/yr compared to traditional open fires, the global mitigation potential of advanced ICS was estimated to be between 0.6 and 2.4 Gt CO_2eq/yr. This estimate does not consider the additional potential reduction in black carbon emissions. Actual figures depend on the renewability of the biomass fuel production, stove and fuel characteristics, and the actual adoption and sustained used of improved cookstoves. Reduction in fuelwood and charcoal use due to the adoption of advanced ICS may help reduce pressure on forest and agricultural areas and improve aboveground biomass stocks and soil and biodiversity conservation (Ravindranath et al., 2006; García-Frapolli et al., 2010).

2.5.5 Environmental impacts other than greenhouse gas emissions

2.5.5.1 Impacts on air quality and water resources

Air pollutant emissions from bioenergy production depend on technology, fuel properties, process conditions and installed emission reduction technologies. Compared to coal and oil stationary applications, sulphur dioxide (SO_2) and nitrous oxide (NO_x) emissions from bioenergy applications are mostly lower (see also Section 9.3.4.2). When biofuel replaces gasoline and diesel in the transport sector, SO_2 emissions are reduced, but changes in NO_x emissions depend on the substitution pattern and technology. The effects of replacing gasoline with ethanol and biodiesel also depend on engine features. Biodiesel can have higher NO_x emissions than petroleum diesel in traditional direct-injected diesel engines that are not equipped with NO_x control catalysts (e.g., Verhaeven et al., 2005; Yanowitz and McCormick, 2009).

Bioenergy production can have both positive and negative effects on water resources (see also Section 9.3.4.4). Bioenergy production generally consumes more water than gasoline production (Wu et al., 2009; Fingerman et al., 2010). However, this relationship and the water impacts of bioenergy production are highly dependent on location, the specific feedstock, production methods and the supply chain element.

Feedstock cultivation can lead to leaching and emission of nutrients that increase eutrophication of aquatic ecosystems (Millennium Ecosystem Assessment, 2005; SCBD, 2006; Spranger et al., 2008). Pesticide emissions to water bodies may also negatively impact aquatic life. Given that several types of energy crops are perennials grown in arable fields being used temporarily as a pasture for grazing animals or woody crops grown in multi-year rotations, the increasing bioenergy demand may drive land use towards systems with substantially higher water productivity. On the other hand, shifting demand to alternative—mainly lignocellulosic—bioenergy can decrease water competition. Perennial herbaceous crops and short-rotation woody crops generally require fewer agronomic inputs and have reduced impacts compared to annual crops, although large-scale production can require high levels of nutrient input (see Sections 2.2.4.2 and 2.3.1). Water impacts can also be mitigated by integrating lignocellulosic feedstocks in agricultural landscapes as vegetation filters to capture nutrients in passing water (Börjesson and Berndes, 2006). A prolonged growing season may redirect unproductive soil evaporation and runoff to plant transpiration (Berndes, 2008a,b). Crops that provide a continuous cover over the year can also conserve soil outside the growing season of annual crops by diminishing the erosion from precipitation and runoff (Berndes, 2008a,b). A number of bioenergy crops can be grown on a wide spectrum of land types that are not suitable for conventional food or feed crops. These marginal lands, pastures and grasslands could become available for feedstock production under sustainable management practices (if adverse downstream water impacts can be mitigated).

The subsequent processing of the feedstock into biofuels and electricity can increase chemical and thermal pollution loads from effluents and generate waste to aquatic systems (Martinelli and Filoso 2007, Simpson et al., 2008). These environmental impacts can be reduced if suitable equipment is installed (Wilkie et al., 2000; BNDES/CGEE, 2008).

Water demand for bioenergy can be reduced substantially through process changes and recycling (D. Keeney and Muller, 2006; BNDES/CGEE, 2008). Currently, most water is lost to the atmosphere through evapotranspiration during the production of cultivated feedstock (Berndes, 2002). Feedstock processing into fuels and electricity requires much less water (Aden et al., 2002; Berndes, 2002; D. Keeney and Muller, 2006; Phillips et al., 2007; NRC, 2008; Wang et al., 2010), but water needs to be extracted from lakes, rivers and other water bodies.

2.5.5.2 Biodiversity and habitat loss

Habitat loss is one of the major drivers of biodiversity decline globally and is projected to be the major driver of biodiversity loss and decline over the next 50 years (Sala et al., 2000; UNEP, 2008b; see Sections 9.3.4.5 and 9.3.4.6). Increased biomass output for bioenergy can directly impact wild biodiversity through conversion of natural ecosystems into bioenergy plantations or through changed forest management. Habitat and biodiversity loss may also occur indirectly, such as when productive land use displaced by energy crops is re-established by converting natural ecosystems into croplands or pastures elsewhere. Because biomass feedstocks can generally be produced most efficiently in tropical regions, there are strong economic incentives to replace tropical natural ecosystems—many of which host high biodiversity values (Doornbosch and Steenblik, 2008). However, forest clearing is mostly influenced by local social, economic, technological, biophysical, political and demographic forces (Kline and Dale, 2008).

Increasing demand for oilseed has put pressure on areas designated for conservation in some OECD member countries (Steenblik, 2007). Similarly, the rising demand for palm oil has contributed to extensive deforestation in parts of Southeast Asia (UNEP, 2008a). The palm oil plantations support significantly fewer species than the forest they replaced (Fitzherbert et al., 2008).

To the extent that bioenergy systems are based on conventional food and feed crops, biodiversity impacts from pesticide and nutrient loading can be expected from bioenergy expansion. Bioenergy production can also impact agricultural biodiversity when large-scale monocultures, based on a narrow pool of genetic material, reduce the use of traditional varieties.

Depending on a variety of factors, bioenergy expansion can also lead to positive outcomes for biodiversity. Using bioenergy to replace fossil fuels can reduce climate change, which is expected to be a major driver of habitat loss. Establishment of perennial herbaceous plants or short-rotation woody crops in agricultural landscapes has been found to improve biodiversity (Lindenmayer and Nix, 1993; Semere and Slater, 2007; Royal Society, 2008). Bioenergy plantations that are cultivated as vegetation filters can improve biodiversity by reducing the nutrient load and eutrophication in water bodies (Foley et al., 2005; Börjesson and Berndes, 2006) and providing a varied landscape.

Bioenergy plantations can be located in the agricultural landscape to provide ecological corridors through which plants and animals can move between spatially separated natural and semi-natural ecosystems. Thus, bioenergy plantations can reduce the barrier effect of agricultural lands (Firbank, 2008). However, bioenergy plantations can contribute to habitat fragmentation, as has occurred with some oil palm plantations (Danielsen et al. 2009; Fitzherbert, 2008).

Properly located biomass plantations can also protect biodiversity by reducing the pressure on nearby natural forests. A study from Orissa, India, showed that introducing village biomass plantations increased biomass consumption (as a consequence of increased availability) while decreasing pressure on the surrounding natural forests (Köhlin and Ostwald, 2001; Francis et al., 2005).

When crops are grown on degraded or abandoned land, such as previously deforested areas or degraded crop- and grasslands, the production of feedstocks for biofuels could have positive impacts on biodiversity by restoring or conserving soils, habitats and ecosystem functions (Firbank, 2008). For instance, several experiments with selected trees and intensive management on severely degraded Indian wastelands (such as alkaline, sodic or salt-affected lands) showed increases in soil carbon, nitrogen and available phosphorous within eight years (Garg, 1998).

2.5.5.3 Impacts on soil resources

The considerable soil impacts of increased biofuel production include soil carbon oxidation, changed rates of soil erosion, and nutrient leaching. However, these effects are heavily dependent on agronomic techniques and the feedstock under consideration (UNEP, 2008a). Land preparation required for feedstock production, as well as nutrient demand, varies widely across feedstocks. For instance, wheat, rapeseed and corn require significant tillage compared to oil palm, sugarcane and switchgrass (FAO, 2008a; UNEP, 2008a). In sugarcane production, soil quality benefits greatly from recycled nutrients from sugar mill and distillery wastes (IEA, 2006).

Using agricultural residues without proper management can lead to detrimental impacts on soil organic matter through increased erosion. However, this impact depends heavily on management, yield, soil type and location. In some areas, the impact of residue removal may be minimal.

Certain cultivation practices, including conservation tillage and crop rotations, can mitigate adverse impacts and in some cases improve environmental benefits of biofuel production. For example, *Jatropha* can stabilize soils and store moisture while it grows (Dufey, 2006). Other potential benefits of planting feedstocks on degraded or marginal lands include reduced nutrient leaching, increased soil productivity and increased carbon content (Berndes, 2002). If lignocellulosic energy crop plantations, which require low-intensity management and few fossil energy inputs relative to current biofuel systems, are established on abandoned agricultural or degraded land, soil carbon and soil quality could increase over time. This beneficial effect would be especially significant with perennial species.

2.5.6 Environmental health and safety implications

2.5.6.1 Feedstock issues

Currently, many crops used in fuel ethanol manufacturing are also traditional feed sources (e.g., maize, soy, canola and wheat). However, considerable efforts are focused on new crops that either enhance fuel ethanol production (e.g., high-starch corn) or that are not traditional food or feed crops (e.g., switchgrass). If the resultant distillers' grains from these new crops are used as livestock feed or could inadvertently end up in livestock feeds, pre-market assessment of their acceptability in feed prior to their use in fuel ethanol production will be necessary (Hemakanthi and Heller, 2010).

Concerns about cross-pollination, hybridization, pest resistance and disruption of ecosystem functions (FAO, 2004; FAO, 2008; IAASTD, 2009) have limited the use of genetically engineered (GE) crops in some regions. Transgene movement leading to weediness or invasiveness of the crop itself or of its wild or weedy relatives is a major reason (Warwick et al., 2009). Clarity, predictability and established risk assessment processes are literature recommendations to decrease GE crop use concerns (Warwick et al., 2009).[59] The first assessment (NRC, 2010) of the impact of GE crops in use in the USA since 1996 found that benefits to the farmer included increased worker safety from pesticide handling; indicated that water quality improves with GE crops; and acknowledged that more work needs to be done, particularly to install infrastructure to measure water quality impacts, develop weed management practices, and address the needs of farmers whose markets depend on the absence of GE traits.

Several grasses and woody species that are candidates for biofuel production have traits commonly found in invasive species (Howard and Ziller, 2008). These traits include rapid growth, high water-use efficiency and long canopy duration (Clifton-Brown et al., 2000). There are fears that if these crops are introduced, they could become invasive, displace indigenous species and decrease biodiversity. For example, *Jatropha curcas* is considered weedy in several countries, including India and many South American states (Low and Booth, 2007). Warnings have been raised about *Miscanthus* and switchgrass (*Panicum virgatum*). *Sorghum halepense* (Johnson grass), *Arundo donax* (giant reed) and *Phalaris arundinacea* (reed canary grass) are known to be invasive in the USA. A number of protocols have evolved that allow for a systematic assessment and evaluation of the inherent risk associated with species introduction (McWhorter, 1971; Randall, 1996; Molofsky et al., 1999; Dudley, 2000; Forman, 2003; Raghu et al., 2006). DiTomaso et al. (2010) address policies to keep these agro-ecosystems in check while developing desirable biofuels crops, such as preventive actions prior to and during cultivation of biofuel plants.

2.5.6.2 Biofuels production issues

Globally, most biofuels are produced with conventional production technologies (see Section 2.3) that have been used in many industries for many years (Gunderson, 2008; Abbasi and Abbasi, 2010). Hazards associated with most of these technologies are well characterized, and it is possible to limit risks to very low levels by applying existing knowledge and standards (see, e.g., Astbury, 2008; Hollebone and Yang, 2009; Marlair et al., 2009; Williams et al., 2009) and their typology is under development (Rivière and Marlair, 2009, 2010).

The literature highlights environmental health and safety areas for further evaluation as new technologies (see Section 2.6) are developed (e.g., Madsen et al., 2004; Madsen, 2006; Vinnerås et al., 2006; Narayanan et al., 2007; Gunderson, 2008; McLeod et al., 2008; Hill et al., 2009; Martens and Böhm, 2009; Moral et al., 2009; Perry, 2009; Sumner and Layde, 2009). Key areas include:

- Health risk to workers using engineered microorganisms or their metabolites.
- Potential ecosystem effects from the release of engineered microorganisms.
- Impact to workers, biofuel consumers or the environment from pesticides and mycotoxins that accumulate in processing intermediates, residues or products (e.g., spent grains, spent oil seeds).
- Risks to workers from infectious agents that can contaminate feedstocks in production facilities.
- Exposure to toxic substances, particularly for workers at biomass thermochemical processing facilities that use routes not currently practised by the fossil fuels industry.
- Fugitive air emissions and site runoff impacts on public health, air quality, water quality and ecosystems.

59 Other concerns include: reduction in crop diversity, increases in herbicide use, herbicide resistance (increased weediness), loss of farmer's sovereignty over seed, ethical concerns over transgenes origin, lack of access to intellectual property rights held by the private sector, and loss of markets owing to moratoriums on genetically modifed organisms (GMOs) (IAASTD, 2009).

- Exposure to toxic substances, particularly if production facilities become as commonplace as landfill sites or natural gas-fired electricity generating stations.

- Cumulative environmental impacts from the siting of multiple biofuel/bioenergy production facilities in the same air- and/or watershed.

2.5.7 Socioeconomic aspects

The large-scale and global development of bioenergy will be associated with a complex set of socioeconomic issues and trade-offs, ranging from local issues (e.g., income and employment generation, improved health conditions, agrarian structure, land tenure, land use competition and strengthening of regional economies) to national issues (e.g., food security, a secure energy supply and balance of trade). Participation of local stakeholders, in particular small farmers and poor households, is essential to ensure socioeconomic benefits from bioenergy projects.

2.5.7.1 Socioeconomic impact studies and sustainability criteria for bioenergy systems

The complex nature of bioenergy, with many conversion routes and the multifaceted potential socioeconomic impacts, makes the overall impact analysis difficult to conduct. Also, many impacts are not easily quantifiable in monetary or numerical terms. To overcome these problems, semi-quantitative methods based on stakeholder involvement have been used to assess social criteria such as societal product benefit and social dialogue[60] (von Geibler et al., 2006).

Regarding economic impacts, the most commonly reported variables are private production costs over the value chain, assuming a fixed set of prices for basic commodities (e.g., for fossil fuels and fertilizers). The bioenergy costs are usually compared to alternatives already on the market (fossil-based) to judge the potential competitiveness. Bioenergy systems are mostly analyzed at a micro-economic level, although interactions with other sectors cannot be ignored because of the competition for land and other resources. Opportunity costs may be calculated from food commodity prices and gross margins to account for food-bioenergy interactions. Social impact indicators include consequences for local employment, although this impact is difficult to assess because of possible offsets between fossil and bioenergy chains. Impacts at a macro-economic level include the social costs incurred because of fiscal measures (e.g., tax exemptions) to support bioenergy chains (DeLucchi, 2005). Fossil energy's negative externalities also need to be assessed (Bickel and Friedrich, 2005).

Several sustainability frameworks and certification systems have been proposed to better document and integrate the socioeconomic impacts of bioenergy systems, particularly at the project level (Bauen et al., 2009b; WBGU, 2009; van Dam et al., 2010; see also Section 2.4). Specifically, criteria and indicators related to the development of liquid biofuels have been proposed for these issues: human rights, including gender issues; working and wage conditions, including health and safety issues; local food security; rural and social development, with special regard to poverty reduction; and land rights (Table 2.12). So far, while rural and local development are included, specific economic criteria for the cost-effectiveness of the projects, level of subsidies and other financial aspects have not been included in the sustainability frameworks. Most of the frameworks are still under development. The progress of certification systems was reviewed by van Dam et al. (2008, 2010). The FAO's Bioenergy and Food Security Criteria and Indicators project has compiled bioenergy sustainability initiatives (see also Sections 2.4.5.1 and 2.4.5.2).

60 Multi Criteria Analysis methods have been applied in the bioenergy field during the past 15 years (Buchholz et al., 2009).

2.5.7.2 Socioeconomic impacts of small-scale systems

The inefficient use of biomass in traditional devices such as open fires has significant socioeconomic impacts including drudgery for getting the fuel, the cost of satisfying cooking needs, and significant health impacts from the very high levels of indoor air pollution, especially for women and children (Masera and Navia, 1997; Pimentel et al., 2001; Biran et al., 2004; Bruce et al., 2006; Romieu et al., 2009). Indoor air pollutants include respirable particles, CO, oxides of nitrogen and sulphur, benzene, formaldehyde, 1, 3-butadiene, and polyaromatic compounds such as benzo(a)pyrene (Smith et al., 2000). Wood smoke exposure can increase respiratory symptoms and problems (Thorn et al., 2001; Mishra et al., 2004; Schei et al., 2004; Boman et al., 2006). Exposures of household members have been measured to be many times higher than World Health Organization guidelines and national standards (Smith et al., 2000; Bruce et al., 2006) (see also Sections 9.3.4.3 and 9.4.4). More than 200 studies over the past two decades have assessed levels of indoor air pollutants in households using solid fuels. The burden from related diseases was estimated at 1.6 million excess deaths per year, including 900,000 children under five, and a loss of 38.6 million DALY (Disability Adjusted Life Year) per year (Smith and Haigler, 2008). This burden is similar in magnitude to the burden of disease from malaria and tuberculosis (Ezzati et al., 2002).

Properly designed and implemented ICS projects, based on the new generation of biomass stoves, have led to significant health improvements (von Schirnding et al., 2001; Ezzati et al., 2004). ICS health benefits include a 70 to 90% reduction in indoor air pollution, a 50% reduction in human exposure, and reductions in respiratory and other illnesses (Armendáriz et al., 2008; Romieu et al., 2009). Substantial health benefits can accrue even with modest reductions in exposure to indoor air pollutants. For example, in Guatemala, a 50% reduction in exposure has been shown to produce a 40% improvement in childhood pneumonia cases. In India, the health benefits from the dissemination of advanced ICS have been estimated to be potentially equivalent to eliminating nearly half the entire cancer burden in 2020. These health benefits include 240,000 averted premature deaths from acute lower respiratory infections in children younger than five years and more than 1.8 million averted premature adult deaths from ischemic heart disease and chronic obstructive pulmonary disease (Bruce et al., 2006; Wilkinson et al., 2009).

Figure 2.14 shows the cost effectiveness of treatment options for the eight major risk factors that account for 40% of the global disease burden (Glass, 2006). ICS are among the most cost-effective options in terms of the cost per avoided DALY. Overall, ICS and other small-scale biomass systems represent a very cost-effective intervention with benefits to cost ratios of 5.6:1, 20:1 and 13:1 found in Malawi, Uganda and Mexico, respectively (Frapolli et al., 2010).

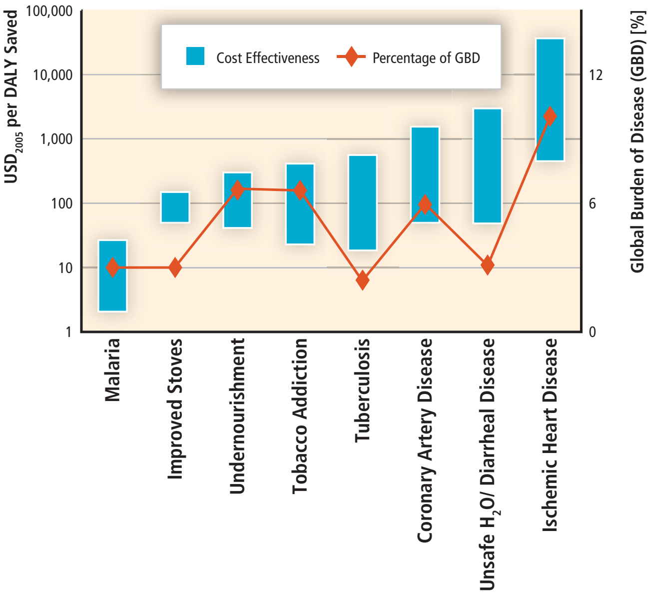


Figure 2.14 | Cost effectiveness of interventions expressed in dollars per disability adjusted life year (DALY) saved (Glass, 2006) on the left scale (logarithmic scale), and contributions to the global burden of disease (GBD) from eight major risk factors and diseases (in %, right scale). The figure shows that the dissemination of improved biomass stoves—depicted here as an intervention to reduce the health effects of indoor air pollution due to fuelwood use—compares well with the cost of interventions aimed at combating major health problems and diseases such as undernourishment, tuberculosis, heart diseases and others (Bailis et al., 2009 with permission from Elsevier B.V.).

Increased use of ICS frees up time for women to engage in income-generating activities. Reduced fuel collection times and savings in cooking time can also translate into increased time for education of rural children, especially girls (Karekezi and Majoro, 2002). ICS use fosters improvements in local living conditions, kitchens and homes, and quality of life (Masera et al., 2000). The manufacture and dissemination of ICS also represents an important source of income and employment for thousands of local small businesses around the world (Masera et al., 2005). Similar impacts were found for small-scale biogas plants, which have the added benefits of providing lighting for individual households and villages and increasing the quality of life. More efficient technologies than currently employed in small-scale industries (such as improved brick and charcoal kilns) are available that increase work productivity, quality of products and overall working conditions (FAO, 2006, 2010b).

2.5.7.3 Socioeconomic aspects of large-scale bioenergy systems

Large-scale bioenergy systems have sparked heated controversies around food security, income generation, rural development and land tenure. The controversy makes clear that there may be both advantages and disadvantages to the further development of large-scale bioenergy systems, depending on their characteristics, local conditions and the mode of implementation.

Impacts on job and income generation
Increased demand for agricultural and forestry waste materials (i.e., residues) can supplement farmers' and foresters' incomes, particularly if the wastes were previously burned or landfilled. Bioenergy can also generate jobs; in general, bioenergy generates more jobs per unit of energy delivered than other energy sources, largely due to feedstock production, especially in developing countries and rural areas (FAO, 2010b).

Wage income is a key contribution to the livelihoods of many poor rural dwellers (Ivanic and Martin, 2008). The benefits from bioenergy jobs depend on the relative labour intensity of the feedstock crop compared to the crop that was previously grown on the same land. For example, cultivation of perennial energy crops requires less labour than cereal crop cultivation, and this displacement effect should be taken into account (Thornley et al., 2009). While increased employment is an important potential benefit, highly labour-intensive operations might also reduce competitiveness (depending on the relative prices of labour and capital) (see Section 9.3.1.3).

The number of jobs created is very location-specific and varies considerably with plant size, the degree of feedstock production mechanization (Berndes and Hansson, 2007) and the contribution of imports to meeting demand (Nusser et al., 2007; Wydra, 2009). Estimates of the employment creation potential of bioenergy options differ substantially, but liquid biofuels based on traditional agricultural crops seem to provide the most employment, especially when the biofuel conversion plants are small (Berndes and Hansson, 2007). Even within liquid biofuel options, the use of different crops introduces wide differences. For ethanol, the number of direct and indirect jobs generated ranges from 45 (corn) to 2,200 (sugarcane) jobs/PJ of ethanol. For biodiesel, the number of direct and indirect jobs generated ranges from 100 (soybean) to 2,000 (oil palm) jobs/PJ of biodiesel (Dias de Moraes, 2007; Clayton et al., 2010). For electricity production, mid-scale power plants in developing countries using a low-mechanized system (25 MW) are estimated to generate approximately 400 jobs/plant or 250 jobs/PJ, of which 94% are in the production and harvesting of feedstocks. For instance, in a detailed UK study, 1.27 jobs/GWh were calculated for power generation from a 25 MW_e plant using dedicated crops (woody or *Miscanthus*). During the complete lifecycle, 4,000 to 6,000 person-year jobs are created, representing on a yearly basis 200 jobs/PJ (15, 73, and 12% at the electricity plant, feedstock production and delivery, and induced, respectively) (Thornley et al., 2008).

In Europe, if the EU25 scenario is followed, Berndes and Hansson (2007) estimate that biomass production for energy can create employment at a magnitude that is significant relative to total agricultural employment (up to 15% in selected countries) but small compared to the total industrial employment in a country. The latest analysis also shows some trade-offs—for instance, agricultural options for liquid biofuels create more employment, but forest-based options for electricity and heat production produce more climate benefits. In Brazil, the biofuel sector accounted for about one million jobs in rural areas in 2001, mostly for unskilled labour related to manual harvesting after field burning of sugarcane (Moreira, 2006). Indeed, mechanization, already ongoing in about 50% of the Center South production (responsible for 90% of the country's harvest), reduces demand for unskilled labour for manual harvest but produces an environmental benefit. Meanwhile, worker productivity continues to grow and part of the workforce is retrained for the skilled higher-paying jobs required for mechanized operations (Oliveira, 2009).

2.5.7.4 Risks to food security

Unless the feedstocks are grown on abandoned land or use residues that previously had no economic value, liquid biofuel production creates additional demand for food and agricultural commodities that places additional pressure on natural resources such as land and water and thus raises food commodity prices (Chakravorty et al., 2009; B. Wright, 2009). Lignocellulosic biofuels, because they can be grown more easily on land that is not suitable for food production, can reduce but not eliminate competition (Chakravorty et al., 2009). To the extent that domestic food markets are linked to international food markets, even countries that do not produce bioenergy may be affected by the higher prices.

Commodity prices are determined by a complex set of factors, of which biofuels is only one, and projections of future prices are highly uncertain. Nevertheless, several studies have examined the contribution of increased biofuels production to the surge in food prices that occurred in the mid-2000s. These studies use different analytical methods and report their results in different ways (for a comprehensive review of these studies, see DEFRA, 2009). For example, the OECD-FAO Agricultural Outlook (OECD-FAO, 2008) model found that if biofuel production were frozen at 2007 levels, coarse grains prices would be 12% lower and vegetable oil prices 15% lower in 2017 compared with a situation where biofuels production continues to increase as expected. Rosegrant et al. (2008) estimated that world maize prices would be 26% higher under a scenario of continued biofuel expansion according to the existing national development plans and more than 70% higher under a drastic biofuel expansion scenario where biofuel demand is double that under the first scenario (these scenarios are relative to a baseline of modest biofuel development where biofuel production remains constant at 2010 levels in most countries). IFPRI (2008) estimated that 30% of the weighted average increase in world cereal prices was attributable to biofuels between 2000 and 2007. Elobeid and Hart (2007) compared two modelled scenarios, with and without biofuel utilization barriers, and found that removing utilization barriers doubled the projected increases in corn and food basket prices. These studies generally agree that increased biofuels production played some role in increased food prices, but there is no consensus about the size of this contribution (FAO, 2008a; Mitchell, 2008; DEFRA, 2009; Baffes and Haniotis, 2010). Other factors include the weak US dollar, increased energy costs, increased agricultural production costs, speculation on commodities, and adverse weather conditions (Headey and Fan, 2008; Mitchell, 2008; DEFRA, 2009; Baffes and Haniotis, 2010). The eventual impact of biofuels on prices will depend, among other factors, on the specific technology used, the strength of government mandates for biofuel use, the design of trade policies that favour inefficient methods of biofuel production, and oil prices.

The impact of higher prices on the welfare of the poor depends on whether the poor are net sellers of food (benefit from higher prices) or net buyers of food (harmed by higher prices). On balance, the evidence indicates that higher prices will adversely affect poverty and food security in developing countries, even after taking into account the benefits of higher prices for farmers (Ivanic and Martin, 2008; Zezza et al., 2008). A major FAO study on the socioeconomic impacts of the expansion of liquid biofuels (FAO, 2008a) indicates that poor urban consumers and poor net food buyers in rural areas are particularly at risk. Rosegrant et al. (2008) estimated that the number of malnourished children would double under the two scenarios mentioned above.

A significant increase in the cultivation of crops for bioenergy indicates a close coupling of the markets for energy and food (Schmidhuber, 2008), and an analysis by the World Bank (2009) confirmed a strong association between food and energy prices when oil prices are above USD_{2005} 45 per barrel. Thus, if energy prices increase, there may be spillovers into food markets that increase food insecurity.

Meeting the food demands of the world's growing population will require a 70% increase in global food production by 2050 (Bruinsma, 2009). At the same time, FAO (2008b) estimates that the increase in arable land between 2005 and 2050 will be just 5% (Alexandratos et al., 2009). This limited increase indicates that economically exploitable arable land is scarce. Because biomass production is land-intensive, there could be significant competition between food and fuel for the use of agricultural land (Chakravorty et al., 2009). Increased biofuels production could also reduce water availability for food production, as more water is diverted to production of biofuel feedstocks (Chakravorty et al., 2009; Hoekstra et al., 2010).

2.5.7.5 Impacts on rural and social development

Growing demand for biofuels and the resulting rise in agricultural commodity prices can present an opportunity for promoting agricultural growth and rural development in developing countries (Schmidhuber, 2008). The development potential critically depends on whether the bioenergy market is economically sustainable without government subsidies. If long-term subsidies are required, fewer government funds will be available for the wide range of other public goods that are essential for economic and social development, such as agricultural research, rural roads, and education. Even short-term subsidies need to be considered very carefully, as once subsidies are implemented they can be difficult to remove. Latin American experience shows that governments that use agricultural budgets for investment in public goods experience faster growth and alleviate poverty and environmental degradation more rapidly than those that apply them for subsidies (López and Galinato, 2007).

Bioenergy may reduce dependence on fossil fuel imports and increase energy supply security. In many cases these benefits are not likely to be large, although the contribution could be substantial for countries with large amounts of arable land per person (FAO, 2008a). Recent analyses of the use of indigenous resources implies that much of the expenditure on energy is retained locally and recirculated within the local or regional economy, but there are trade-offs to consider. For example, the increased use of biomass for electricity production and the corresponding increase in demand for some types of biomass (e.g., pellets) could cause a temporary lack of biomass supply during periods of high demand. Households are particularly vulnerable to this market distortion.

The biofuels production technologies and institutions will also be an important determinant of rural development outcomes. In some instances, private investors will look to establish biofuel plantations to ensure security of supply. If plantations are established on non-productive land without harming the environment, there should be benefits to the economy. It is essential not to overlook the uses of land that are important to the poor. Governments may need to establish clear criteria for determining whether land is marginal or productive, and these criteria must protect vulnerable communities and female farmers who may have less secure land rights (FAO, 2008a). Research in Mozambique shows that, compared with a more capital-intensive plantation approach, an out-grower approach to producing biofuels helps to reduce poverty due to the greater use of unskilled labour and accrual of land rents to smallholders (Arndt et al., 2010).

Increased investment in rural areas will be crucial for making biofuels a positive development force. If governments rely exclusively on short-term farm-level supply side economic response, the negative effects of higher food prices will predominate. If higher prices motivate greater public and private investment in agriculture (e.g., rural roads and education, R&D), there is tremendous potential for sparking medium- and long-term rural development (De La Torre Ugarte and Hellwinckel, 2010). As one example, proposed biofuel investments in Mozambique could increase annual economic growth by 0.6% and reduce the incidence of poverty by about 6% over a 12-year period between 2003 and 2015 (Arndt et al., 2010).

2.5.7.6 Trade-offs between social and environmental aspects

Some important trade-offs between environmental and social criteria exist and need to be considered in future bioenergy developments. In the case of sugarcane, the environmental sustainability criteria promoted by certification frameworks (such as the Roundtable for Sustainable Biofuels) favour mechanical harvesting due to the avoided emissions from sugarcane field burning required in manual systems. Several other organizations are concerned about the large number of workers that will be displaced by these new systems. Also, the mechanized model tends to favour further concentration of land ownership, potentially excluding small- and medium-scale farmers and reducing employment opportunities for rural workers (Huertas et al., 2010).

Strategies for addressing such concerns can include providing support for small- and medium-size stakeholders that lack the capacity to meet the certification system requirements and/or developing alternative income possibilities for the seasonal workers that presently earn a substantial part of their annual income by cutting sugarcane (Huertas et al., 2010). Retraining workers from manual to skilled labour, such as truck driving, is already taking place in Center South Brazil (Oliveira, 2009).

2.5.8 Synthesis

As a component of the much larger agriculture and forestry systems of the world, traditional and modern biomass affects social and environmental issues ranging from health and poverty to biodiversity and water quality. Land and water resources need to be properly managed in concert with each specific region's economic development situation and suitable types of bioenergy. Bioenergy has the opportunity to contribute positively to climate change mitigation, secure energy supply and diversity goals, and economic development in developed and developing countries alike. However, the effects of bioenergy on environmental sustainability may also be negative depending upon local conditions, how criteria are defined, and how actual projects are designed and implemented, among many other factors.

- Climate change and biomass production can be influenced by interactions and feedbacks among land and water use, energy and climate at scales that range from micro through macro (see Figure 2.15). Social and environmental trade-offs may be present but can be minimized to a large extent with appropriate project design and implementation.

- Although crops grown as biofuels feedstocks currently use less than 1% of the world's agricultural land, the expansion of large-scale bioenergy systems raises several important socioeconomic issues including food security, income generation, rural development, land tenure and water scarcity in specific regions.

- Estimates of LUC effects require value judgments about the temporal scale of analysis, the land use under the assumed 'no action' scenario, the expected uses in the longer term, and the allocation of impacts among different uses over time. Regardless, a system that ensures consistent and accurate inventory of and reporting on carbon stocks is considered an important first step towards LUC carbon accounting.

- Emissions of pollutants, like SO_2 and NO_x, are generally lower for bioenergy than for coal, gasoline and diesel, though the NO_x results for biodiesel are more variable. Thus, bioenergy can reduce negative impacts on air quality. Bioenergy impacts on water resources can be positive or negative, depending on the particular feedstock, supply chain element and processing methodologies. Bioenergy systems similar to conventional food and feed crop systems can contribute to loss of habitat and biodiversity, but bioenergy plantations can be designed to provide filters for nutrient loss, to function as ecological corridors, to reduce pressure on natural forests and to restore degraded or abandoned land. Genetically engineered and potentially invasive bioenergy crops have raised concerns. More research and protocols are needed to monitor and evaluate the introduction of new or modified species.

- Advanced ICS for traditional biomass use can provide large and cost-effective mitigation of GHG emissions (GHG mitigation potential of 0.6 to 2.4 Gt CO_2eq/yr) with substantial co-benefits in health and living conditions, particularly for the poorest 2.7 billion people in the world. Efficient technologies for cooking are cost-effective and comparable to major health interventions such as those for tobacco addiction, undernourishment or tuberculosis.

- Biofuel production has contributed to increases in food prices, but additional factors affect food prices, including weather conditions, changes in food demand and increasing energy costs. Even considering the benefit of increased prices to poor farmers, increased food prices have adversely affected poverty, food security and malnourishment of children. On the other hand, biofuels can also

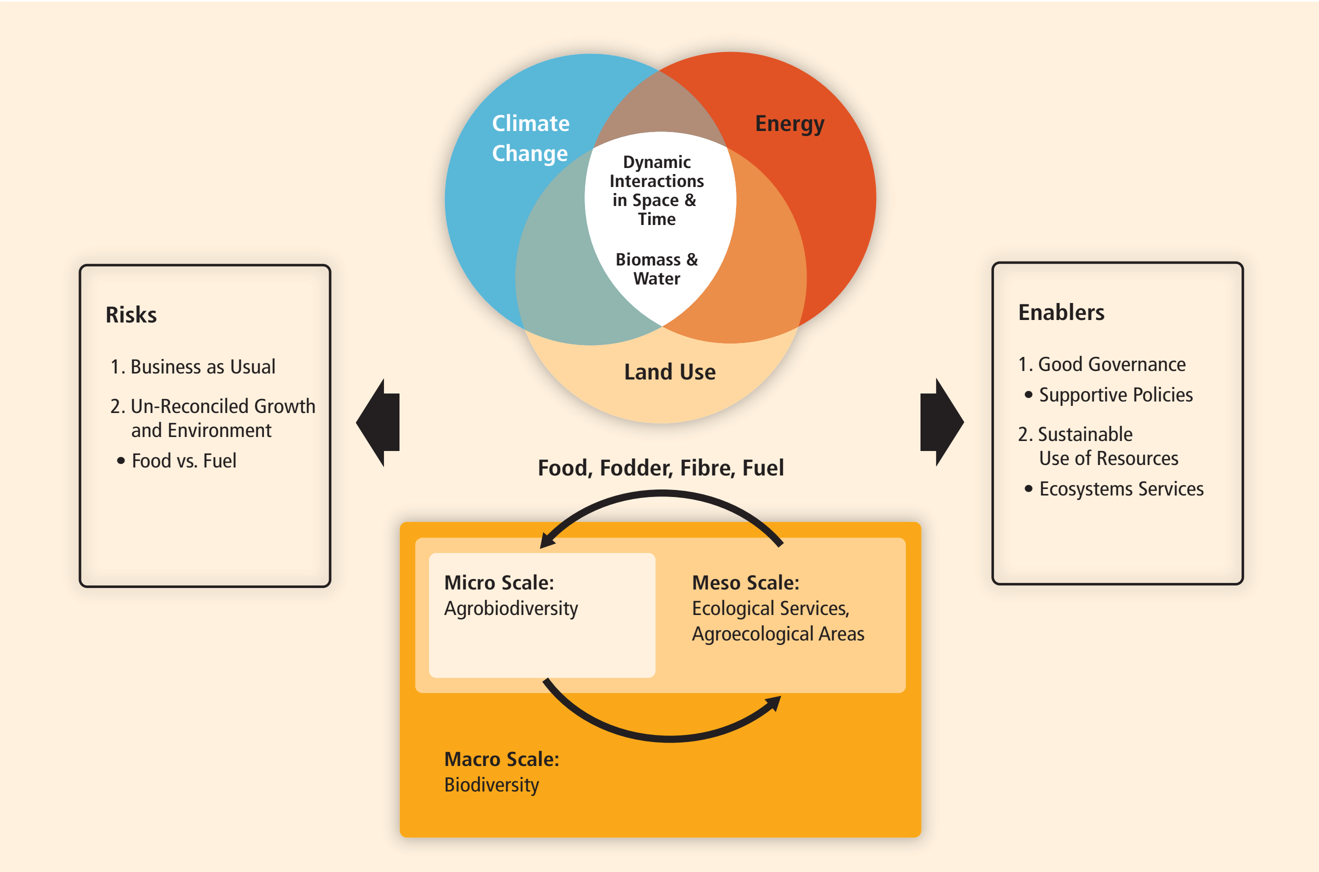


Figure 2.15 | Bioenergy's complex, dynamic interactions among society, energy and the environment include climate change feedbacks, biomass production and land use with direct and indirect impacts at various spatial and temporal scales on all resource uses for food, fodder, fibre and energy (Dale et al., 2011). Biomass resources need to be produced in sustainable ways as their impacts can be felt from micro to macro scales (van Dam et al., 2010). Risks are maintenance of business-as-usual approaches with uncoordinated production of food and fuel. Opportunities are many and include good governance and sustainability frameworks that generate effective policies that also lead to sustainable ecosystem services.

provide opportunities for developing countries to make progress in rural development and agricultural growth, especially when this growth is economically sustainable. Proper design, implementation, monitoring and adherence to sustainability frameworks may help minimize negative socioeconomic impacts and maximize benefits, particularly for local people.

- These social and environmental impacts should be compared with those of the energy systems they replace. Many lifecycle assessments that characterize the amount of RE provided relative to fossil energy used in biofuel production and compare that with the reference system show GHG emission savings for biofuels. These studies can be expanded to use multiple indicators and more comprehensively analyze the whole chain from feedstock to final energy use.

2.6 Prospects for technology improvement and innovation[61]

This section provides a literature overview of the sets of developing technologies, their performance characteristics and projections of cost performance for biomass feedstocks, logistics and supply chains, and conversion routes to a variety of biofuels alone or in combination with heat and power or with other bio-based products. Advanced power routes are also discussed. As illustrated in Figure 2.2 and Table 2.5, many such advanced biomass energy chains are commercial or in development at various stages ranging from small-scale R&D through near commercialization for each component of the chain, including some examples of integrated systems. Linkages are made with the various applications, with the suppliers of feedstocks, which can be residues from urban or rural areas, and with the existing and developing biomass conversion industry to products. The integration of biomass energy and related products into the electricity, natural gas, heating (residential and district, commercial and public services), industrial and fossil liquid fuels systems for transport is discussed more thoroughly in Chapter 8. The structure of this section parallels that of Section 2.3, following the bioenergy supply chain from feedstocks (Section 2.6.1) to logistics (Section 2.6.2) to end products (e.g., various advanced secondary energy carriers in gaseous or liquid states) made by various conversion technologies (Section 2.6.3).

2.6.1 Improvements in feedstocks

2.6.1.1 Yield gains

Increasing land productivity, whether for food or energy purposes, is a crucial prerequisite for realizing large-scale future deployment of biomass for energy because it would make more land available for growing biomass and reduce the associated demand for land. Much of the increase in agricultural productivity over the past 50 years came about through plant breeding and improved agricultural management practices including irrigation, fertilizer and pesticide use. The adoption of these techniques in the developing world is most advanced in Asia, where productivity grew strongly during the past 50 years, and also in Brazil, with sugarcane. Considerable potential exists for extending the same kind of gains to other regions, particularly sub-Saharan Africa, Latin America, Eastern Europe and Central Asia, where adoption of these techniques has been slower (Evenson and Gollin, 2003; FAO, 2008a). A recent long-term forecast by the FAO expects global agricultural production to rise by 1.5% per year for the next three decades, still significantly faster than projected population growth (World Bank, 2009). For the major food staple crops, maximum attainable yields may increase by more than 30% by switching from rain-fed to irrigated and optimal rainwater use production (Rost et al., 2009), while moving from intermediate- to high-input technology may result in 50% increases in tropical regions and 40% increases in subtropical and temperate regions. The yield increase when moving from low- to intermediate-input levels can reach 100% for wheat, 50% for rice and 60% for maize (Table 2.14), due to better pest control and adequate nutrient supply. However, important environmental trade-offs may be involved with agricultural intensification, and avenues for more sustainable management practices may need exploration and adoption (IAASTD, 2009).

Biotechnologies or conventional plant breeding could improve biomass production by focusing on traits relevant to energy production such as biomass per hectare, increased oil or fermentable sugar yields, or other characteristics that facilitate their conversion to energy end-products (e.g., Sannigrahi et al., 2010). Also, considerable genetic improvement is still possible for drought-tolerant plants (Nelson et al., 2007; Castiglioni et al., 2008; FAO, 2008b).

The projected increases in productivity reflect present knowledge and technology (Duvick and Cassman, 1999; Fischer and Schrattenholzer, 2001) and vary across the regions of the world (FAO, 2008a). In developed countries where cropping systems are already highly input-intensive, productivity increases will be more limited. Also, projections do not always account for the strong environmental limitations in many regions, such as water or temperature (Nelson et al., 2007; Castiglioni et al., 2008; FAO, 2008b).

Doubling the current yields of perennial grasses appears achievable through genetic manipulation such as marker-assisted breeding (Turhollow, 1994; Eaton et al., 2008; Tobias et al., 2008; Okada et al., 2010). Shifts to sustainable farming practices and large improvements in crop and residue yield could increase the outputs of residues from arable crops (Paustian et al., 2006).

Future feedstock production cost projections are scant because of their connections with food markets (which are, as all commodities, volatile and uncertain) and because many candidate feedstock types are still in the R&D phase. Cost figures for growing these feedstock species in commercial farms are not well understood yet but will likely reduce over time

61 Section 10.5 offers a complementary perspective on drivers and trends of technological progress across RE technologies.

Table 2.14 | Prospects for yield improvements by 2030 relative to 2007 to 2009 data from Table 2.4.

Feedstock type	Regions	Yield trend (%/yr)	Potential yield increase by 2030 (%)	Improvement routes	Ref.
DEDICATED CROPS					
Wheat	Temperate	0.7	20-50	New energy-oriented varieties	1,10
	Subtropics		30-100	Higher input rates, irrigation	
Maize	N America	0.7	20-35	New varieties, GMOs, higher plantation density, reduced tillage Higher input rates, irrigation	
	Subtropics		20-60		
	Tropics		50		
Soybean	USA	0.7	15-35	Breeding	2,3,10
	Brazil	1.0	20-60		
Oil palm	World	1.0	30	Breeding, mechanization	3
Sugarcane	Brazil	1.5	20-40	Breeding, GMOs, irrigation inputs	2,3,8,10
SR Willow	Temperate	—	50	Breeding, GMOs	3
SR Poplar	Temperate	—	45		
Miscanthus	World	—	100	Breeding for minimal input, improved management	
Switchgrass	Temperate	—	100	Genetic manipulation	
Planted forest	Europe Canada	1.3	20 20	Species choice, breeding, fertilization, shorter rotations, increased rooting depth	4,9 11
PRIMARY RESIDUES					
Cereal straw	World	—	15	Improved collection equipment, breeding for higher residue-to-grain ratios (soybean)	5,6
Soybean straw	N America	—	50		
Forest residues	Europe	1.0	25	Ash recycling, cutting increases, increased roundwood, productivity	4,7

Abbreviations: SR = short rotation; GMO = genetically modified organism.

References: 1. Fischer and Schrattenholzer (2001); 2. Bauen et al. (2009a); 3. WWI (2006); 4. Nabuurs et al. (2002); 5. Paustian et al. (2006); 6. Perlack et al. (2005); 7. EEA (2007); 8. Matsuoka et al. (2009); 9. Loustau et al. (2005); 10. Jaggard et al. (2010). 11. APEC (2003).

as farmers descend the learning curves, as past experience has shown in Brazil (van den Wall Bake et al., 2009).

Under temperate conditions, the expenses for the farm- or forest-gate supply of lignocellulosic biomass from perennial grasses or short-rotation coppice are expected to fall to less than USD_{2005} 2.5/GJ by 2020 (WWI, 2006) from a USD_{2005} 3 to 16/GJ range today (Table 2.6, without land rental cost). However, these are marginal costs, which do not account for the competition for land with other sectors and markets that would increase unit costs as the demand for biomass increases. This is reflected in supply curves (see Section 2.2 and Figure 2.5(b)). Recent studies in Northern Europe that include such land-related costs thus report somewhat higher projections, in a USD_{2005} 2 to 7.5/GJ range for herbaceous grasses and USD_{2005} 1.5 to 6/GJ range for woody biomass (Ericsson et al., 2009; de Wit and Faaij, 2010). For perennial species, the transaction costs required to secure a supply of energy feedstock from farmers may increase the production costs by 15% (Ericsson et al., 2009). Delivered prices for herbaceous crops are shown in Figure 2.5(d) for the USA and about 8 EJ could be delivered at USD_{2005} 5/GJ to the conversion facility.

In recent decades, forest productivity has increased more than 1% per year in temperate and boreal regions due to higher CO_2 concentrations and nitrogen deposition or fertilization rates (Table 2.14). This trend is projected to continue until 2030 when productivity might plateau due to increased stand ages and increased respiration rates in response to warmer temperatures (Nabuurs et al., 2002). However, yield trends vary across climatic zones at a finer scale. Water limitations in Mediterranean/semi-arid environments lead to zero or even negative variations in biomass yield increments by 2030 (Loustau et al., 2005). This may be counteracted by adaptive measures such as choosing species more tolerant to water stress or using appropriate thinning regimes (Loustau et al., 2005). Where water is non-limiting, productivity may be maximized by more intensive silvicultural practices, including shorter rotations, optimum row spacing, fertilization and improved breeding stock (Loustau et al., 2005; Feng et al., 2006). Increased roundwood extraction would also generate extra logging residues and carbon sequestration in forest soils as a co-benefit, outweighing several-fold the GHG emissions generated by management practices (Markewitz, 2006).

2.6.1.2 Aquatic biomass

Aquatic phototrophic organisms dominate the world's oceans, producing 350 to 500 billion tonnes of biomass annually and include 'algae', both microalgae (such as *Chlorella* and *Spirulina*) and macroalgae (i.e., seaweeds) and cyanobacteria (also called 'blue-green algae') (Garrison, 2008). Oleaginous microalgae such as *Schizochytrium* and *Nannochloropsis* can accumulate neutral lipids, analogous to seed oil triacylglycerides, at greater than 50% of their dry cell weight (Chisti, 2007). Weyer et al. (2009) reported yields of 40 x 10^3 to 50 x 10^3 litres/ha/yr (0.04 to 0.05 litres/m^2/yr) in unrefined algal oil from biomass grown in the Equator region and containing 50% oil. Assuming a neutral lipid yield ranging from 30 to 50%, algae productivity can be several-fold higher than palm oil productivity at 4.7 x 10^3 litres/ha/yr (0.0047 litres/m^2/yr). Photosynthetic cyanobacteria used to produce nutraceuticals at commercial scales (J. Lee, 1997; Colla et al., 2007) could also directly produce fuels such as H_2 (Hu et al., 2008; Sections 3.3.5 and 3.7.5).

Macroalgae do not accumulate lipids like microalgae do. Instead, they synthesize polysaccharides from which various fuels could be made (see Figure 2.6). Uncultivated macroalgae can have polysaccharide yields higher than those of terrestrial plants (per unit area) (Zemke-White and Ohno, 1999; Ross et al., 2009) and can live in marine environments. Halophiles, another group of phototrophic organisms, live in environments with high salt concentration.

Microalgae can photoproduce chemicals, fuels or materials in non-agricultural land such as brackish waters and highly saline soils. Hundreds of microalgae species, out of hundreds of thousands of species, have been tested or used for industrial purposes. Understanding the genetic potential, lipid productivity, growth rates and control, and use of genetic engineering allows broader use of land and decreases the LUC impacts of biofuels production (Hu et al., 2008). Microalgae can be cultivated in open ponds and closed photobioreactors (PBRs) (Sheehan et al., 1998a; van Iersel et al., 2009) but scale-up can involve logistical challenges, can require high cost to produce the biomass, and requires water consumption minimization (Borowitzka et al., 1999; Molina Grima et al., 2003). Production costs using low- to high-productivity scenarios currently range approximately from USD_{2005} 30 to 80/GJ for open ponds and from USD_{2005} 50 to 140/GJ for PBR (EPA, 2010).

Macroalgae are typically grown in offshore cultivation systems (Ross et al., 2009; van Iersel et al., 2009) that require shallow waters for light penetration (Towle and Pearse, 1973). The impact of biofuel production on competing uses (fisheries, leisure) and on marine ecosystems needs assessment. Using aquatic biomass harvested from algal blooms may provide multiple benefits (Wilkie and Evans, 2010).

The bioenergy potential from aquatic plants is usually excluded from resource potential determinations because of insufficient data available for such an assessment. However, the potential may be substantial compared to conventional energy crops, considering the high yield potential of cultivated microalgae production (up to 150 dry t/ha/yr, 0.015 t/m^2/yr) (Kheshgi et al., 2000; Smeets et al., 2007). With the large number of diverse algal species in the world, upper range productivity potentials of up to several hundred EJ for microalgae and up to several thousand EJ for macroalgae (Sheehan et al., 1998a; van Iersel et al., 2009) have been reported. Figure 2.10 shows very approximate ranges for GHG reductions relative to the fossil fuel replaced. Comparable or increased emission reductions relative to crop biodiesel could be achieved with successful RD&D and commercialization (EPA, 2010).

Some key conclusions from current efforts (US DOE, 2009; IEA Bioenergy, 2010; Darzins et al., 2010) are the following: (1) Microalgae can offer productivity levels above those possible with terrestrial plants. (2) There are currently several significant barriers to widespread deployment and many information gaps and opportunities for improvement and breakthroughs. (3) Various systems suited to different types of algal organisms, climatic conditions, and products are still being considered. (4) Basic information related to genomics, industrial design and performance is still needed. (5) Cost estimates for algal biofuels production vary widely, but the best estimates are promising at this early stage of technology development. (6) The cost of processing algae solely for fuel production is still too high. Producing a range of products for the food, fodder and fuel markets offers opportunities for economical operation of algal biorefineries. (7) Lifecycle assessments are needed to guide future developments of sustainable fuel production systems.

2.6.2 Improvements in biomass logistics and supply chains

Optimization of supply chains includes achieving economies of scale in transport, in pretreatment and in conversion technologies. Relevant factors include spatial distribution and seasonal supply patterns of the biomass resources, transportation, storage, handling and pretreatment costs, and economies of scale benefiting from large centralized plants (Dornburg and Faaij, 2001; Nagatomi et al., 2008). Smart utilization of a combination of biomass resources over time can help conversion plants gain economies of scale through year-round supplies of biomass and thus efficiently utilize the investment cost (Junginger et al., 2001; McKeough et al., 2005; Nishi et al., 2005; Ileleji et al., 2010; Kang et al., 2010) and technology transfer (Asikainen et al., 2010).

Over time the lower-cost biomass residue resources are increasingly depleted and more expensive (e.g., cultivated) biomass needs to cover the growing demand for bioenergy. Part of this growing demand may be met by learning and optimization, but, for example, future heat generation from pellets in the UK may be more costly (2020) than it is today due to a shift from local to imported feedstocks (E4tech, 2010). Similar effects are found in scenarios for large-scale deployment of biofuels in Europe (Londo et al., 2010).

Learning and optimization in the past one to two decades in Europe (Scandinavia and the Baltic in particular), North America, Brazil and also in various developing countries have shown steady progress in market development and cost reduction of biomass supplies (Section 2.7.2; Junginger et al., 2006). Well-working international biomass markets and substantial investments in logistics capacity are key prerequisites to achieve this (see also Section 2.4).

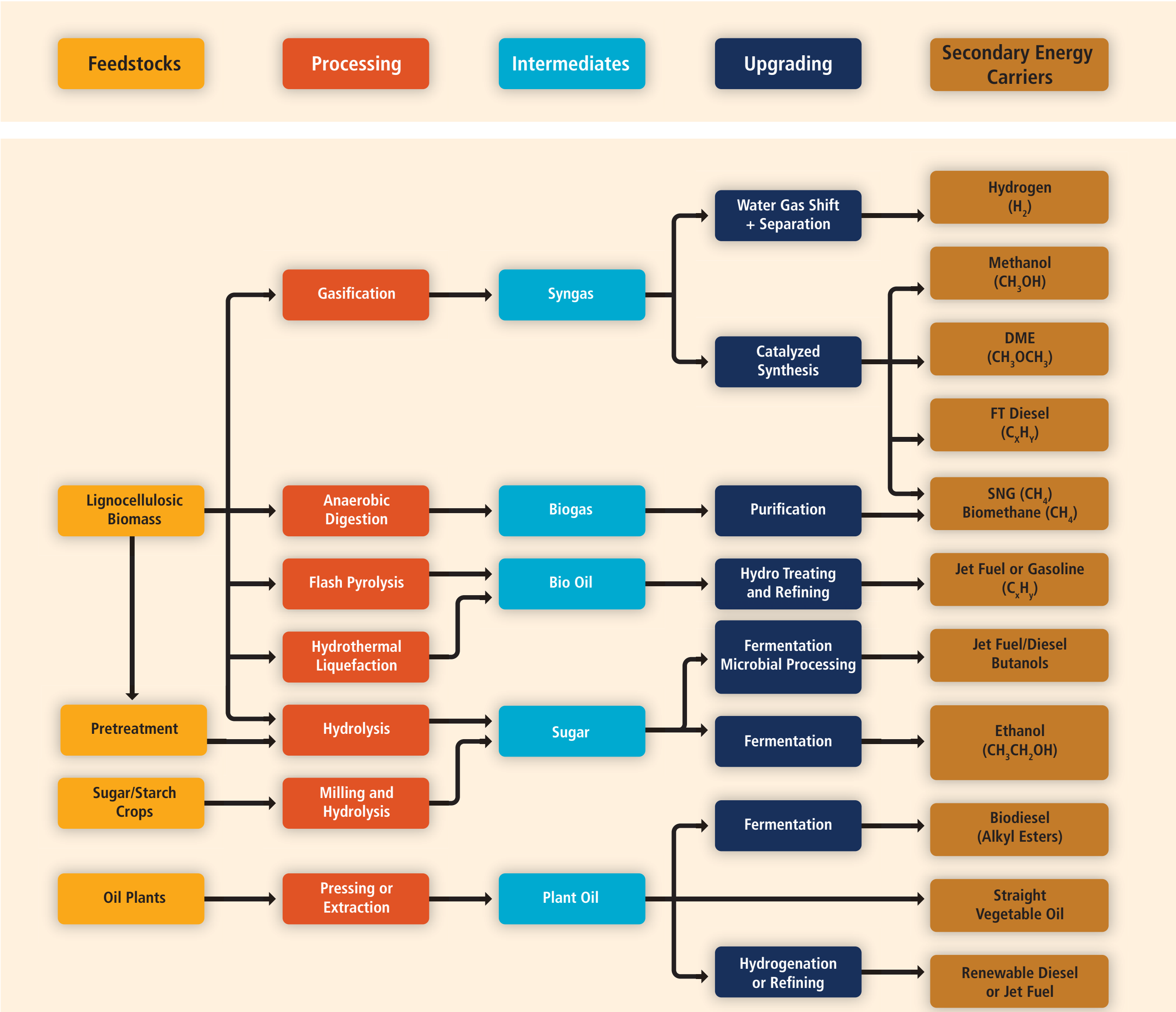


Figure 2.16 | Overview of lignocellulosic biomass, sugar/starch crops and oil plants (feedstocks) and the processing routes to key intermediates, which can be upgraded through various routes to secondary energy carriers, such as liquid and gaseous biofuels. Fuel product examples are (1) oxygenated biofuels to blend with current gasoline and diesel fuels or to use in pure form, such as ethanol, butanols, methanol, liquid ethers, biodiesel, and gaseous DME (dimethyl ether); (2) hydrocarbon biofuels such as Fischer Tropsch (FT) liquids, renewable diesel and some microbial fuels (which are compatible with the current infrastructure of liquid fuels because their chemical composition is similar to that of gasoline, diesel, and jet fuels (see Table 2.15.C)), or the simplest hydrocarbon methane for natural gas replacement (SNG) from gasification or biomethane from anaerobic digestion; and (3) H_2 for future transportation (adapted from Hamelinck and Faaij, 2006 and reproduced with permission from Elsevier B.V.).

Notes: Microbial fuels include hydrocarbons derived from isoprene, the component of natural rubber; a variety of non-fermentative alcohols with three to six carbon atoms including butanols (four carbons); and fatty acids which can be processed as plant oils to hydrocarbons (Rude and Schirmer, 2009).[1] For sugar and starch crops the sugar box indicates six-carbon sugars, while for lignocellulosic biomass this box is more complex and has mixtures of six- and five-carbon sugars, with proportions dependent on the feedstock type. Hardwoods and agricultural residues contain xylan and other polymers of five-carbon sugars in addition to cellulose that yield glucose, a six-carbon sugar.

1. Not shown are the aquatic plants (see Section 2.6.1.2) that can utilize the same types of processing shown for their vegetable oil and carbohydrate fractions.

Pretreatment technologies

Torrefied wood is manufactured by heating wood in a process similar to charcoal production. At temperatures up to 160°C, wood loses water, but it keeps its physical and mechanical properties and typically maintains 70% of its initial weight and 90% of the original energy content (D. Bradley et al., 2009). Torrefied wood only absorbs 1 to 6% moisture (Uslu et al., 2008). Torrefaction can produce uniform quality feedstock, which eliminates inefficient and expensive methods designed to handle feedstock variations and thus makes conversion more efficient (Badger, 2000) and more predictable.

Pyrolysis processes convert solid biomass to liquid bio-oil, a complex mixture of oxidized hydrocarbons. Although this liquid product is toxic and needs stabilization for longer-term storage, bio-oil is relatively easy to transport. Pyrolysis oil production is more expensive and less efficient per unit of energy delivered compared to torrefaction of wood pellets. Section 2.3.4 discusses the cost data for multiple countries based on Bain (2007); McKeough et al. (2005) arrive at similar figures of USD_{2005} 6.2 to 7.0/GJ. The process allows for separation of a solid fraction (biochar) that contains the bulk of the nutrients of the biomass. With proper handling, such biochars could be used to improve soil quality and productivity, recycle nutrients and possibly store carbon in the soil for long periods of time (Laird, 2008; Laird et al., 2009; Woolf et al., 2010).

2.6.3 Improvements in conversion technologies for secondary energy carriers from modern biomass

Different conversion technologies (or combinations) including mechanical, thermochemical, biochemical and chemical steps, as shown in Figure 2.2, are needed to transform the variety of potential feedstocks into a broader range of secondary energy carriers. In addition to electricity and heat as products, a variety of liquid and gaseous fuels or products can be made from biomass as illustrated in Figure 2.16, where key chemical intermediates that could make identical, similar or new products as energy carriers, chemicals and materials are highlighted (see Section 2.6.3.4 for further detail):

- **Sugars**, mixtures of five- and six-carbon sugars from lignocellulosic materials, are converted primarily through biochemical or chemical processes into liquid or gaseous fuels and a variety of chemical products.

- **Syngas** from thermochemical gasification processes, which can be converted in integrated gasification combined cycle (IGCC) systems to electricity, through a variety of thermal/catalytic processes to gaseous or liquid fuels, or through biological processes at low temperature to H_2 or polymers.

- **Oils** from pyrolysis or hydrothermal treatment, which can be upgraded into a variety of fuels and chemicals.

- **Lipids** from plant oils, seeds or microalgae, which can be converted into a wide variety of fuels, such as diesel or jet fuels, and chemicals.

- **Biogas** is a mixture of methane and CO_2 released from anaerobic degradation of organic materials with a lower heat content than its upgraded form, mostly methane, called biomethane. If upgraded, it can be added to natural gas grids or used for transport.

Table 2.15 contains process efficiency and projected improvements along with cost information expressed in USD_{2005}/GJ for several bioenergy systems and chains, in various stages of development, from various studies from multiple sources. Part A details processes for alcohols; Part B summarizes microalgal fuels; Part C details hydrocarbon fuels; and Part D includes gaseous fuels and electricity from IGCC. Financial assumptions are provided at the end of the table; some groups of references use the same assumptions but not all. First-of-a-kind plants are more expensive as there are technical uncertainties in the chemical, biochemical, thermochemical or mechanical component steps in a route, as shown by Kazi et al. (2010) and Swanson et al. (2010) compared to Bauen et al. (2009a) or Foust et al. (2009). Such combination of steps is often significantly more complex than a similar petroleum industry process because of the characteristics of solid biomass. Scaling up is conducted after initial bench-scale experimentation and encouraging initial techno-economic evaluation. As experience in operating the process and correcting design or operating parameters is gained, cost evaluations are conducted and the plant is operated until costs decrease at a slower pace. At this point, the technical and economic risks of the plant have decreased and the production costs have reached so-called nth plant status. The uncertainties in these studies are variable and higher for the least-developed concepts (Bauen et al., 2009a).

An overview of advanced pilot, demonstration and commercial-scale bioenergy projects in 33 countries is provided by Bacovsky et al. (2010a,b), including the site at Kalundborg, Denmark, where a wheat straw ethanol is made in the pilot plant and sold to a gasoline distributor in 2010.[62] The number of actual projects moving to pilot and demonstration scale is probably larger. The reference contains descriptions of most of the development projects listed in Table 2.15. See also the IEA (Renewable Energy Division, 2010) report on global sustainable second-generation technologies and future perspectives in the context of the transport sector and the recently published technology roadmap for biofuels (IEA, 2011).

This section focuses on bioenergy products to avoid repetition of technology descriptions provided in Section 2.3—for instance, a thermochemical technology such as gasification can produce multiple fuels and electricity. Similarly, a variety of end products can be made from sugars.

An initial meta-analysis of advanced conversion routes (Hamelinck and Faaij, 2006) for methanol, H_2, Fischer-Tropsch liquids and biochemical ethanol produced from lignocellulosic biomass under comparable financial assumptions suggests that these systems compare favourably with starch-based biofuels and offer more competitive fuel prices and opportunities in the longer term because of their inherently lower feedstock costs and because of the variety of sources of lignocellulosic biomass, including agricultural residues from cereal crop production, and forest residues. The feedstock cost range used in this meta-analysis is in line with costs highlighted in Section 2.6.1.1 and the low range of the supply curves shown in Figure 2.5. In the EU study, Northern Europe projected production costs are in the USD_{2005} 2 to 7.5/GJ range for herbaceous grasses and USD_{2005} 1.5 to 6/GJ for woody biomass (land-related costs included). For perennial species, transaction costs may need to increase by 15% to secure a supply of energy feedstock from farmers. This additional cost (e.g., transport to the conversion plant and payment to secure the feedstock) is already built into the prices of the US supply

62 An interactive website with this information is maintained by the IEA Bioenergy Task 39: biofuels.abc-energy.at/demoplants.

Table 2.15 | Summary of developing technologies costs projected for 2030 biofuel production and their 2010 industrial development level. Using today's performance for a pioneer plant built in the near term increases costs, and the majority of the references assumes that technology learning will occur upon development, referred to as nth plant costs. Costs expressed in USD_{2005}.

A: Fuels – Alcohols by Biochemical and Gasification Processes

Process	Feedstock	Efficiency and process economics. Eff. = Energy product/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development (see Bacovsky et al., 2010a,b)
Consolidated bioprocessing (CBP)	Lignocellulosic	Eff. ~49% for wood and 42% for straw (ethanol) + 5% power.[19]	Scenarios analyzed[30]	Lignin engineering cellulose access.[7] Develop CBP organisms.[44]	15.5[19] future	Demonstration and pilots. Reduce enzyme and pretreatment costs. Several pilots in many countries. First commercial plants. Lignin residues co-firing.[32]
Separate hydrolysis/ co-fermentation		Eff. ~39% (ethanol) + 10% power.[1]		Efficient 5-carbon sugar conversion.[2,3] R&D investment.[5] Advanced enzyme.[6]	25[1]–27[19] 28–35[48]	
Simultaneous saccharification/ co- fermentation	Barley straw	Steam explosion, enzyme hydrolysis, ethanol fermentation.[9] High solids 15%.	N/A	System integration, high solids, decrease toxicity for fermentation.	30[9] (Finland) from pilot data	
Simultaneous saccharification and fermentation	Corn stover	Dilute acid hydrolysis, 260 million L/yr; FC: 6.6, CC*: 10.1, CR: 1.1 for ethanol.[24]	83–88 Depending on co-product credit method[25]	Pretreatment, process integration, enzyme costs.[24]	15.5 (US) nth plant, future[24]	
	Lignocellulosic Various Eff. 35% ethanol + 4% power.[1]	Generic; 90 million L/yr; FC:14; CC*:14. At 360 million L/yr; FC:14; CC*:10; CR:0.5.[45]		Meta-analysis conditions.[45]	28 (2015)[45] 23.5 (2022)[45]	
		Eff. kg/L ethanol (poplar, *Miscanthus*, switchgrass, corn stover, wheat: 3.7, 3.2, 2.6, 2.6, 2.4). Plant sizes 1,500 to 1,000 t/day. FC 50% of total.[10]		Process integration—capital costs per installed litre of product USD 0.9 to 1.3 for plants of 150 to 380 million litres/yr (2020 estimates). Project a 25% operating cost reduction by 2025 and a 40% operating cost reduction by 2035.[10]	18–22[10] (2020) breakeven USD 100/barrel; + CCS USD 95/ barrel; USD 50/t CO_2	
	Bagasse	Standalone plant[35] 370 L/t dry (ethanol) + 0.56 kWh/L ethanol (elec.).	86 Advanced CHP: 120% (replace NG peak power).[36]	Mechanical harvest improvements sugarcane residues (occurring).[35,36]	6[35]–15[35] w/o and w FC	
Gasification/catalytic synthesis ethanol	Lignocellulosic	170 million L per year plant (varies in size).[18] By-product propanol/butanols.	90[38]	Improvements in catalyst development and syngas cleaning.	12[49]–15[18] 14.5[24]	RD&D, pilot.
Fermentation; product compatible with gasoline infrastructure to butanols, in particular biobutanol	Sugar/starch	Development of an integrated biobutanol production and removal systems using the solvent-producing bacteria *Clostridia* improved by genetic engineering.[29] Initial acetone, butanol, and ethanol (ABE) fermentation is costly.	5–31 Depending on co-product credit method.[29]	For high selectivity to biobutanol: (1) mutated strain of *Clostridium beijernekei* BA101, or protein engineering in *E. coli* to increase selectivity/lower cost to biobutanol.[15,16] (2) dual fermentation to butyric acid and reduction to butanols.	29.6 for ABE;[18] 25.2 for mutated *Clostridia*[17] or 21.6 for dual process[17]	Large and small venture companies in different routes, including yeast host. Hydrocarbon precursor.
Gasification to butanols	Lignocellulosic	Catalytic process for synthesis of predominantly butanols.	N/A	Estimated production costs include return on capital.[17]	13[17]	N/A
Gasification/synthesis to methanol for fuel and/or power	Lignocellulosic	Eff. 55% fuel only[19] Eff. 48% fuel and 12% power.[19]	90[27]	Methanol (and dimethyl ether) production possible in various configurations that co-produce power.	12–18 (fuel)[19] 7.1–9.5 (fuel and power)[19]	Pilots, demos, and first commercial.

Continued next Page →

curves based on county-level data; the projected price of delivery to the conversion facility for forest and related residues is USD_{2005} 1 to 3/GJ up to about 1.5 EJ, and for woody and herbaceous plants and sorghum delivered to the conversion facility the projected price is USD_{2005} 2 to 4/GJ up to about 5 EJ (or more at higher price).

2.6.3.1 Liquid fuels

Alcohols. Estimated production costs for various fuel processes are assembled in Part A of Table 2.15, and they range from USD_{2005} 13 to 30/GJ.

B: Fuels – Algae

Process	Feedstock	Efficiency and process economics Eff. = Energy product/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development
Lipid production, extraction, and conversion of microalgae neutral lipids to biodiesel or renewable diesel. Remainder of algal mass digested or used in other process	Microalgae lipids; see Section 2.6.1.2	Assuming biomass production capacity of 10,000 t/yr, cost of production per kg is USD 0.47 and 0.60 for photobioreactors (PBR) and raceways, respectively.[23]	28–76 Scenarios for open pond and bioreactor[34]	Assuming[34] biomass contains 30% oil by weight, cost of biomass for providing a litre of oil would be USD 1 to 3 and USD 1.5 to 5 for algae of low productivity = 2.5 g/m²/day or high productivity = 10 g/m²/day in open ponds or photobiological reactors.	Preliminary Results 95 or more[23] 30–80[34] for open ponds 50–140[34] for PBR going from low to high productivity	Active R&D by companies small and large including pilots pursuing jet and diesel fuel substitutes.

C: Fuels – Hydrocarbons by Gasification, Pyrolysis, Hydrogenation and Isomerization of Vegetable Oils and Wastes

Process	Feedstock	Efficiency and process economics Eff. = Energy product/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development
Gasification to syndiesel followed by FT (Fischer-Tropsch) process. Known as biomass to liquids. With and without CCS. Process makes hydrocarbons fuels (number of carbon atoms) for gasoline (5–10); kerosene (jet fuel) (10–15); diesel (15–20); fuel oil (20–30)	Lignocellulosic	Eff. = 0.42 fuel only; 0.45 fuel + power.[19]	91[27] (EU)	CCS for CO_2 from processing.	14–20 (fuel only) 8–11 (fuel/power)[19] 15.2-18.6[43]	One first commercial plant (wood) under way. Many worldwide demonstration and pilot processes under way.
		80 million L/yr; FC:12, CC*17 (2015); 280 million L/yr; FC:12, CC*8 (2022).[45]		Meta-analysis conditions.[45]	20–29.5[45]	
		Eff. = 0.52 w/o CCS and 0.5 w/ CCS + 35 and 24 MW_e. 4000 t/day switchgrass. Plant cost ~ USD 650 Mi.[10]	90[26] (US)	Gas clean-up costs and scale/volume. Breakeven with barrel of crude oil of USD 122 (USD 113 with CCS and USD 50/t CO_2).[10]	25[10] (w/o CCS US) 30[10] (w/ CCS US) see[38] for cost breakdown (2020)	
		Eff. = 0.52 + 22 MW_e. Capital USD 500 million; wide range of densified feeds imported into EU for processing.[39]	Detailed Well-to-Wheel EU[39] US[14] scenarios	Breakeven with barrel of crude oil of USD 75. Mixture of 50% biomass and coal is climate neutral.	16–22.5[39]	
		Coal and biomass co-gasification.	See Fig. 2.10	Switchgrass and mixed prairie grasses.	29[38]	
Hydrogenation to renewable diesel	Plant oils, animal fat, waste	Technology well known. Cost of feedstock is the barrier.	63–130[26] Depending on the co-product treatment method	Feedstock costs drive this process. Process is standard in petrochemical operations.	17–18[34]	One large and few small commercial (see, e.g., footnote 68 in the main text); many demos.
Biomass pyrolysis[4] and catalytic upgrading to diesel/jet fuel; vegetable oils processed directly into a refinery [33]	Biomass/wastes, plant oils, animal fat, waste oils	Developing pyrolysis[8,13] process (also from hydrothermal processing)[46] to a blendstock for a refinery,[33] for direct coupled firing in a boiler (e.g., with coal)[32] or a final product.		Catalyst development, process yield improvements with biomass.	14–24[47] for pyrolysis oils to refinery blendstocks	Demos and fuel product tests in USA, Brazil, EU. Test flights using biojet fuels from plant oils conducted.[33]

Continued next Page →

While some methanol, butanols and other alcohol production processes from biomass exist in various stages of technical development, the most predominant alcohol production pathways have ethanol as their finished product. Lignocellulosic ethanol technologies have many possible process chains (e.g., Sánchez and Cardona, 2008; Sims et al., 2010). Those with the highest sugar yields and with low environmental impact were considered more promising (Wooley et al., 1999) and involve chemical/biochemical, mechanical/chemical/biochemical, and biological/chemical/biochemical processing steps. Most of these chains involve a pretreatment step to overcome the recalcitrance of the plant cell wall, with separate and partial hydrolysis of the cellulose and hemicelluloses fibres to release the complex streams of five- and six-carbon sugars for fermentation. Simultaneous saccharification and fermentation (SSF), simultaneous saccharification and co-fermentation (SSCF) and consolidated bioprocessing

D: Gaseous Fuels, Power and Heat from Gasification

Process	Feedstock	Efficiency and process economics Eff. = product energy/biomass energy Component costs in USD_{2005}/GJ	% GHG reduction from fossil reference	Potential technical advances and challenges	Production cost by 2030 (USD_{2005}/GJ)	Industrial development
Gasification/syngas processing of H_2 to fuel and power	Lignocellulosic	Eff. 60% (fuel only). Needs 0.19 GJ of elect. per GJ H_2 for liquid estimated at USD 11–14/GJ (long term), wood USD 2.4/GJ, USD 568/kW_{th} capital.[19]	88[30]	Co-production H_2 and power (55% fuel efficiency, 5% power) in the longer term.[19] USD 426/kW_{th} capital.[19]	4–5[19] (longer) 6[20]–12[12] 5.5–7.7[41]	R&D stage.
Gasification/methanation to methane for fuel, heat and/or power	Lignocellulosic	Eff. ~60% (or higher for dry feed).[42] Combined fuel and power production possible.	98[27]	RD&D on gas clean up and methanation catalysts. For wet feedstocks wet gasification developing.[46]	10.6–11.5[42] wood USD 2.8/GJ	RD&D stage.
Anaerobic digestion, upgrading of gas, liquefaction	Organic wastes, sludges	Eff. ~20 to 30%; includes mixtures of animal and agriculture residues.		Improve technology robustness with new metagenomic tools, reduce costs.	15–16[21]	
Integrated gasification combined cycle for CHP	Lignocellulosic	District heating; power-to-heat ratio 0.8 to 1.2; power production efficiency 40 to 45%; total efficiency 85 to 90%. Investment USD 1,200/kW_{th}. Wood residues in Finland.[22]	96[31]	Gas cleaning, increased efficiency cycles, cost reductions.	8–11[11]	Demos at 5 to 10 MW projected cost at USD 29–38/GJ or US cents 10–13.5/kWh.[45]
				IGCC at 30 to 300 MW[45] with a capital cost of USD 1,150 to 2,300/kW_e, at 10% discount rate, 20 year plant life, and USD 3/GJ. Meta-analysis conditions.	13–19[45] or US cents 4.5–6.9/kWh	

Notes: Abbreviations: *Conversion costs (CC) include investment costs and operating expenses; CR = Co-product Revenue; FC = feedstock cost; CC = conversion cost. All CC, CR, FC costs are given in USD_{2005}/GJ.

System Boundaries: Many references use a 10% discount rate, 20-yr plant life referred to as meta-analysis conditions. 17. Production costs include return on capital; 24.10% IRR (Internal Rate of Return), 39% tax rate, 20-yr plant life, Double-declining-balance depreciation method, 100% equity, nth plant, for the biochemical pathway costs are FC: 6, CC*: 10.6, CR: 1.1 and for thermochemical pathway costs are FC: 6.7, CC*: 10, CR: 2.5; 3012% IRR, 39% tax rate, 25-yr plant life, Modified Accelerated Cost Recovery System depreciation method (MACRS dep.), 65/35 equity/debt, 7% debt interest, nth plant, FC: 8.2, CC*: 16.9, CR: 2.6; 37. Pioneer (first-of-a-kind) plant example: 10% IRR, 39% tax rate, 20-yr plant life, MACRS dep., 100% equity, FC: 12.2–20.7, CC*: 27.3–38, CR: 0–6; 38. 7% discount rate, 39% tax rate, 20-yr plant life, MACRS dep., 45/55 equity/debt, 4.4% debt interest, nth plant, FC w/ CCS: 16, FC w/o CCS: 8.8, CC* w/ CCS: 14.7, CC* w/o CSS: 15.7, CR w/ CCS: 2, CR w/o CCS: 2.1; 39.10% discount rate, 10-yr plant life; 40. Pioneer plant example: 10% IRR, 39% tax rate, 20-yr plant life, MACRS dep, 100% equity, FC: 9.5, CC*: 24.5, CR: 1.1; 41.10% IRR, 15-yr plant life.

References: 1. Hamelinck et al. (2005a); 2. Jeffries (2006); 3. Jeffries et al. (2007); 4. Balat et al. (2009) and see IEA Bioenergy Pyrolosis Task (www.pyne.co.uk); 5. Sims et al. (2008); 6. Himmel et al. (2010); 7. Sannigrahi et al. (2010); 8. Bain (2007); 9. von Weyman (2007); 10. NRC (2009a); 11. IEA Bioenergy (2007); 12. Kinchin and Bain (2009); 13. McKeough et al 2005; 14. Wu et al. (2005); 15. Ezeji et al. (2007a); 16. Ezeji et al. (2007b); 17. Cascone (2008); 18. Tao and Aden (2009); 19. Hamelinck and Faaij (2006); 20. Hoogwijk (2004); 21. Sustainable Transport Solutions (2006); 22. Helynen et al. (2002); 23. Chisti (2007); 24. Foust et al. (2009); 25. Wang et al. (2010); 26. Kalnes et al. (2009); 27. Edwards et al. (2008); 28. Huo et al. (2009); 29. Wu et al. (2008); 30. Laser et al. (2009); 31. Daugherty (2001); 32. Cremers (2009) (see IEA co-firing database at www.ieabcc.nl/database/cofiring.php); 33. IATA (2009); 34. EPA (2010); 35. Seabra et al. (2010); 36. Macedo et al. (2008); 37. Kazi et al. (2010); 38. Larson et al. (2009); 39. van Vliet et al. (2009); 40. Swanson et al. (2010); 41. Hamelinck and Faaij (2002); 42. Mozaffarian et al. (2004); 43. Hamelinck et al. (2004); 44. van Zyl et al. (2007); 45. Bauen et al. (2009a); 46. Elliott (2008); 47. Holmgren et al. (2008); 48. Dutta et al. (2010); 49. Phillips et al. (2007).

(CBP), which combines all of the hydrolysis, fermentation and enzyme production steps into one, were defined as short-, medium- and longer-term approaches, respectively. For CBP, efficiencies and yields are expected to increase and costs to decrease by 35 and 66% relative to SSF and SSCF, respectively (Hamelinck et al., 2005a, and see Table 2.15).

Pretreatment is one of the key technical barriers causing high costs, and a multitude of possible options exist. So far, no 'best' technology has been identified (da Costa Sousa et al., 2009; Sims et al., 2010). Pretreatment overcomes the recalcitrance of the cell wall of woody, herbaceous or agricultural residues and makes carbohydrate polymers accessible to hydrolysis (e.g., by enzymes) and in some cases liberates a portion of the sugars for fermentation to ethanol (or butanols) and the lignin for process heat or electricity. Alternatively, multiple steps (including pretreatment) can be combined with other downstream conversion steps and material can be bioprocessed with multiple organisms simultaneously. To evaluate pretreatment options,[63] the use of common

63 The areas of biomass pretreatment and low-cost ethanol emerged as essential in 2009 with fourteen core papers establishing a biology/biochemistry/biomass chemical analysis concentration area (sciencewatch.com/dr/tt/2009/09-octtt-BIO/). Included were coordinated pretreatment research in multiple US and Canadian institutions, investigating common samples and analytical methodology and conducting periodic joint evaluation of technical and economic performance of these processes.

feedstocks and common analytical methodology (Wyman et al., 2005) is needed to differentiate between the performance of the many chains and combinations. For corn stover, among the evaluated options of ammonia fibre expansion (AFEX), dilute acid and hot water pretreatments, dilute acid pretreatment had the lowest cost and the hot water process cost was the highest by 25%. This ranking, however, does not hold for other feedstocks (Elander et al., 2009). On-site enzyme preparation increased the cost of the dilute acid pretreatment by 4.5% (Kazi et al., 2010). Apart from pretreatment, enzymes are another key variable cost and are the focus of major global efforts in RD&D and cost reduction (e.g., Himmel et al., 2010; Sims et al., 2010). Finally, all of the key individual conversion steps (e.g., pretreatment, enzymatic hydrolysis and fermentation) are highly interdependent. Therefore, process integration is another very important focus area, as many steps are either not yet optimized or have not been optimized in a fully integrated process.

The US National Academies analyzed liquid transport fuels from biomass (NRC, 2009a), and their cost analysis found the breakeven point for cellulosic ethanol with crude oil to be USD_{2005} 100/barrel (USD_{2005} 0.64/litre) in 2020, which translates to USD_{2005} 18 to 22/GJ. This projection is similar[64] to the USD_{2005} 23.5/GJ projected by Bauen et al. (2009a) for 2022. The National Research Council (NRC, 2009a) projects that by 2035, process improvements could reduce the plant-related costs by up to 40%, or to within USD_{2005} 12 to 15/GJ, in line with estimates for nth plant costs of USD_{2005} 15.5/GJ (Foust et al., 2009). Further cost reductions in some of the processing pathways may come from converting bagasse to ethanol, as the feedstock is already at the conversion facility, and the bagasse has the potential to produce an additional 30 to 40% yield of ethanol per unit land area in Brazil (Seabra et al., 2010). A similar strategy is currently being employed in the USA, where the coupling of crop residue collection and collocation of the second-generation (residue) and first-generation (corn) ethanol facilities are being pursued by two of the first commercial cellulosic ethanol plant developments by the U.S. Department of Energy.[65]

Several strains of microorganisms have been selected or genetically modified to increase the enzyme production efficiency (FAO, 2008b) for SSF (Himmel et al., 2010), for SSCF (e.g., Dutta et al., 2010) and for CPB (van Zyl et al., 2007; Himmel et al., 2010). Many of the current commercially available enzymes are produced in closed fermenters from genetically modified (GM) microorganisms. The final enzyme product does not contain GM microorganisms (Royal Society, 2008), which facilitates acceptance of the routes (FAO, 2008b).

Microbial fuels. Industrial microorganisms[66] with imported genes to accelerate bioprocessing functions (Rude and Schirmer, 2009) can make hydrocarbon fuels, higher alcohols, lipids and chemicals from sugars. Researchers in synthetic biology have imported pathways, and more recently used artificial biology to design alternative biological paths into microorganisms, which may lead to increased efficiency of fuels and chemicals production (Keasling and Chou, 2008; S. Lee et al., 2008). Another route is to alter microorganisms' existing functions with metabolic engineering tools. Detailed production costs are not available in the literature but Regalbuto (2009) and E4tech (2009) summarize some data.[67] Additionally, some microalgae can metabolize sugars in the absence of light (heterotrophically) to make lipids (similar to plant oils) that are easily converted downstream to biodiesel and/or renewable diesel or jet fuel. With additional genetic engineering, the microorganisms can excrete lipids, leading to a decrease in production costs. Microbial biofuels and chemicals are under active development (Alper and Stephanopoulos, 2009; Rude and Schirmer, 2009).

Gasification-derived products (see Table 2.15.A and B)

Gasification of biomass to syngas (CO and H_2) followed by catalytic upgrading to either ethanol or butanols has estimated production costs (USD_{2005} 12 to 20/GJ) comparable to the biochemical chains discussed above. The lowest-cost liquid fuel is methanol (produced in combination with power) at USD_{2005} 7 to 10/GJ (USD_{2005} 12 to 18/GJ for fuel only). Further reduction in production costs of fuels derived from gasification will depend on significant development of IGCC (currently at the 5 to 10 MW_e demonstration phase) to obtain practical experience and reduce technical risks. Costs are projected to be USD_{2005} 13 to 19/GJ (US $cents_{2005}$ 4.6 to 6.9/kWh) for 30 to 300 MW_e plants (see Table 2.15; Bauen et al., 2009a). Although process reliability is still an issue for some designs, niche markets have begun to develop (Kirkels and Verbong, 2011).

Even though the cost bases are not entirely comparable, the recent estimates for Fischer-Tropsch (FT) syndiesel from Bauen et al. (2009a), van Vliet et al. (2009), the NRC (2009a) and Larson et al. (2009) are (in USD_{2005}/GJ), respectively: 20 to 29.5, 16 to 22, 25 to 30, and 28 (coal and biomass). The breakeven point would occur around USD_{2005} 80 to 120/barrel (USD_{2005} 0.51 to 0.74/litre). High efficiency gains are expected, especially in the case of polygeneration with FT fuels (Hamelinck and Faaij, 2006; Laser et al., 2009; Williams et al., 2009).

Process intensification is the combination of multiple unit operations conducted in a chemical plant into one thus reducing its footprint and

64 See Table 2.15 for financial assumptions that are not identical; Bauen et al. (2009a) and Foust et al. (2009) are close.

65 Impact Assessment of first-of-a-kind commercial ethanol from corn stover and cobs collocated with grain ethanol facilities is provided by the Integrated Bioenergy Projects. U.S. DOE Golden Field Office web site: www.eere.energy.gov/golden/Reading_Room.aspx; www.eere.energy.gov/golden/PDFs/ReadingRoom/NEPA/Final_Range_Fuels_EA_10122007.pdf; www.eere.energy.gov/golden/PDFs/ReadingRoom/NEPA/POET_Project_LIBERTY_Final_EA.pdf; and www.biorefineryprojecteis-abengoa.com/Home_Page.html.

66 E.g., *Escherichia coli* and *Saccharomyces cerevisiae* have well-established genetic tools and industrial use.

67 Rude and Schimer (2009) report stoichiometric data, for example, per tonne of glucose the number of litres is 297 of farnesene (for diesel), and 384 of microbial biocrude oil (for jet fuel) compared with 648 of ethanol (for gasoline). Metabolic mass yields are 25 and 30% for farnesene and biocrude, respectively, compared to 51% for ethanol. The routes grow the intermediate cell mass that then starts producing biofuels or intermediates—these steps are usually aerobic and require air and agitation that reduce the overall energy efficiency.

capital costs and enabling plants to operate more cost effectively at smaller scale. Therefore chemical/thermal processing that previously could only be conducted at very large scale could now be downsized to match the supply of biomass cost effectively. Efficient heat and mass transfer in micro-channel reactors has been explored to compact reactors by 1-2 orders of magnitude in water-gas-shift, steam reforming and FT processes for conventional natural gas or coal gasification streams (Nehlsen et al., 2007) and significantly reduce capital costs (Schouten et al., 2002; Sharma, 2002; Tonkovich et al., 2004). Such intensification could lead to distributed biomass to liquids (BTL) production, as capital requirements would be significantly reduced (as they would be for coal to liquids (CTL) or gas to liquids (GTL) (Shah, 2007). Methanol/DME synthesis could be intensified as well. Additionally, combined biomass/coal gasification options could capture some of the economies of scale while taking advantage of biomass' favourable CO_2 mitigation potential.

Other intermediates: vegetable or pyrolysis/ hydrothermal processing oils

For **diesel substitution**, hydrogenation technologies are already commercially producing direct hydrocarbon diesel substitutes from hydrogenation of vegetable oils to renewable diesel in 2011.[68] Costs depend on the vegetable oil prices and subsidies (see Table 2.15.C and Section 2.3.4). Lignocellulosic residues from vegetable oil production could provide the energy for standalone hydrogenation. The downstream processing of the lipids/plant oils to finished fuels is often conducted in conjunction with a petroleum refinery, in which case jet fuel and other products can be made.

Fast **pyrolysis** processes or **hydrothermal liquefaction** processing of biomass make low-cost intermediate oil products (Bain, 2007; Barth and Kleinert, 2008; Section 2.7.1). Holmgren et al. (2008) estimated production costs for lignocellulose pyrolysis upgrading to a blendstock (component that can be blended with gasoline at a refinery) as USD_{2005} 14 to 24/GJ, from bench scale data.

Under mild conditions of **aqueous phase reforming** and in the presence of multifunctional supported metal catalysts, biomass-derived sugars and other oxygenated organics can be combined and chemically rearranged (with retention of carbon and hydrogenation) to make hydrocarbon fuels. These processes can also make hydrogen at moderate temperature and pressure (Cortright et al., 2002; Huber et al., 2004, 2005, 2006; Davda et al., 2005; Gurbuz et al., 2010). These developments have reached the pilot and demonstration phase (Regalbuto, 2009).

From carbon dioxide, water and light energy with photosynthetic algae (Table 2.15.B)

Microalgal lipids (microalgal oil) are at an early stage of R&D and currently have significant feedstock production and processing costs, ranging from USD_{2005} 30 to 140/GJ (EPA, 2010). Exploring the biodiversity of microbial organisms for their chemical composition and their innate microbial pathways can lead to use of highly saline lands, brackish waters or industrial waste waters, avoiding competition with land for food crops but the potential of microalgae is highly uncertain.

Prospects. In the near to medium term, the biofuel industry, encompassing first- and second-generation technologies that meet agreed-upon environmental and economic sustainability and policy goals, will grow at a steady rate. It is expected that the transition to an integrated first- and second-generation biofuel landscape will likely require another decade or two (Sims et al., 2008, 2010; NRC, 2009a; Darzins et al., 2010).

2.6.3.2 Gaseous fuels

Part D of Table 2.15 compares estimated production costs for the production of gaseous fuels from lignocellulosic biomass and various waste streams:

Anaerobic digestion. Production of methane from a variety of waste streams, alone or combined with agricultural residues, is being used throughout the world at various levels of performance. The estimated production costs depend strongly on the application: USD_{2005} 1 to 2/GJ for landfill gas, USD_{2005} 15 to 20/GJ for natural gas or transport applications, USD_{2005} 50 to 60/GJ for on-farm digesters/small engines and USD_{2005} 100 to 120/GJ for distributed electricity generation (see Tables 2.6 and 2.15). The reliability, predictability and cost of individual technologies and assembled systems could be decreased using advanced metagenomics tools[69] and microbial morphology and population structure (Cirne et al., 2007). Also, control and automation technologies and improved gas clean-up and upgrading and quality standards are needed to permit injection into natural gas lines, which could result in more widespread application. Avoided methane emissions provide a significant climate benefit with simultaneous generation of energy and other products.

Synthesis gas-derived methane (a substitute for natural gas), methanol-dimethyl ether (DME), and H_2 are gaseous products from biomass gasification that are projected to be produced in the USD_{2005} 5 to 18/GJ range. After suitable gas cleaning and tar removal, the syngas is converted in a catalytic synthesis reactor into other products by designing catalysts and types of reactors used (e.g., nickel/magnesium catalysts will lead to SNG, while copper/zinc oxide will preferentially make methanol and DME). Processes developed for use with multiple feedstocks in various proportions can decrease investment risks by ensuring continuous feedstock availability throughout the year and decreasing vulnerability to weather and climate. Methanol synthesis from natural gas (and coal) is practised commercially, and synthesis from biomass is being developed at demonstration and first commercial plants. H_2 production has the lowest potential costs, but more developed infrastructure

68 Renewable Diesel is currently produced by Neste Oil in Singapore from Malaysian palm oil and then shipped to Germany (see biofuelsdigest.com/bdigest/2011/03/11/neste-oil-opens-giant-renewable-diesel-plant-in-singapore/). The development of the process took about 10 years from proof of principle as described in www.climatechange.ca.gov/events/2006-06-27+28_symposium/presentations/CalHodge_handout_NESTE_OIL.PDF (nesteoil.com/).

69 See, for instance, www.jgi.doe.gov/sequencing/why/99203.html.

is needed for transportation applications (Kirkels and Verbong, 2011). DME is another product from gasification and upgrading (jointly produced with methanol). It can be made from wood residues and black liquor and is being pursued as a transportation fuel. Sweden considered scenarios for multiple bioenergy products, including a substantial replacement of diesel fuel and gasoline with DME and methanol (Gustavsson et al., 2007).

Microbial fuel cells using organic matter as a source of energy are being developed for direct generation of electricity. Electricity is generated through what may be called a microbiologically mediated oxidation reaction, which implies that overall conversion efficiencies are potentially higher for microbial fuel cells compared to other biofuel processes (Rabaey and Verstraete, 2005). Microbial fuel cells could be applied for the treatment of liquid waste streams and initial pilot winery wastewater treatment is described by Cusick et al. (2011).

2.6.3.3 Biomass with carbon capture and storage: long-term removal of greenhouse gases from the atmosphere

Bioenergy technologies coupled with CCS (Obersteiner et al., 2001; Möllersten et al., 2003; Yamashita and Barreto, 2004; IPCC, 2005; Rhodes and Keith, 2008; Pacca and Moreira, 2009) could substantially increase the role of biomass-based GHG mitigation if the geological technologies of CCS can be developed, demonstrated and verified to maintain the stored CO_2 over time. These technologies may become a cost-effective indirect mitigation, for instance, through offsets of emission sources that are expensive to mitigate directly (IPCC, 2005; Rhodes and Keith, 2008; Azar et al., 2010; Edenhofer et al., 2010; van Vuuren et al., 2010).

Corn ethanol manufacturers in the USA supply CO_2 for carbonated beverages, flash freezing meat and to enhance oil recovery in depleted fields, but due to the low commercial value of CO_2 markets and requirements for regional proximity, the majority of the ethanol plants vent it into the air. CO_2 capture from sugar fermentation to ethanol is thus possible (Möllersten et al., 2003) and may now be used for carbon sequestration. Demonstrations of these technologies are proceeding.[70] The impact of this technology was projected to reduce the lifecycle GHG emissions of a natural gas-fired ethanol plant from 39 to 70% relative to the fossil fuel ethanol replaced, while the energy balance is degraded by only 3.5% (see Table 2.13 for performance in different functional units) ((S&T)[2] Consultants, 2009).

Similarly, van Vliet et al. (2009) estimated that a net neutral climate change impact could be achieved by combining 50% BTL and 50% coal FTL fuels with CCS, if biomass gasification and CCS can be made to work at an industrial scale and the feedstock is obtained in a climate-neutral manner (see Figure 2.10). Perhaps additional removal could be achieved by using crops that increase soil carbon content (e.g., on degraded lands) as indicated by Larson et al. (2009).

2.6.3.4 Biorefineries

The concept of biorefining is analogous to petroleum refining in that a wide array of products including liquid fuels, chemicals and other products (Kamm et al., 2006) can be produced. Even today's first generation biorefineries are making a variety of products (see Table 2.7), many of which are associated with food and fodder production. For example, sugarcane ethanol biorefineries produce multiple energy products (EPE, 2008, 2010). Sustainable lignocellulosic biorefineries can also enhance the integration of energy and material flows (e.g., Cherubini and Strohman 2010). These biorefineries optimize the use of biomass and resources in general (including water and nutrients) while mitigating GHG emissions (Ragauskas et al., 2006). The World Economic Forum (King et al., 2010) projects that biorefinery revenue potentials with existing policies along the entire value chain could be significant and could reach about USD_{2005} 295 billion by 2020.[71]

2.6.3.5 Bio-based products

Bio-based products are defined as non-food products derived from biomass. The term is typically used for new non-food products and materials such as bio-based plastics, lubricants, surfactants, solvents and chemical building blocks. Plastics represent 73% of the total petrochemical product mix, followed by synthetic fibres, solvents, detergents and synthetic rubber (2007 data; Gielen et al., 2008). Bio-based products can therefore be expected to play a pivotal role in these product categories, in particular plastics and fibres.

The four principal ways of producing polymers and other organic chemicals from biomass are: (1) direct use of several naturally occurring polymers, usually modified with some thermal treatment, chemical transformation or blending; (2) thermochemical conversion (e.g., pyrolysis or gasification) followed by synthesis and further processing; (3) fermentation (for most bulk products) or enzymatic conversion (mainly for specialty and fine chemicals) of biomass-derived sugars or other intermediates; and (4) bioproduction of polymers or precursors in genetically modified field crops such as potatoes or *Miscanthus.*

Worldwide production of recently emerging bio-based plastics is expected to grow from less than 0.4 Mt in 2007 to 3.45 Mt in 2020 (Shen et al., 2009). Cost-effective bio-based products with properties superior to those in conventional materials, not just renewability, are

70 See sequestration.org/report.htm and www.netl.doe.gov/technologies/carbon_seq/database/index.html. In the USA, through the Midwest Geological Sequestration Consortium, a coal-fired wet-milled ethanol plant is planning over three years to inject 1 Mt of CO_2 into the Mount Simon sandstone saline formation in central Illinois at a depth of about 2 km in a verification phase test project including monitoring, verification and accounting, which is in the characterization phase (June 2010).

71 Approximate values (USD_{2005} billion by 2020) of business potential for the various parts of the value chain were estimated as: agricultural inputs (15), biomass production (89), biomass trading (30), biorefining inputs (10), biorefining fuels (80), biorefining chemicals and products (6), and biomass power and heat (65).

projected to penetrate the markets (King et al., 2010). For synthetic organic materials production, scenario studies indicate that at a productivity of 0.15 ha/t, an area of 75 million hectares globally could supply the equivalent of 15 to 30 EJ of value-added products (Patel et al., 2006).

Given the early stage of development, the GHG abatement costs differ substantially. The current abatement costs for polylactic acid are estimated at USD_{2005} 100 to 200/t of abated CO_2. Today's abatement costs for bio-based polyethylene, if produced from sugarcane-based ethanol, may be of the order of USD_{2005} 100/t CO_2 or lower. For all processes, technological progress in chemical and biochemical conversion and the combined production of bioenergy is likely to reduce abatement costs by USD_{2005} 50 to 100/t CO_2 in the medium term (Patel et al., 2006).

2.6.4 Synthesis

Lignocellulosic feedstocks offer significant promise because they (1) do not compete directly with food production; (2) can be bred specifically for energy purposes (or energy-specific products), enabling higher production per unit land area, and have a very large market for the products; (3) can be harvested as residues from crop production and other systems that increase land use efficiency; and (4) allow the integration of waste management operations with a variety of other industries offering prospects for industrial symbiosis at the local level.

Drivers and challenges for converting biomass to fuels, power, heat and multiple products are economic growth and development, environmental awareness, social needs, and energy and climate security. The estimated revenue potential along the entire value chain could be of the order of USD_{2005} 295 billion in 2020 with current policies (King et al., 2010).

Residues from crop harvests and from planted forests are projected to increase on average by about 20% by 2030 to 2050 in comparison to 2007 to 2009. Production costs of bioenergy from perennial grasses or short rotation coppice are expected to fall to under USD_{2005} 2.5/GJ by 2020 (WWI, 2006), from a range of USD_{2005} 3 to 16/GJ today. Supply curves projecting the costs and quantities available at specific sites are needed, and they should also consider competing uses as shown in examples in Figure 2.5. For example, EU and US lignocellulosic supply curves show more than 20 EJ at reasonable delivered costs by 2025 to 2030.

A new generation of aquatic feedstocks that use sunlight to produce algal lipids for diesel, jet fuels or higher-value products from CO_2 and water can provide strategies for lowering land use impacts because they enable use of lands with brackish waters or industrial waste water. Today's estimated production costs are very uncertain and range from USD_{2005} 30 to 140/GJ in open ponds and engineered reactors.

Many microbes could become microscopic factories to produce specific products, fuels or materials that decrease society's dependence on fossil energy sources.

Although significant technical progress has been made, the more complex processing required by lignocellulosic biomass and the integration of a number of new steps take time and support to bring development through the 'Valley of Death' in demonstration plants, first-of-a kind plants and early commercialization. Projected costs from a wide range of sources and process variables are very sensitive to feedstock cost and range from USD_{2005} 10 to 30/GJ. The US National Academies project a 40% reduction in operating costs for biochemical routes by 2035.

Cost projections for pilot integrated gasification combined cycle plants in many countries are USD_{2005} 13 to 19/GJ (US $cents_{2005}$ 4.6 to 6.9/kWh at USD_{2005} 3/GJ feedstock cost). In addition to providing power, syngas can be used to produce a wide range of fuels or can be used in a combined power and fuels approach. Estimated projected costs are in the range of USD_{2005} 12 to 25/GJ for methanol, ethanol, butanols and syndiesel. Biomass to liquids technology uses a commercial process already developed for fossil fuel feedstocks. Gaseous products (H_2, methane, SNG) have lower estimated production costs (USD_{2005} 6 to 12/GJ) and are in an early commercialization phase.

The production of biogas from a variety of waste streams and its upgrading to biomethane is already penetrating small markets for multiple applications, including transport in Sweden and heat and power in Nordic and European countries. A key factor is the combination of waste streams with agriculture residues. Improved upgrading and further cost reductions are still needed.

Pyrolysis oil/hydrothermal oils are low-cost transportable oils (see Sections 2.3.4 and 2.7.2) that could become a feedstock for upgrading either in standalone facilities or coupled to a petrochemical refinery. Pyrolysis oils have low estimated production costs of about USD_{2005} 7/GJ and provide options for electricity, heat and chemicals production. Pyrolysis-oil stabilization and subsequent upgrading still require cost reductions and are active areas of research.

Many bioenergy/biofuels routes enable CCS with significant opportunities for removal of GHGs from the atmosphere. As CCS technologies are further developed and verified, coupling concentrated CO_2 streams from fermentation or IGCC for electricity or biomass and coal to liquids through Fischer-Tropsch processes with CCS offer opportunities to achieve carbon-neutral fuels, and in some cases carbon-negative fuels, within the next 35 years. Achieving this goal will be facilitated by well-designed systems that span biomass selection, feedstock supply systems, conversion technologies to secondary energy carriers, and integration of these carriers into the existing energy systems of today and tomorrow.

2.7 Cost trends[72]

2.7.1 Determining factors

Determining the production costs of energy (or materials) from biomass is complex because of the regional variability in the costs of feedstock production and supply and the wide variety of deployed and possible biomass conversion technology combinations. Key factors that affect the costs of bioenergy production are:

- For crop production: the cost of land and labour, crop yields, prices of various inputs (such as fertilizer), water supply and the management system (e.g., mechanized versus manual harvesting) (Sections 2.3.1 and 2.6.1; see Wiskerke et al., 2010 for a local specific example).

- For delivering biomass to a conversion facility: spatial distribution of biomass resources, transport distance, mode of transport and the deployment (and timing) of pretreatment technologies in the chain. Supply chains range from onsite use (e.g., fuelwood or use of bagasse in the sugar industry, or biomass residues in other conversion facilities) all the way to international supply chains with shipped pellets or liquid fuels such as ethanol (Sections 2.3.2 and 2.6.2); see Dornburg and Faaij (2001) on regional transport for power; Hamelinck et al. (2005b) on international supply chains.

- For final conversion to energy carriers (or biomaterials): the scale of conversion, financing mechanisms, load factors, production and value of co-products and ultimate conversion costs (in the production facility). These key factors vary between technologies and locations. The type of energy carrier used in the conversion process influences the climate mitigation potential (Wang et al., 2011).

The analyses of Hoogwijk et al. (2009) provide a global and long-term outlook for potential biomass production costs (focused on perennial cropping systems) of different IPCC SRES scenarios (IPCC, 2000) discussed in Sections 2.8.4 and 2.8.5 (see Table 2.16 and Figure 2.17). Land rental/lease costs, although a smaller cost factor in most world regions, are dependent on intensity of land use in the underlying scenarios. Capital costs vary due to different levels of mechanization. Based on these analyses, a sizeable part (100 to 300 EJ) of the long-range technical potentials based on perennial cropping systems could cost around USD_{2005} 2.3/GJ. The cost range depends on the assumed scenario conditions, and is shown in Figure 10.23 (Hoogwijk et al., 2009; see also cost supply curves and potentials shown in Figure 2.5 for near-term production). More details on costs of both annual and perennial energy crop production are described in Sections 2.3.1 and 2.6.1.

Biomass supplies are, as with any commodity, subject to complex pricing mechanisms. Biomass supplies are strongly affected by fossil fuel prices (OECD-FAO, 2008; Schmidhuber, 2008; Tyner and Taheripour, 2008) and by agricultural commodity and forest product markets. In an ideal situation, demand and supply will balance and price levels will provide a good measure of actual production and supply costs (see also Section 2.5.3 for discussions on LUC). At present, market dynamics determine the costs of the most important biofuel feedstocks, such as corn, rapeseed, palm oil and sugarcane. For wood pellets, another important internationally traded feedstock for modern bioenergy production, prices have been strongly influenced by oil prices, because wood pellets partly replace heating oil, and by supportive measures to stimulate green electricity production, such as FITs for co-firing (Section 2.4; Junginger et al., 2008). In addition, prices of solid and liquid biofuels are determined by national settings, and specific policies and the market value of biomass residues for which there may be alternative applications is often determined by price mechanisms of other markets influenced by national policies (see Junginger et al., 2001 for a specific example for Thailand).

2.7.1.1 Recent levelized costs of electricity, heat and fuels for selected commercial systems

The factors discussed above make it clear that it is difficult to generate generic cost information for bioenergy that is valid worldwide. Nonetheless, this section provides estimates for the recent levelized cost of electricity (LCOE), heat (LCOH) and fuels (LCOF) typical of selected commercial bioenergy systems, some of which are described in more technological detail in Section 2.3.4.[73] The methodology for calculating levelized cost is described in Annex II. Data and assumptions used to produce these figures are provided in Annex III, with those assumptions derived in part from the literature summarized earlier.

The results of the LCOE, LCOH and LCOF calculations for a selected set of commercially available bioenergy options, and based on recent costs, are summarized in Figure 2.18 and discussed below.

To calculate the LCOE for electricity generation, a standardized range of feedstock cost of USD_{2005} 1.25 to 5/GJ was assumed (based on High Heating Value, HHV). To calculate the LCOE of CHP plants where both electricity and heat are produced, the heat was counted as a co-product with revenue that depended on the assumed quality and application of the heat. For large-scale CHP plants, where steam is generated for process heat, the co-product revenue was set at USD_{2005} 5/GJ. For small-scale CHP plants, on the other hand, the revenue was effectively set according to the cost of hot water, or USD_{2005} 13/GJ (applicable, e.g., in Nordic countries and Europe).

The LCOH for heating systems illustrated in the light blue bars of Figure 2.18 is less certain due to a more limited set of available literature. For

72 Discussion of costs in this section is largely limited to the perspective of private investors producing secondary energy carriers. Chapters 1 and 8 to 11 offer complementary perspectives on cost issues covering e.g. costs of integration, external costs and benefits, economy-wide costs and costs of policies.

73 The levelized cost of energy represents the cost of an energy generating system over its lifetime; it is calculated as the per-unit price at which energy must be generated from a specific source over its lifetime to break even. It usually includes all private costs that accrue upstream in the value chain, but does not include the downstream cost of delivery to the final customer the cost of integration or external environmental or other costs. Subsidies and tax credits are also not included.

Table 2.16 | Estimated regional technical potential of energy crops for 2050 (in EJ) on abandoned agricultural land and rest of land at various cut-off costs (in USD_{2005}/GJ biomass harvested, including local transport) for the two extreme SRES land use scenarios A1 and A2 (Hoogwijk et al., 2009; reproduced with permission from Elsevier B.V.).

Region	A1: high crop growth intensity and maximum international trade in 2050			A2: low crop growth intensity and minimum trade and low technology development in 2050		
cut-off cost	<1.15 USD/GJ	<2.3 USD/GJ	<4.6 USD/GJ	<1.15 USD/GJ	<2.3 USD/GJ	<4.6 USD/GJ
Canada	0	11.4	14.3	0.0	7.9	9.4
USA	0	17.8	34.0	0.0	6.9	18.7
C America	0	7.0	13.0	0.0	2.0	2.9
S America	0	11.7	73.5	0.0	5.3	14.8
N Africa	0	0.9	2.0	0.0	0.7	1.3
W Africa	6.6	26.4	28.5	7.9	14.6	15.5
E Africa	8.1	23.8	24.4	3.6	6.2	6.4
S Africa	0	12.5	16.6	0.1	0.3	0.7
W Europe	0	3.0	11.5	0.0	5.6	12.5
E Europe	0	6.8	8.9	0.0	6.2	6.3
Former USSR	0	78.6	84.9	0.8	41.9	46.6
Middle East	0	0.1	3.0	0.0	0.0	1.3
South Asia	0.1	12.1	15.3	0.6	8.2	9.8
East Asia	0	16.3	63.6	0.0	0.0	5.8
SE Asia	0	8.8	9.7	0.0	6.9	7.0
Oceania	0.7	33.4	35.2	1.6	16.6	18.0
Japan	0	0.0	0.1	0.0	0.0	0.0
Global	**15.5**	**271**	**438**	**14.6**	**129**	**177**

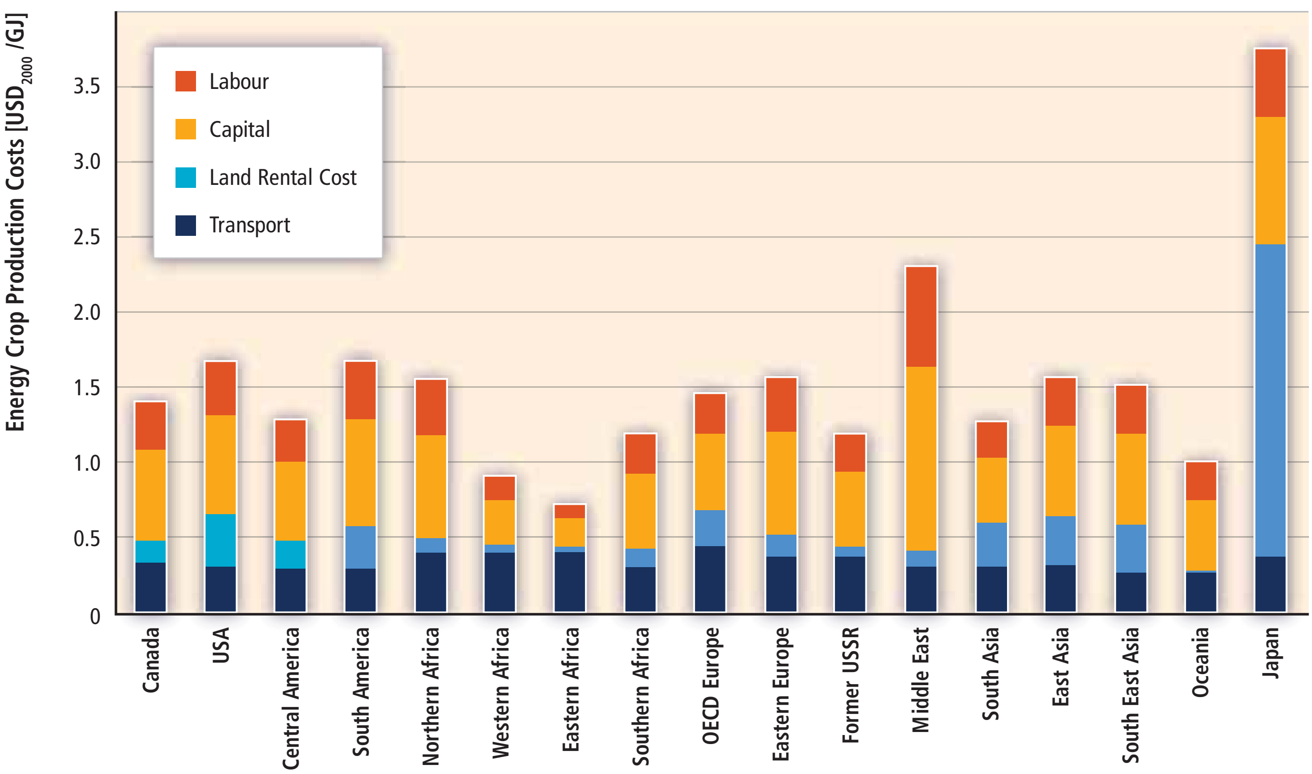


Figure 2.17 | Cost breakdown for energy crop production costs in the grid cells with the lowest production costs within each region for the SRES A1 scenario (IPCC, 2000) in 2050 (in USD_{2000} instead of USD_{2005})(Hoogwijk et al., 2009; reproduced with permission from Elsevier B.V.).

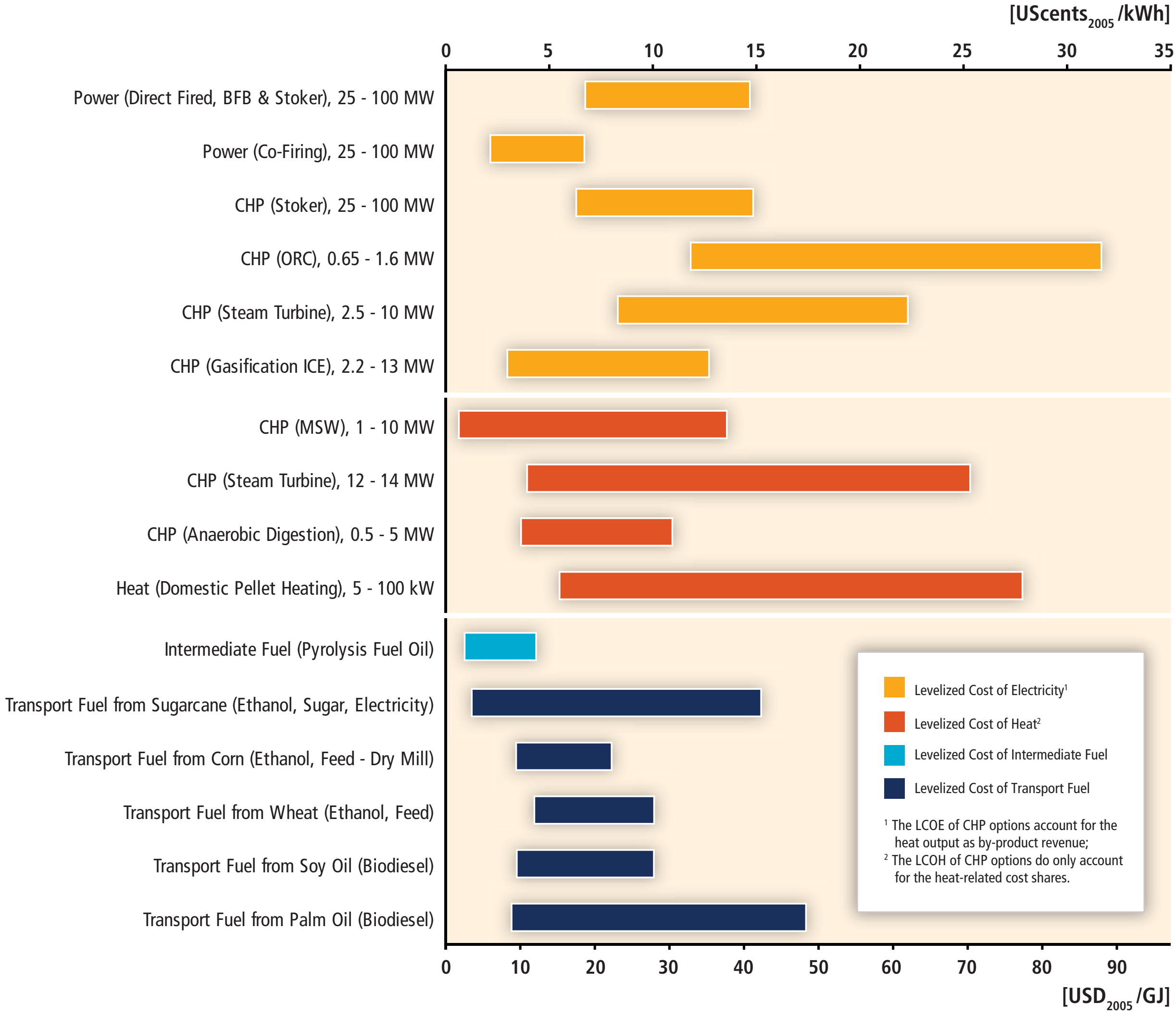


Figure 2.18 | Typical recent levelized cost of energy service from commercially available bioenergy systems at 7% discount rate. Feedstock cost ranges differ between technologies. For levelized cost at other discount rates (3 and 10%) see Annex III and Section 10.5. For biofuels, the range of LCOF represents production in a wide range of countries whereas LCOE and LCOH are given only for major user markets of the technologies for which data were available. The underlying cost and performance assumptions used in the calculations are summarized in Annex III. Calculations are based on HHV.

Abbreviations: BFB: Bubbling fluidized bed; ORC: Organic Rankine cycle; ICE: Internal combustion engine.

heating applications, investment cost assumptions came principally from literature from European and Nordic countries, which are major users of these applications (see Figure 2.8). Feedstock cost ranges came from the same literature and therefore may not be representative of other world regions: feedstock costs were assumed to be USD_{2005} 0 to 3.0/GJ for MSW and low-cost residues, USD_{2005} 2.5 to 3.7/GJ for anaerobic digestion, USD_{2005} 3.7 to 6.2/GJ for steam turbine and USD_{2005} 10 to 20/GJ for pellets. The LCOH figures presented here are therefore most representative of European systems.

LCOF estimates were derived from a techno-economic evaluation of the production of biofuels in multiple countries (Bain, 2007).[74] Underlying feedstock cost assumptions represent the maximum and minimum recent feedstock cost in the respective regions, and are provided in Annex III. All routes for biofuel production take into account sometimes multiple co-product revenues, which were subtracted from expenditures to calculate the LCOF. In the case of ethanol from sugarcane, for example,

74 The study was done in conjunction with a preliminary economic characterization of feedstock supply curves for the Americas, China and India (Kline et al., 2007) described in Section 2.2.3. The biomass market potential associated with these calculations (Alfstad, 2008) is shown in Figure 2.5(c) (45 EJ, 25 EJ and 8 EJ respectively for the high-growth, baseline and low-growth cases for these countries).

the revenue from sugar was set at USD_{2005} 4.3/GJ_{feed}, though this value varies with sugar market prices and can go up to about USD_{2005} 5.6/GJ_{feed}. For the LCOF calculations, however, average by-product revenues were assumed. Along with ethanol and sugar (and potentially other bio-materials in the future), the third co-product is electricity, revenues for which were also assumed to be deducted in calculating the LCOF. A similar approach was used for other biofuel pathways (see Annex III). This single example, however, illustrates the complexity of biofuel production cost assessments.

Finally, the levelized cost of pyrolysis oil as an intermediate fuel, a densified energy carrier, was also assessed, because pyrolysis oils are already used for heating and CHP applications and are also being investigated for stationary power and transport applications (see Sections 2.3.3.2, 2.6.2 and 2.6.3.1).

Figure 2.18 presents a broad range of values, driven by variations not only in feedstock costs but also investment costs, efficiencies, plant lifetimes and other factors. Feedstock costs, however, not only vary substantially by region but also represent a sizable fraction of the total levelized cost of many bioenergy applications. The effect of different feedstock cost levels on the LCOE of the electricity generation technologies considered here is shown more clearly in Figure 2.19, where variations are also shown for investment costs and capacity factors.[75] Similar effects are shown for the levelized cost of biofuels (LCOF) in Figure 2.20. (Though a figure is not shown for heating systems, a similar relationship would

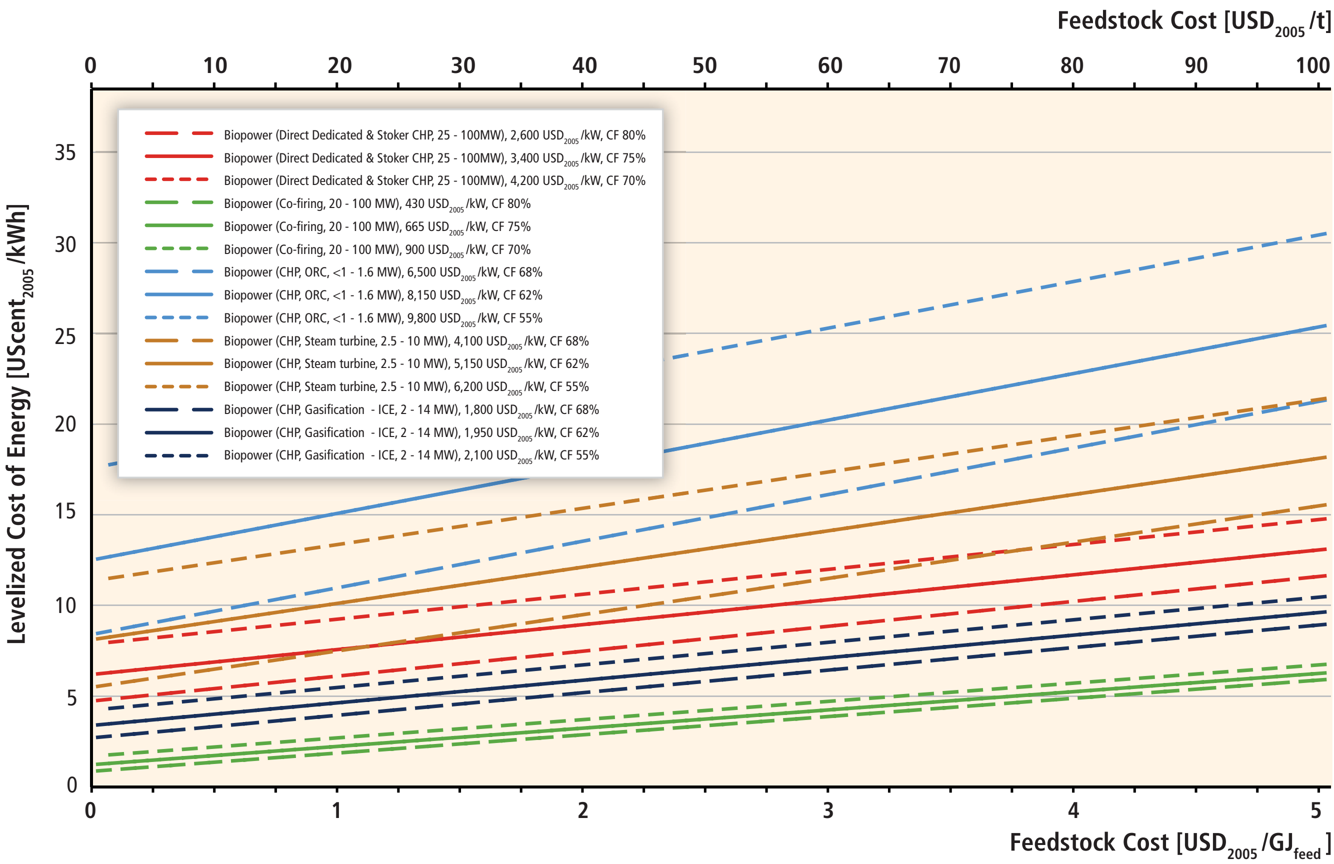


Figure 2.19 | Sensitivity of LCOE with respect to feedstock cost for a variety of investment costs and plant capacity factors (CF). LCOE is based on a 7% discount rate, the mid-value of the operations and maintenance (O&M) cost range, and the mid-value of the lifetime range (see Annex III). Calculations are based on HHV.

References: DeMeo and Galdo (1997); Bain et al. (2003); EIA (2009); Obernberger and Thek (2004); Sims (2007); McGowin (2008); Obernberger et al. (2008); EIA (2010b); Rauch (2010); Skjoldborg (2010); Bain (2011); OANDA (2011).

75 Note that large-scale power only and CHP technologies have been aggregated in Figure 2.18, while they are shown separately in Figure 2.19.

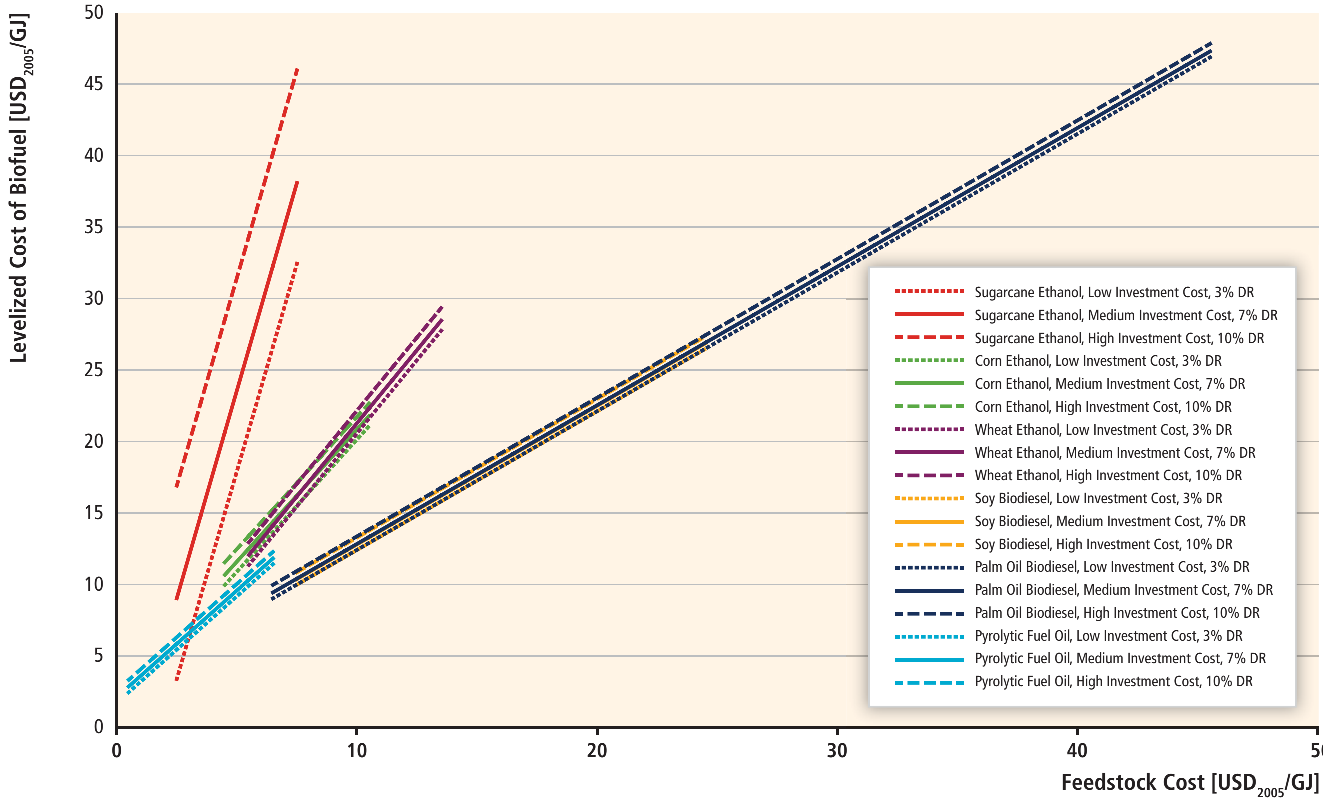


Figure 2.20 | Sensitivity of LCOF with respect to feedstock cost for different discount rates and the mid-values of other cost components from multiple countries (see Annex III). Calculations are based on HHV.

References: Delta-T Corporation (1997); Sheehan et al. (1998b); McAloon et al. (2000); Rosillo-Calle et al. (2000); McDonald and Schrattenholzer (2001); Ibsen et al. (2005); Jechura (2005); Bohlmann (2006); CBOT (2006); Haas et al. (2006); Oliverio (2006); Oliverio and Ribeiro (2006); Ringer et al. (2006); Shapouri and Salassi (2006); USDA (2006); Bain (2007); Kline et al. (2007); USDA (2007); Alfstad (2008); RFA (2011); University of Illinois (2011).

exist.) References used to generate the cost data are assembled in notes to the figures.

2.7.2 Technological learning in bioenergy systems

Cost trends and technological learning in bioenergy systems are not as well described as those for solar or wind energy technologies. Recent literature, however, gives more detailed insights into the learning curves of various bioenergy systems. Table 2.17 and Figure 2.21 summarize a number of analyses that have quantified learning, expressed by learning rates (LR) and learning (or experience) curves, for three commercial biomass systems:

1. Sugarcane-based ethanol production (van den Wall Bake et al., 2009),
2. Corn-based ethanol production (Hettinga et al., 2009),
3. Wood fuel chips and CHP in Scandinavia (Junginger et al., 2005 and a number of other sources).

The LR is the rate of a unit cost decline associated with each doubling of cumulative production (see Section 10.2.5 for a more detailed discussion). For example, a LR of 20% implies that after one doubling of cumulative production, unit costs decreased by 20% of the original costs. The definition of the 'unit' depends on the study variable.

Learning curve studies have accuracy limitations (Junginger et al., 2008; see also Section 10.5.3). Yet, there are a number of general factors that drive cost reductions that can be identified: For biomass feedstocks for ethanol production such as sugar crops (sugarcane) and starch crops (corn), increasing crop yields have been the driving force behind cost reductions.

- For sugarcane, cost reductions have come from R&D efforts to develop varieties with increased sucrose content and thus ethanol yield, increasing the number of harvests from the crop ratoon (from shoots) before replanting the field, increasingly efficient manual harvesting and the use of larger trucks for transportation. More recently, mechanical harvesting of sugarcane is replacing manual harvest, increasing the amount of residues for electricity production (van den Wall Bake et al., 2009; Seabra et al., 2010).

- For the production of corn, the highest cost decline occurred in costs for capital, land and fertilizer until 2005. Additional drivers behind cost reductions were increased plant sizes through cooperatives that

Table 2.17 | Experience curves for major components of bioenergy systems and final energy carriers expressed as reduction (%) in cost (or price) per doubling of cumulative production.

Learning system	LR (%)	Time frame	Region	N	R^2
Feedstock production					
Sugarcane (tonnes sugarcane)[1]	32±1	1975–2005	Brazil	2.9	0.81
Corn (tonnes corn)[2]	45±1.5	1975–2005	USA	1.6	0.87
Logistic chains					
Forest wood chips (Sweden)[3]	12–15	1975–2003	Sweden/Finland	9	0.87–0.93
Investment and O&M costs					
CHP plants[3]	19–25	1983–2002	Sweden	2.3	0.17–0.18
Biogas plants[4]	12	1984–1998		6	0.69
Ethanol production from sugarcane[1]	19±0.5	1975–2003	Brazil	4.6	0.80
Ethanol production from corn (only O&M costs)[2]	13±0.15	1983–2005	USA	6.4	0.88
Final energy carriers					
Ethanol from sugarcane[5]	7 29	1970–1985 1985–2002	Brazil	~6.1	n.a.
Ethanol from sugarcane[1]	20±0.5	1975–2003	Brazil	4.6	0.84
Ethanol from corn[2]	18±0.2	1983–2005	USA	7.2	0.96
Electricity from biomass CHP[4]	8–9	1990–2002	Sweden	~9	0.85–0.88
Electricity from biomass[6]	15	Unknown	OECD	n.a.	n.a.
Biogas[4]	0–15	1984–2001	Denmark	~10	0.97

Notes: Abbreviations: LR: Learning Rate, N: Number of doublings of cumulative production, R^2: Correlation coefficient of the statistical data.

References: 1. van den Wall Bake et al. (2009); 2. Hettinga et al. (2009); 3. Junginger et al. (2005); 4. Junginger et al. (2006); 5. Goldemberg et al. (2004); 6. IEA (2000).

enabled higher production volumes, efficient feedstock collection, decreased investment risk through government loans and the introduction of improved efficiency natural gas-fired ethanol plants, which are responsible for nearly 90% of ethanol production in the USA (Hettinga et al., 2009). Higher yields were achieved from corn hybrids genetically modified to have higher pest resistance and increased adoption of no-till practices that improved water quality (NRC, 2010). While it is difficult to quantify the effects of these factors, it seems clear that R&D efforts (realizing better plant varieties), technology improvements and learning by doing (e.g., more efficient harvesting) played important roles.

For ethanol production, industrial costs from both sugarcane and corn mainly decreased because of increasing scales of the ethanol plants.

- Cost breakdowns of the sugarcane production process showed reductions of around 60% within all sub processes from 1975 to 2005. Ethanol production costs (excluding feedstock costs) declined by a factor of three between 1975 and 2005 (in real terms, i.e., corrected for inflation). Investment and operation and maintenance costs declined mainly due to economies of scale. Other fixed costs, such as administrative costs and taxes, did not fall dramatically, but cost reductions can be ascribed to automated administration systems. Decreased costs can be primarily ascribed to increased scales and load factors (van den Wall Bake et al., 2009).

- For ethanol from corn, the conversion costs (without costs for corn) declined by 45% from USD_{2005} 240/ m^3 in the early 1980s to USD_{2005} 130/m^3 in 2005. Costs for energy, labour and enzymes contributed in particular to the overall decline in costs. Additional drivers behind these reductions are higher ethanol yields, the introduction of automation and control technologies that require less energy and labour and the up-scaling of average dry grind plants (Hettinga et al., 2009).

2.7.3 Future scenarios of cost reduction potentials

2.7.3.1 Future cost trends of commercial bioenergy systems

For the production of ethanol from sugarcane and corn, future production cost scenarios based on direct experience curve analysis were found in the literature:

For Brazilian sugarcane ethanol (van den Wall Bake et al., 2009), total production costs in 2005 were approximately USD_{2005} 340/m^3 (USD_{2005} 16/GJ). Based on the experience curves for the cost components shown in Figure 2.21 (feedstock and ethanol without feedstock costs), total ethanol production costs in 2020 are estimated between USD_{2005} 200 and 260/m^3 (USD_{2005} 9.2 to 12.2/GJ). These costs compare well with those in Table 2.7 for Brazil with a current production cost estimate of USD_{2005} 14.8/GJ and projected 2020 cost of USD_{2005} 9 to 10/GJ. Ethanol production costs without feedstocks are in a range of USD_{2005} 139 to 183/m^3 (USD_{2005} 6.5 to 8.6/GJ) in 2005 and could reach about USD_{2005}113/m^3 (USD_{2005} 6.6/GJ) by 2020, assuming a constant 82 m^3 hydrous ethanol per t of sugarcane.

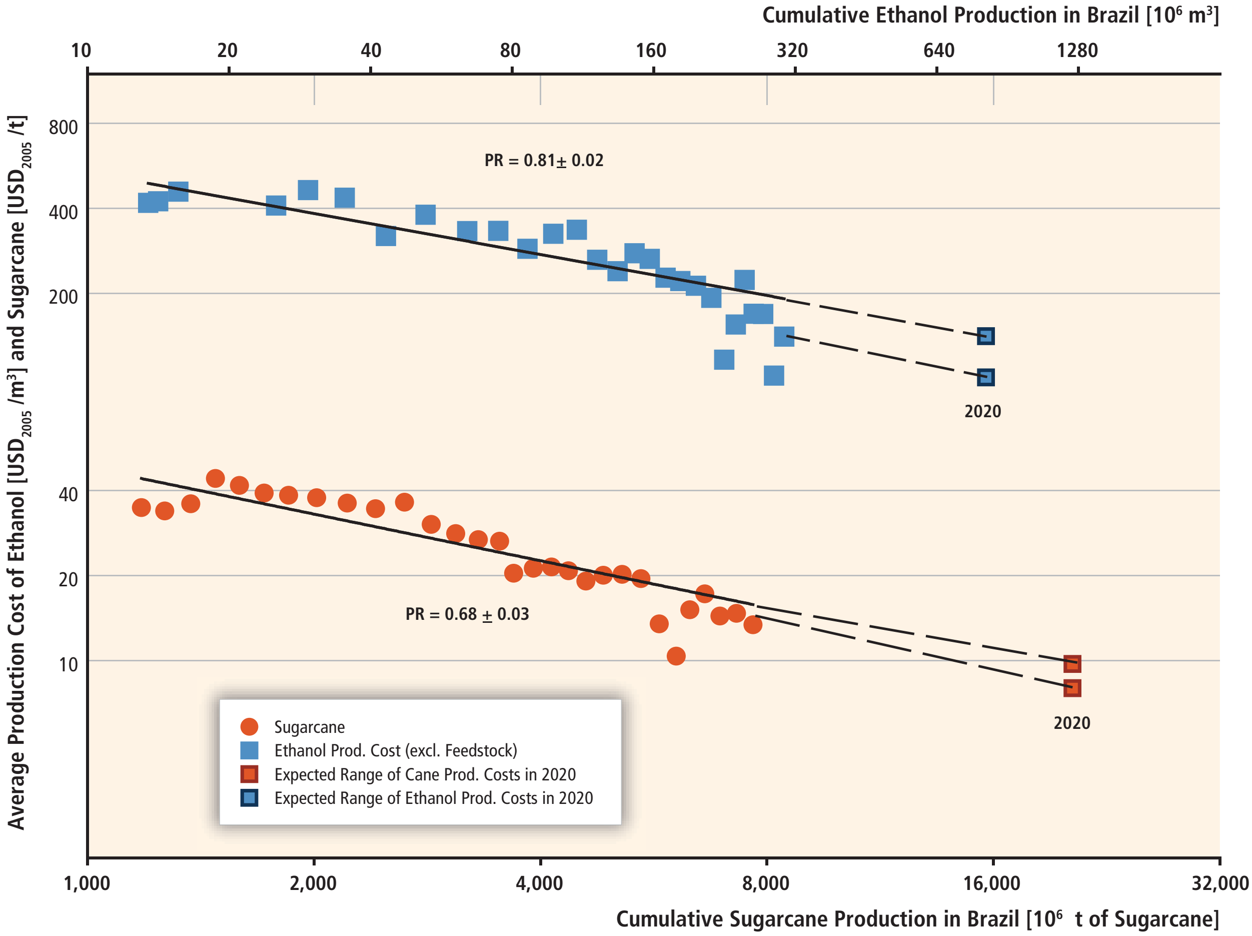


Figure 2.21 | Brazilian sugarcane and ethanol production cost learning curves for between 1975 and 2005 and extrapolated to 2020 (in USD_{2005}). Progress ratio (PR=1-LR) is obtained by best fit to data (van den Wall Bake et al., 2009; reproduced with permission from Elsevier B.V.).

For US ethanol from corn (Hettinga et al., 2009), costs of corn production and ethanol processing are estimated respectively as USD_{2005} 75/t and USD_{2005} 60 to 77/m³ by 2020. Overall ethanol production costs could decline from a current level of USD_{2005} 310/m³ to USD_{2005} 248/m³ (USD_{2005} 14.7 to 11.7/GJ) by 2020. This estimate excludes the investment costs and the effect of future corn prices. The EPA (2010) Regulatory Impact Analysis of the Renewable Fuel Standard 2 modelled the current corn ethanol industry in detail and projected a decrease in total production cost from USD_{2005} 17.5 to 16/GJ by 2022 by taking into account both feedstock and process improvements listed in Table 2.7 and the anticipated co-product revenue.

Confirming the trend and supporting the projections to 2020, Table 2.13 illustrates key indicators for environmental performance of a North American corn dry-grind natural gas-fired mill and the Brazilian sugarcane benchmark of 44 mills in terms of GHG emissions per carbon content of the biomass feedstock (displacement factor), emissions reductions relative to the reference fossil fuel in the production region (GHG savings), and a land use efficiency (volume of production per unit area) indicator. The commercial North American system's performance improved with time; for instance, using the relative GHG savings, which were 26% in 1995 and 39% in 2005, and the projected efficiency improvements through application of commercial CHP systems alone or in combination with CCS, would lead to 55 and 72% emissions savings by 2015, respectively. Similarly, the Brazilian sugarcane ethanol/electricity/sugar mill would go from 79 to 120 and 160% in relative GHG savings for the 2005-2006 baseline and the CHP and CCS scenarios, respectively.

In the Renewable Fuels for Europe project that focused on deployment of biofuels in Europe (de Wit et al., 2010; Londo et al., 2010), specific attention was paid to the effects of learning for lignocellulosic biofuels technologies on projections of future costs. The analyses showed two key points:

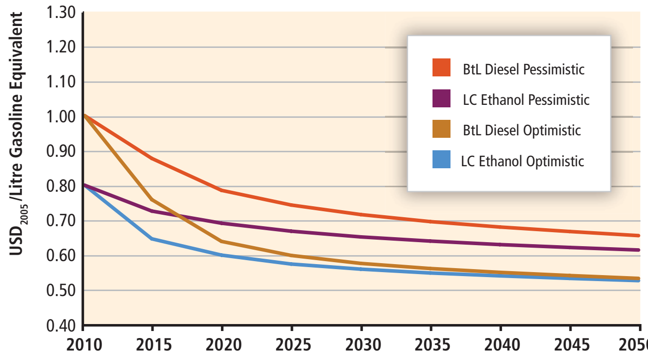
- Lignocellulosic biofuels have considerable potential for improvement in the areas of crop production, supply systems and the conversion technology. For conversion in particular, economies of scale are a very important element of the future cost reduction potential as specific capital costs can be reduced (partly due to improved conversion efficiency). Biomass resources may become somewhat more expensive due to a reduced share of (less costly) residues over time. It was estimated that lignocellulosic biofuel production cost could compete with gasoline and diesel from oil at USD_{2005} 60 to 70/barrel by 2030 (USD_{2005} 0.38 to 0.44/litre) (Hamelinck and Faaij, 2006).

- The penetration of lignocellulosic biofuel options depends considerably on the rate of learning. This rate is in turn dependent on increased market penetration (which allows for producing with larger production facilities), which makes the LR partly dependent on market support or mandates in earlier phases of market penetration.

The IEA Energy Technology Perspectives report (IEA, 2008a) and the WEO (IEA, 2009b) project a rapid increase in production of lignocellulosic biofuels, especially between 2020 and 2030, accounting for all incremental biomass increases after 2020. The biofuels analysis projects an almost complete phase-out of cereal- and corn-based ethanol production and edible oilseed-based biodiesel after 2030. The potential cost reductions from current demonstration projects to future commercial-scale facilities for production of specific lignocellulosic biofuels are shown in Figure 2.22. Such potential cost reductions are also quantified in Hamelinck and Faaij (2006) and van Vliet et al. (2009).

2.7.3.2 Future cost trends for pre-commercial bioenergy systems

A number of bioenergy systems are evolving, as shown in Figure 2.2 and discussed in Section 2.6. The key intermediates that enable generation of bioenergy from modern biomass include syngas, sugars, vegetable oils/lipids, thermochemical oils derived from biomass (pyrolysis or other thermal treatments), and biogas. These intermediates can produce higher efficiency electricity and heat, a wider range of liquid hydrocarbon fuels, alcohols (including some with higher energy density), ethers, and chemical products and polymers (bio-based materials) in the developing biorefineries that are discussed in Section 2.6. Initial R&D on producing hydrocarbon fuels is starting with sugar and starch crops and covering the range of gasoline, diesel and higher-energy content transport fuels such as jet fuels and chemicals. Both improved first-generation crops, perennial sugarcane-derived, in particular, and second-generation plants have the potential to provide a variety of energy products suited to specific geographic regions, and high-volume chemicals and materials traditionally derived from the petrochemical industry, maximizing the outputs of end products per unit of feedstock.



Note: BtL = Biomass-to-Liquids; LC = Lignocellulose

Figure 2.22 | Cost projections for lignocellulosic ethanol and BTL diesel (*Energy Technology Perspectives 2008*, © OECD/IEA, Figure 9.11, p. 335 in IEA (2008a); for additional future cost considerations see also Sims et al. (2008), IEA Renewable Energy Division (2010) and IEA (2011)).

Table 2.18 presents projected ranges of production costs for developing technologies such as integrated gasification combined cycle for the production of higher efficiency electricity and gasification-(syngas) derived fuels, including diesel, jet fuel, and H_2, methane, dimethyl ether and other oxygenated fuels through catalytic upgrading of the syngas. The sugar intermediates, lignocellulosic for instance, can be converted through biochemical routes to a variety of fuels with the properties of petroleum-based fuels. Similarly, pyrolysis oil-based hydrocarbon fuels are under development. Oilseed crop and tree seed oil development could also expand the range of fuel products with properties of petroleum fuels because they are readily upgraded to hydrocarbons. Finally, algae for biomass production are photosynthetic, using CO_2, water, and sunlight to biologically produce a variety of carbohydrates, lipids, plastics, chemicals or fuels like H_2, along with oxygen. In addition, heterotrophic microbes, such as certain algae are engineered to metabolize sugars and excrete lipids in the dark. Microorganisms or their consortia can consolidate various processing steps; genetically engineered yeasts or bacteria can make specific fuel products, including hydrocarbons and lipids, developed either with tools from synthetic biology or through metabolic engineering (see also IEA, 2011).

2.7.4 Synthesis

Despite the complexities of determining the economic performance and regional specificities of bioenergy systems, several key conclusions can be drawn from available experiences and literature:

- Several important bioenergy systems today can be deployed competitively, most notably sugarcane-based ethanol and heat and power generation from residues and waste.

- Although not all bioenergy options discussed in this chapter have been investigated in detail with respect to technological learning, several important bioenergy systems have reduced their cost and improved environmental performance over time. These systems still

Table 2.18 | Projected production cost ranges estimated for developing technologies (see Section 2.6.3).

Selected Bioenergy Technologies	Energy Sector (Electricity, Thermal, Transport)*	2020-2030 Projected Production Costs (USD_{2005}/GJ)
IGCC [1]	Electricity and/or transport	12.8–19.1 (4.6–6.9 cents/kWh)
Oil plant-based renewable diesel and jet fuel	Transport and electricity	15–30
Lignocellulose sugar-based biofuels[2]	Transport	6–30
Lignocellulose syngas-based biofuels[3]		12–25
Lignocellulose pyrolysis-based biofuels[4]		14–24 (fuel blend components)
Gaseous biofuels[5]	Thermal and transport	6–12
Aquatic plant-derived fuels, chemicals	Transport	30–140

Notes: 1. Feed cost USD_{2005} 3.1/GJ, IGCC (future) 30 to 300 MW, 20-yr life, 10% discount rate; 2. ethanol, butanols, microbial hydrocarbons from sugar or starch crops or lignocellulose sugars; 3. syndiesel, methanol and gasoline, etc.; syngas fermentation routes to ethanol; 4. biomass pyrolysis (or other thermal treatment) and catalytic upgrading to gasoline and diesel fuel blend components or to jet fuels; 5. synfuel to SNG, methane, dimethyl ether, or H_2 from biomass thermochemical and anaerobic digestion (larger scale). *Several applications could be coupled with CCS when these technologies, including CCS, are mature and thus could remove GHGs from the atmosphere.

require government subsidies that are put in place for economic development, poverty reduction, a secure and diverse energy supply, and other reasons.

- There is clear evidence that further improvements in power generation technologies, production of perennial cropping systems and development of supply systems can bring the costs of power (and heat) generation from biomass down to attractive cost levels in many regions. With the deployment of carbon taxes of up to USD_{2005} 50/t, biomass can, in many cases, also be competitive with coal-based power generation. Nevertheless, the competitive production of bio-electricity depends also on the performance of alternatives such as wind and solar energy, CCS coupled with coal, and nuclear energy (see Section 10.2.2.4 and Chapter 8).

- Bioenergy systems for ethanol and biopower production show technological learning and related cost reductions with LRs comparable to those of other RE technologies. This applies to cropping systems (following progress in agricultural management of annual crops), supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics) and in conversion (ethanol production, power generation and biogas).

- With respect to lignocellulosic biofuels, recent analyses have indicated that the improvement potential is large enough to make them competitive with oil prices of USD_{2005} 60 to 70/barrel (USD 0.38 to 0.44/litre). Currently available scenario analyses indicate that if shorter-term R&D and market support are strong, technological progress could allow for commercialization around 2020 (depending on oil price developments and level of carbon pricing). Some scenarios also indicate that this would mean a major shift in the deployment of biomass for energy, because competitive production would decouple deployment from policy targets (mandates) and demand for biomass would move away from food crops to biomass residues, forest biomass and perennial cropping systems. The implications of such a (rapid) shift have not been studied.

- Data about the production of biomaterials and cost estimates for chemicals from biomass are rare in peer-reviewed literature. Future projections and LRs are even rarer, because successful bio-based products are just now entering the market place. Two examples are as partial components of otherwise fossil-derived products (e.g., poly(1,3)-propylene terephthalates based on 1,2-propanediol derived from sugar fermentation) or as fully new synthetic polymers such as polylactides based on lactic acid derived from sugar fermentation. This is also the case for biomass conversion coupled with CCS (see Section 2.6.3.3) concepts, which are not developed at present and for which cost trends are not available in literature. CO_2 from ethanol fermentation is commercially sold to carbonate beverages, flash freeze meats or enhance oil recovery, and demonstrations of CCS are ongoing (see Section 2.6.3.3). Nevertheless, recent scenario analyses indicate that advanced biomaterials (and cascaded use of biomass) as well as other biomass conversion coupled to CCS may become attractive medium-term mitigation options. It is therefore important to gain experience so that more detailed analyses on those options can be conducted in the future.

2.8 Potential Deployment[76]

2.8.1 Current deployment of bioenergy

Modern biomass use (for electricity and CHP for the power sector; modern residential, commercial, and public buildings heating; or transport fuels) already provides a significant contribution of about 11.3 EJ (see Table 2.1; IEA, 2010a,b) out of the 2008 TPES from biomass of 50.3 EJ. Between 60 and 70% of the total biomass supply is used in rural areas and relates to charcoal, wood, agricultural residues and manure used for cooking, lighting and space heating, generally by the poorer part of the population in developing countries. From 1990 to 2008, the

76 Complementary perspectives on potential deployment based on a comprehensive assessment of numerous model-based scenarios of the energy system are presented in Sections 10.2 and 10.3 of this report.

average annual growth rate of solid biomass use for bioenergy was 1.5%, while the average annual growth rate of modern liquid and gaseous biofuels use was 12.1 and 15.4%, respectively, during the same period (IEA, 2010c). As a result, biofuels' share of global road transport fuels was about 2% in 2008; and nearly 3% of global road transport fuels in 2009, as oil demand decreased for the first time since 1980 (IEA, 2010b). Government policies in various countries fostered the five-fold increase in global biofuels production from 2000 to 2008. Biomass and renewable waste power generation was 259 TWh (0.93 EJ) in 2007 and 267 TWh (0.96 EJ) in 2008, representing 1% of the world's electricity and a doubling since 1990 (from 131 TWh, 0.47 EJ) (Section 2.4.1). Modern bioenergy heating applications, including space and hot water heating systems such as for district heating, account for 3.4 EJ (see Table 2.1 and Section 2.4.1).

International trade in biomass and biofuels has also become much more important over the recent years, with roughly 6% (reaching levels of up to 9% in 2008) of biofuels (ethanol and biodiesel only) traded internationally and one-third of pellet production dedicated to energy use in 2009 (Figures 2.8 and 2.9; Junginger et al., 2010; Lamers et al., 2010; Sikkema et al., 2011). The latter has proven to be an important facilitating factor in both increased utilization of biomass in regions where supplies are constrained and mobilizing resources from areas where demand is lacking.

The policy context for bioenergy and particularly biofuels has changed rapidly and dramatically since the mid-2000s in many countries. The food versus fuel debate and growing concerns about other conflicts created a strong push for the development and implementation of sustainability criteria and frameworks and changes in temporization of targets for bioenergy and biofuels. Furthermore, the support for advanced biorefinery and second-generation biofuel options drives bioenergy in more sustainable directions.

Nations like Brazil, Sweden, Finland and the USA have shown that persistent and stable policy support is a key factor in building biomass production capacity and working markets, required competitive infrastructure and conversion capacity (see also Section 2.4) and results in considerable economic activity.

2.8.2 Near-term forecasts

Countries differ in their priorities, approaches, technology choices and support schemes for bioenergy development. Although on the one hand complex for the market, this is also a reflection of the many aspects that affect bioenergy deployment: agriculture and land use; forestry and industry development; energy policy and security; rural development; and environmental policies. Priorities, the stage of technology development, and access to, availability of and cost of resources differ widely from country to country and in different settings.

The near-term forecasts reflect that the policies already in place, as shown in Table 2.11, are driving current forecasts. For instance, the WEO (IEA, 2010b) projects that the bioenergy industry will continue the growth observed in the past five years and reach about 60 EJ by 2020 in the Current Policies scenario (which replaces the former Reference scenario), with slightly higher levels of up to 63 EJ in the more ambitious New Policies and 450-ppm CO_2 scenarios (Section 2.4.1). Considering the 2008 starting point at 50 EJ/yr, this represents a 10 to 13 EJ increase in bioenergy consumption over 10 years. Much of the increase happens in the transport sector, with biofuel consumption starting from 2.1 EJ in 2009 and increasing to 4.5 to 5.1 EJ in 2020 in the three presented scenarios. Most of this growth is therefore already expected due to existing policies, and additional growth relying on new policies is expected to only foster an additional 10% increase. The global primary biomass supply (efficiency of about 65% for first-generation biofuels) needed to deliver this amount of biofuels ranges between 7.4 and 8.4 EJ. The increase at the global level goes along with further regional diversification of biofuels adoption. While the currently dominant biofuels markets in Brazil, the USA and the EU are projected to roughly double consumption by 2020, many other regions with very little or no biofuels consumption currently are expected to adopt biofuel policies, resulting in significant growth, most notably in Asia. Electricity generation increases by 85% from 265 TWh/yr (0.96 EJ/yr) in 2008 to 493 TWh/yr (1.8 EJ/yr) in the Current Policies scenario, again with relatively modest additional growth (20%) in the more ambitious policy scenarios (up to 594 TWh/yr or 2.1 EJ/yr) (Table 2.10).

2.8.3 Long-term deployment in the context of carbon mitigation

The AR4 (IPCC, 2007d) demand projections for primary biomass for production of transportation fuel were largely based on WEO (IEA, 2006) global projections, with a relatively wide range of about 14 to 40 EJ of primary biomass, or 8 to 25 EJ of biofuels in 2030. However, higher estimates were also included, in the range of 45 to 85 EJ of demand for primary biomass for electricity generation in 2030 (equivalent to roughly 30 to 50 EJ of biofuel). Demand for biomass for heat and power was stated to be strongly influenced by (availability and introduction of) competing technologies such as CCS, nuclear power and non-biomass RE. The demand in 2030 for biomass was estimated in the AR4 to be around 28 to 43 EJ. These estimates focus on electricity generation. Heat was not explicitly modelled or estimated in the WEO (on which the AR4 was based); therefore it underestimates total demand for biomass. Also, potential future demand for biomass in industry (especially new uses such as biochemicals, but also expansion of charcoal use for iron and steel production) and the built environment (heating as well as increased use of biomass as building material) was highlighted as important, but no quantitative projections were included in potential demand for biomass at the medium or longer term.

A summary of the literature on the possible future contribution of RE supplies in meeting global energy needs under a range of GHG stabilization scenarios is provided in Chapter 10. Focussing specifically on bioenergy, Figure 2.23 presents modelling results for global primary energy supply from biomass (a) and global biofuels production in secondary energy terms (b). Between about 100 and 140 different long-term scenarios underlie Figure 2.23 (Section 10.2). These scenario results derive from a diversity of modelling teams and cover a wide range of assumptions about—among other variables—energy demand growth, the cost and availability of competing low-carbon technologies and the cost and availability of RE technologies (including bioenergy). A description of the literature from which the scenarios have been taken (Section 10.2.2) and how changes in some of these variables impact RE deployment outcomes are displayed in Figure 10.9.

in most scenarios, which means that modern use of biomass as liquid biofuels, biogas, and electricity and H_2 produced from biomass tends to increase even more strongly than suggested by the above primary energy numbers. This trend is also illustrated by the example of liquid biofuels production shown in the right panel of Figure 2.23(b). With increasingly ambitious GHG concentration stabilization levels, bioenergy supply increases, indicating that bioenergy could play a significant long-term role in reducing global GHG emissions. The median levels of biomass deployment for energy in the most stringent mitigation categories I and II (<440 ppm atmospheric CO_2 concentration by 2100) increase significantly compared to the baseline levels to 63, 85 and 155 EJ/yr by 2020, 2030 and 2050, respectively.

Despite these robust trends, there is by no means an agreement about

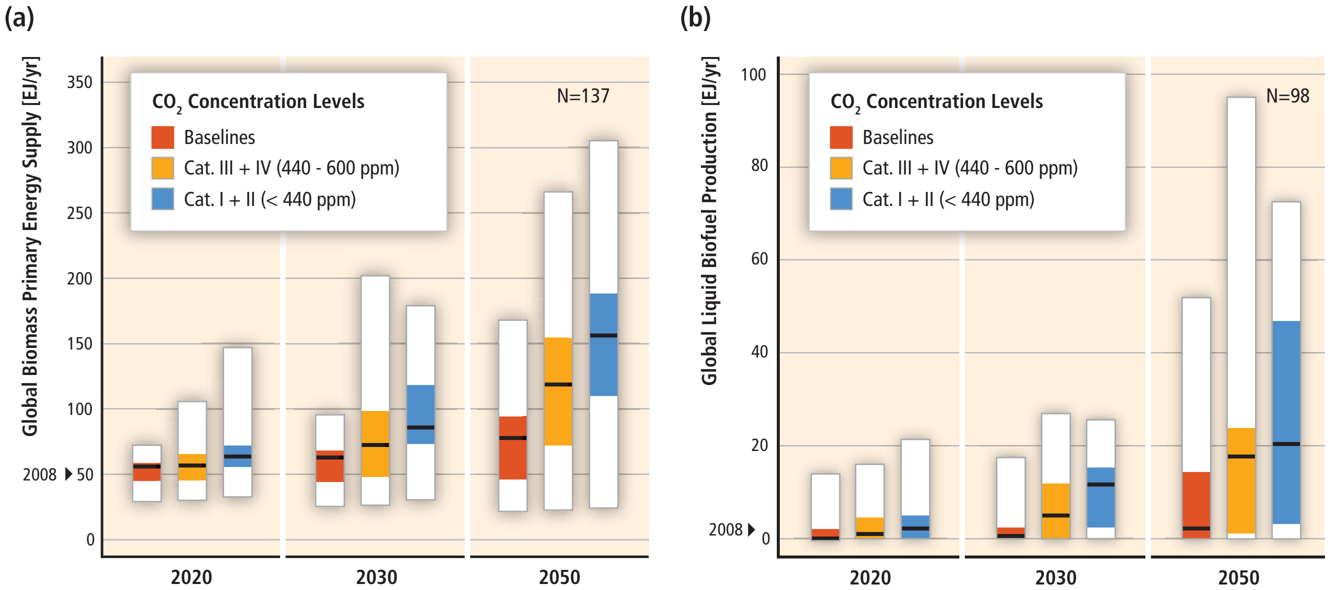
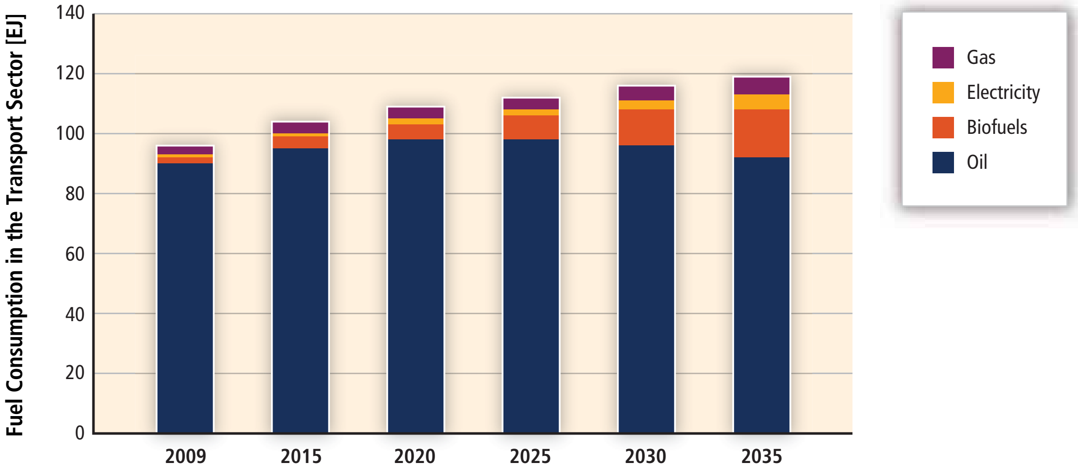


Figure 2.23 | (a) The global primary energy supply from biomass in long-term scenarios; (b) global biofuels production in long-term scenarios reported in secondary energy terms of the delivered product (median, 25th to 75th percentile range and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration levels in 2100; the number of scenarios underlying the figure is indicated in the right upper corner) (adapted from Krey and Clarke, 2011). For comparison, the historic levels in 2008 are indicated by the small black arrows on the left axis.

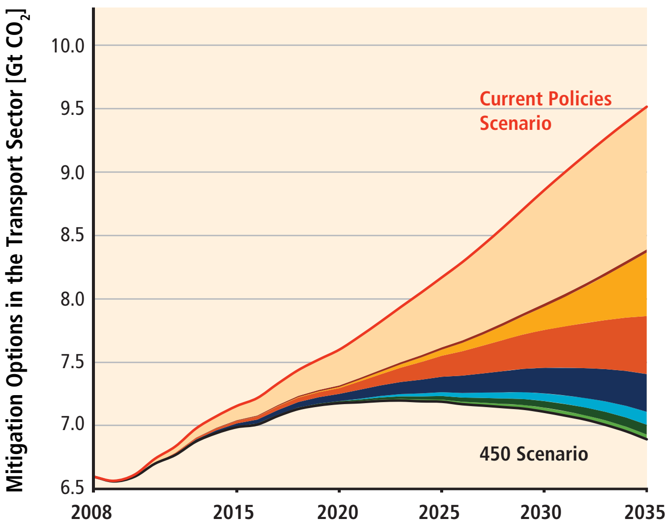
In Figure 2.23, the results for biomass deployment for energy under these scenarios for 2020, 2030 and 2050 are presented for three GHG stabilization ranges based on the AR4: Categories I and II (<440 ppm CO_2), Categories III and IV (440-600 ppm CO_2) and Baselines (>600 ppm CO_2) all by 2100. Results are presented for the median scenario, the 25th to 75th percentile range among the scenarios, and the minimum and maximum scenario results. Figure 2.23(a) shows a clear increase in global primary energy supply from biomass over time in the baseline scenarios, that is, absent climate policies, reaching about 55, 62 and 77 EJ/yr in the median cases by 2020, 2030 and 2050, respectively. At the same time, traditional use of solid biomass is projected to decline

the precise future role of bioenergy across the scenarios, leading to fairly wide deployment ranges in the different GHG stabilization categories. For 2030, primary biomass supply estimates for energy vary (rounded) between 30 and 200 EJ for the full range of results obtained. The 25th to 75th percentiles cover a range of 45 to 120 EJ, with a comparatively narrower range of 44 to 67 EJ/yr in the baselines and much wider ranges of 47 to 98 EJ/yr in the 440 to 600 ppm stabilization category and 73 to 120 EJ/yr in the <440 ppm category. By 2050, the contribution of biomass to primary energy supply in the two GHG stabilization categories ranges from 70 to 120 EJ/yr at the 25th percentile to about 150 to 190 EJ/yr at the 75th percentile, and to about 265-300 EJ/yr in the highest ranges. It should be noted that the net GHG mitigation impact of

(a)



(b)



	Abatement 2020	2030	2035
Road	83%	80%	80%
Increased Efficiency	67%	51%	43%
Switch to Gas	3%	1%	1%
Switch to Electricity	2%	11%	19%
Switch to Biofuels	11%	17%	17%
Aviation	14%	15%	15%
Increase Efficiency	14%	12%	11%
Switch to Biofuels	0%	3%	4%
Navigation	2%	3%	3%
Other Transport	2%	2%	1%
Total [Gt CO_2]	0.4	1.7	2.6

Figure 2.24 | (a) Evolution of fuel consumption in the transport sector including biofuels (*World Energy Outlook 2010*, © OECD/IEA, figure 14.12, page 429 in IEA (2010b)) and (b) shares of carbon mitigation by various technologies including biofuels for road and aviation transport from current policies baseline (upper red line) to the 450 ppm bottom curve of the mitigation scenario. (*World Energy Outlook 2010*, © OECD/IEA, figure 14.14, page 432 in IEA (2010b))

bioenergy deployment is not straightforward because different options result in different GHG savings, and savings depend on how land use is managed, which is a central reason for the wide ranges in the stabilization scenarios.

The sector-level penetration of bioenergy is best explained using a model with detailed transport sector representation such as the WEO (IEA, 2010b) that is also modelling both traditional and modern biomass applications, and includes second-generation biofuels evolution. Additionally, the WEO model takes into account anticipated industrial and government investments and goals. It projects very significant increases in modern bioenergy and a decrease in traditional biomass use, in qualitative agreement with the results from Chapter 10. By 2030, for the 450-ppm mitigation scenario, the model projects that 11% of global transport fuels will be provided by biofuels with second-generation biofuels contributing 60% of the projected 12 EJ, and half of this production is projected to be supplied owing to continuation of current policies (see Table 2.9). Biomass and renewable wastes would supply 5% of the world's electricity generation, or 1,380 TWh/yr (5 EJ/yr) of which 555 TWh/yr (2 EJ/yr) result from the 450 ppm strategy by 2030 (see Table 2.10). Biomass industrial heating applications for process steam and space and hot water heating for buildings would each double in absolute terms from 2008 levels. However, the total heating demand is projected to decrease because of assumed traditional biomass decline. Heating is seen as a key area for continued modern bioenergy growth.

The evolution of biofuels in the transport sector is shown in Figure 2.24a. Biofuels penetration is projected to be significant in both in global road transport and in air transport. Second-generation technologies are projected to provide 66% of the biofuels by 2035 and 14% of world transport energy demand in the 450-ppm scenario (see Figure 2.24a and Table 2.9). Figure 2.24b shows the projected GHG emissions mitigation of biofuels relative to projected road and air transport applications from the current policies to the 450 ppm scenario. For instance, by 2030, 17% of road transport emissions and 3% of air transport emissions could be mitigated by biofuels in the 450-ppm stabilization scenario. A biofuels technology roadmap was recently developed (IEA, 2011).

The potential demand of biomass for materials is not explicitly addressed by many of the scenarios, but it could become significant and add up to several dozens of EJ (Section 2.6.3.5; Hoogwijk et al., 2003).

The expected deployment of biomass for energy in the 2020 to 2050 time frame differs considerably between studies, also due to varying detail in bioenergy system representation in the relevant models. A key message from the review of available insights is that large-scale biomass deployment strongly depends on sustainable development of the resource base, governance of land use, development of infrastructure and cost reduction of key technologies, for example, efficient and complete use of primary biomass for energy from the most promising first-generation feedstocks and second-generation lignocellulosic biomass. The results discussed above are consistent with the *Energy Technology Perspectives* report (IEA, 2008a), which projects a rapid penetration of second-generation biofuels after 2010 and an almost complete phase-out of cereal- and corn-based ethanol production and oilseed-based biodiesel after 2030.[77]

2.8.4 Conditions and policies: Synthesis of resource potentials, technology and economics, and environmental and social impacts of bioenergy

2.8.4.1 Resource potentials

The inherent complexity of biomass resources makes the assessment of their combined technical potential controversial and difficult to characterize. Literature studies range from zero (no biomass potential available as energy) to around 1,500 EJ, the theoretical potential for terrestrial biomass based on modelling studies exploring the widest potential ranges of favourable conditions (Smeets et al., 2007).

Figure 2.25 presents a summary of technical potential found in major studies, including potential deployment data from the scenario analysis of Chapter 10 compared to global TPES (projections). To put technical potential in perspective, because global biomass used for energy currently amounts to approximately 50 EJ/yr, and all harvested biomass used for food, fodder, fibre and forest products, when expressed in equivalent heat content, equals 219 EJ/yr (2000 data, Krausmann et al., 2008), the entire current global biomass harvest would be required to achieve a 200 EJ/yr deployment level of bioenergy by 2050 (Section 2.2.1).

From a detailed assessment, the upper-bound technical potential of biomass was about 500 EJ with a minimum of about 50 EJ in the case that even residues had significant competition with other uses. The assessment of each contributing category performed by Dornburg et al. (2008, 2010) was based on literature up to 2007 (stacked bar of Figure 2.25) and is roughly in line with the conditions sketched in the IPCC SRES A1 and B1 storylines (IPCC, 2000), assuming sustainability and policy frameworks to secure good governance of land use and major improvements in agricultural management (summarized in Figure 2.26). The resources used are:

- Residues originating from forestry, agriculture and organic wastes (including the organic fraction of MSW, dung, process residues etc.) were estimated at around 100 EJ/yr. This part of the technical potential of biomass supply is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range.
- Surplus forestry other than from forestry residues had an additional technical potential of about 60 to 100 EJ/yr.
- Biomass produced via cropping systems had a lower range estimate for energy crop production on possible surplus good quality agricultural and pasture lands of 120 EJ/yr. The potential contribution of water-scarce, marginal and degraded lands could amount to an additional 70 EJ/yr, corresponding to a large area where water scarcity provides limitations and soil degradation is more severe. Assuming strong learning in agricultural technology leading to improvements in agricultural and livestock management would add 140 EJ/yr.

Adding these categories together leads to a technical potential of up to about 500 EJ in 2050, with temporal data on the development of biomass potential ramping from 290 to 320 EJ/yr in 2020 to 330 to 400 EJ/yr in 2030 (Hoogwijk et al., 2005, 2009; Dornburg et al., 2008, 2010).

From the expert review of available scientific literature in this chapter, *potential deployment levels of biomass for energy by 2050 could be in the range of 100 to 300 EJ* (Sections 2.2.1, 2.2.2, and 2.2.5).

Values in this range are described in van Vuuren et al. (2009), which focused on an intermediate development scenario within the SRES scenario family. The lower estimates of Smeets et al. (2007) and Hoogwijk et al. (2005, 2009) are in line with those figures, and further confirmation for such a range is given by Beringer et al. (2011), who report a 26 to 116 EJ range for energy crops alone in 2050 without irrigation (and 52 to 174 EJ with irrigation), and Haberl et al. (2010), who report 160 to 270 EJ/yr in 2050 across all biomass categories. Krewitt et al. (2009), following Seidenberger et al. (2008), also estimated the technical potential to be 184 EJ/yr in 2050 using strong sustainability

77 Contrast these projections with the 2007 and 2008 WEO studies (IEA, 2007b, 2008b), where second-generation biofuels were excluded from the scenario analysis and thus biofuels at large played a marginal role in the 2030 projections.

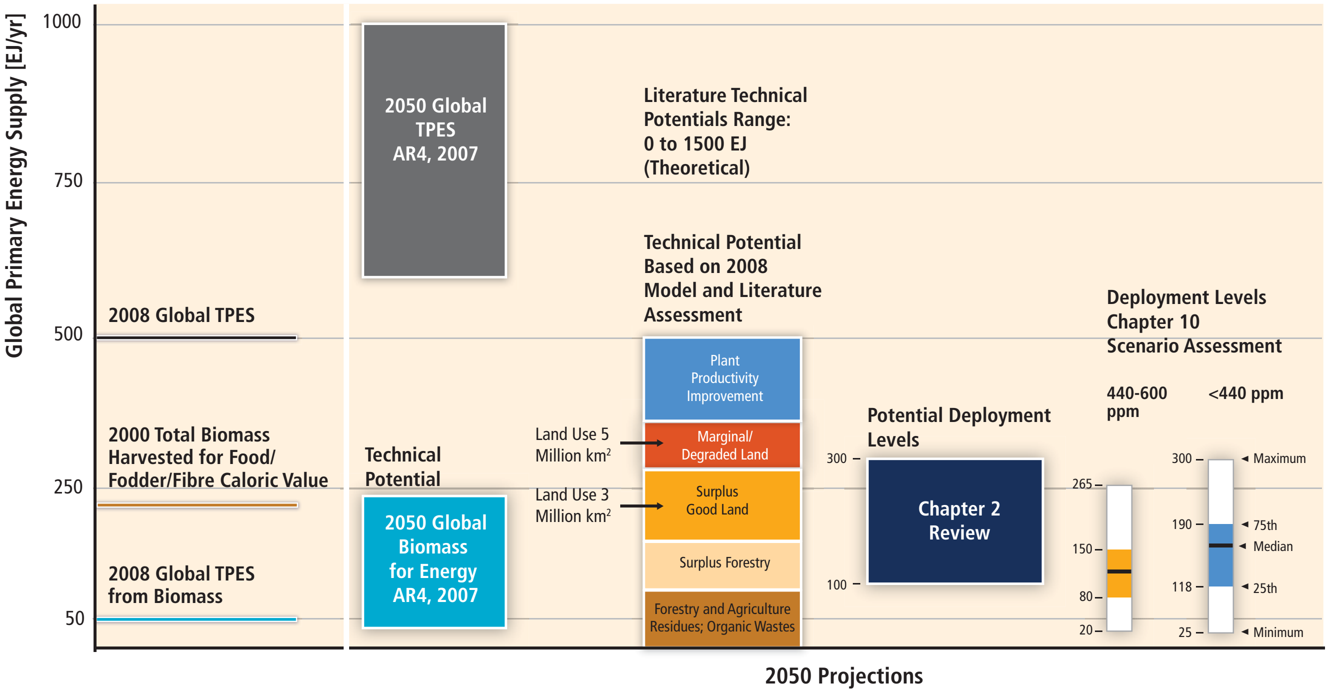


Figure 2.25 | On the left-hand side, the lines represent the 2008 global primary energy supply from biomass, the primary energy supply, and the equivalent energy of the world's total harvest for food, fodder and fibre in 2000. A summary of major global 2050 projections of primary energy supply from biomass is shown from left to right: (1) The global AR4 (IPCC, 2007d) estimates for primary energy supply and technical potential for primary biomass for energy; (2) the theoretical primary biomass potential for energy and the upper bound of biomass technical potential based on integrated global assessment studies using five resource categories indicated on the stacked bar chart and limitations and criteria with respect to biodiversity protection, water limitations, and soil degradation, assuming policy frameworks that secure good governance of land use (Dornburg et al., 2010, reproduced with permission from the Royal Society of Chemistry); (3) from the expert review of available scientific literature, potential deployment levels of terrestrial biomass for energy by 2050 could be in the range of 100 to 300 EJ; and (4) deployment levels of biomass for energy from long-term scenarios assessed in Chapter 10 in two cases of climate mitigation levels (CO_2 concentrations by 2100 of 440 to 600 ppm (orange) or <440 ppm (blue) bars or lines, see Figure 2.23(a)). Biomass deployment levels for energy from model studies described in (4) are consistent with the expert review of potential biomass deployment levels for energy depicted in (3).The most likely range is 80 to 190 EJ/yr with upper levels in the range of 265 to 300 EJ/yr.

criteria and including 88 EJ/yr from residues. They project a ramping-up to this potential from around 100 EJ/yr in 2020 and 130 EJ/yr in 2030.

The expert review conclusions based on available scientific literature (Sections 2.2.2 through 2.2.5) are:

- Important uncertainties include:
  - Population and economic/technology development; food, fodder and fibre demand (including diets); and development in agriculture and forestry;
  - Climate change impacts on future land use including its adaptation capability (IPCC, 2007a; Lobell et al., 2008; Fischer et al., 2009); and
  - Extent of land degradation, water scarcity, and biodiversity and nature conservation requirements (Molden, 2007; Bai et al., 2008; Berndes, 2008a,b; WBGU, 2009; Dornburg et al., 2010; Beringer et al., 2011).
- Residue flows in agriculture and forestry and unused (or extensively used thus becoming marginal/degraded) agricultural land are important sources for expansion of biomass production for energy, both in the near and longer term. Biodiversity-induced limitations and the need to ensure maintenance of healthy ecosystems and avoid soil degradation set limits on residue extraction in agriculture and forestry (Lal, 2008; Blanco-Canqui and Lal, 2009; WBGU, 2009).
- The cultivation of suitable (especially perennial) crops and woody species can lead to higher technical potential. These crops can produce bioenergy on lands less suited for the cultivation of conventional food crops that would also lead to larger soil carbon emissions than perennial crops and woody species. Multi-functional land use systems with bioenergy production integrated into agriculture and forestry systems could contribute to biodiversity conservation and help restore/maintain soil productivity and healthy ecosystems (Hoogwijk et al., 2005; Berndes et al., 2008; Folke et al., 2009; IAASTD, 2009; Malézieux et al., 2009; Dornburg et al., 2010).

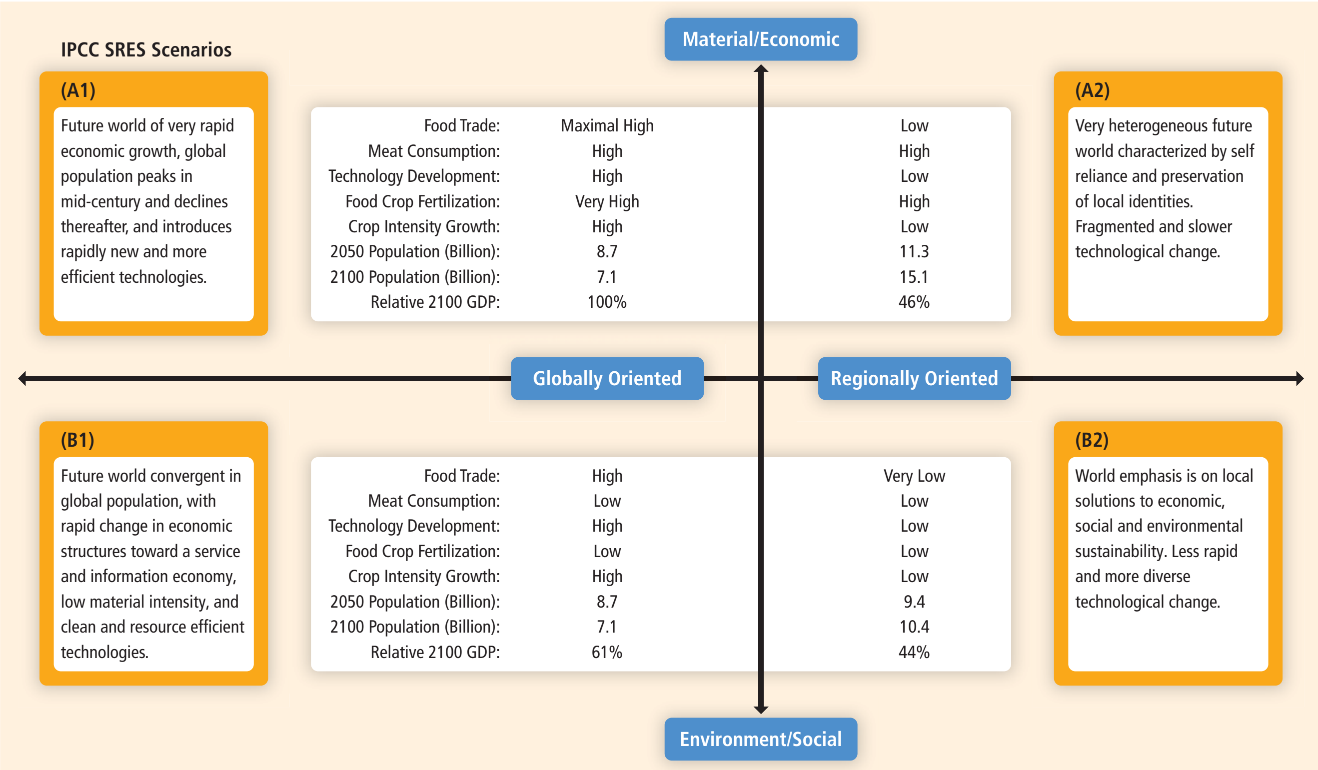


Figure 2.26 | Storylines for the key scenario variables of the IPCC SRES (IPCC, 2000) used to model biomass and bioenergy by Hoogwijk et al. (2005, reproduced with permission from Elsevier B.V.), the basis for the 2050 sketches adapted for this report and used to derive the stacked bar showing the upper bound of the biomass technical potential for energy in Figure 2.25.

- Regions experiencing water scarcity may have limited production. The possibility that conversion of lands to biomass plantations reduces downstream water availability needs to be considered. The use of suitable energy crops that are drought tolerant can help adaptation in water-scarce situations. Assessments of biomass resource potentials need to more carefully consider constraints and opportunities in relation to water availability and competing uses (Jackson et al., 2005; Zomer et al., 2006; Berndes et al., 2008; de Fraiture and Berndes, 2009).

To reach the *upper range of the deployment level* of 300 EJ/yr shown in Figure 2.25 would require major policy efforts, especially targeting improvements and efficiency increases in the agricultural sector and good governance, such as zoning, of land use.

Review scenario studies (as included in Dornburg et al., 2008) that calculate the amount of biomass used if energy demands are supplied cost-efficiently for different carbon tax regimes estimate that in 2050, between about 50 and 250 EJ/yr of biomass are used (cf. Figure 2.25). This is roughly in line with the scenarios reviewed in Chapter 10 (see Figure 2.23, which shows that the maximum demand is 300 EJ and the median value is about 155 EJ; note that the high end is only reached under the stringent mitigation scenarios of Categories I+II (<440 ppm CO_2) only).

2.8.4.2 Bioenergy technologies, supply chains and economics

A wide array of technologies and bioenergy systems exist to produce heat, electricity and fuels for transport, at commercial or development stages. Furthermore, biomass conversion to energy can be integrated with the production of biomaterials and biochemicals in cascading schemes that maximize the outputs of end products per unit input feedstock and land used.

The key currently commercial technologies are heat production at scales ranging from home cooking to district heating; power generation from biomass via combustion, CHP, or co-firing of biomass and fossil fuels; and first-generation liquid biofuels from oil crops (biodiesel) and sugar and starch crops (ethanol).

Modern biomass systems involve a wide range of feedstock types, including dedicated crops or trees, residues from agriculture and forestry, and various organic waste streams. Existing bioenergy systems rely mostly on wood, residues and waste for heat and power production and agricultural crops for liquid biofuels. The economics and yields of feedstocks vary widely across world regions and feedstock types. Energy yields per unit area range from 16 to 200 GJ/ha (1.6 to 20.0 TJ/km²) for crops and oil seeds (biofuel feedstocks), from 80 to 415 GJ/ha (8.0 to 41.5 TJ/km²) for lignocellulosic biomass, and from 2 to 155 GJ/ha

(0.2 to 15.5 TJ/km²) for residues, while costs range from USD_{2005} 0.9 to 16/GJ (data from 2005 to 2007). Feedstock production competes with the forestry and food sectors, but integrated production systems such as agro-forestry or mixed cropping may provide synergies along with additional environmental services.

Handling and transport of biomass from production sites to conversion plants may contribute 20 to up to 50% of the total costs of biomass production. Factors such as scale increase, technological innovations and increased competition contributed to decrease the economic and energy costs of supply chains by more than 50%. Densification via pelletization or briquetting is required for transportation distances over 50 km. Charcoal made from biomass is a major fuel in developing countries, and it should benefit from the adoption of higher-efficiency kilns.

Different end-use applications require that biomass be processed through a variety of conversion steps depending on the physical nature and the chemical composition of feedstocks. Costs vary by world regions, feedstock types, feedstock supply costs for conversion processes, the scale of bioenergy production, and production time during the year. Examples of estimated commercial bioenergy levelized cost ranges are roughly USD 2 to 48/GJ for liquid and gaseous biofuels; roughly US $cents_{2005}$ 3.5 to 25/kWh (USD_{2005} 10 to 50/GJ) for electricity or CHP systems larger than about 2 MW (with feedstock costs of USD_{2005} 3/GJ based on high heating value and a heat value of USD_{2005} 5/GJ (steam) or USD_{2005} 12/GJ (hot water)); and roughly USD_{2005} 2 to 77/GJ for domestic or district heating systems with feedstock costs in the range of USD_{2005} 0 to 20/GJ (solid waste to wood pellets). These calculations refer to 2005 to 2008 data and are expressed in USD_{2005} at a 7% discount rate. Several bioenergy systems have deployed competitively, most notably sugarcane ethanol and heat and power generation from wastes and residues. Other biofuels have also undergone cost and environmental impact reductions but still require government subsidies.

In the medium term, the performance of existing bioenergy technologies can still be improved considerably, while new technologies offer the prospect of more efficient and competitive deployment of biomass for energy (as well as materials). Bioenergy systems, namely for ethanol and biopower production, show rates of technological learning and related cost reductions with learning comparable to those of other RE technologies. This applies to cropping systems (following progress in agricultural management when annual crops are concerned), to supply systems and logistics (as clearly observed in Scandinavia, as well as international logistics) and in conversion (e.g., ethanol production, power generation and biogas). Although not all bioenergy options discussed in this chapter have been investigated in detail with respect to technological learning, several important bioenergy systems have reduced their cost and improved environmental performance (Sections 2.3.4.2 and 2.7.2; Table 2.13). However, they usually still require government subsidies provided for economic development, poverty reduction and a secure energy supply or other country-specific reasons.

There is clear evidence that further improvements in power generation technologies (e.g., via biomass IGCC technology), supply systems for biomass, and production of perennial cropping systems can bring the costs of power (and heat or fuels) generation from biomass down to attractive cost levels in many regions. Nevertheless, the competitive production of bio-electricity (through methane or biofuels) depends on the integration with the end-use systems (Sections 8.2 and 8.3), performance of alternatives such as wind and solar energy, developing CCS technologies coupled with coal conversion, and nuclear energy (Sections 10.2.2.4, 10.2.2.6, 9.3, and 9.4). The implications of successful deployment of CCS in combination with biomass conversion could result in removal of GHG from the atmosphere and attractive mitigation cost levels but have so far received limited attention (Section 2.6.3.3).

With respect to lignocellulosic biofuels, recent analyses have indicated that the improvement potential is large enough for competition with oil at oil prices of USD_{2005} 60 to 80/barrel (USD_{2005} 0.38 to 0.44/litre). Currently available scenario analyses indicate that if shorter-term R&D and market support is strong, technological progress could allow for their commercialization around 2020 (depending on oil and carbon prices). Some scenarios also indicate that this would mean a major shift in the deployment of biomass for energy, because competitive production would decouple deployment from policy targets (mandates), and demand for biomass would move away from food crops to biomass residues, forest biomass and perennial cropping systems. The implications of such a (rapid) shift are so far poorly studied.

Integrated biomass gasification is a major avenue for the development of a variety of biofuels, with equivalent properties to gasoline, diesel and jet fuel (see Table 2.15.C for composition of hydrocarbon fuels). An option highlighted as promising in the literature is fuel product generation passing syngas through the catalytic reactor only once with the unreacted gas going to the power generation system instead of being recycled through the catalytic reactor. Other hybrid biochemical and thermochemical concepts have also been contemplated (Laser et al., 2009). Biomass pyrolysis routes and hydrothermal concepts are also developing in conjunction with the oil industry and have demonstrated that upgrading of oils to blendstocks of gasoline or diesel or even jet fuel quality products is technically possible (IATA, 2009).

Lignocellulosic ethanol development and demonstration continues in several countries. A key development step is pretreatment to overcome the recalcitrance of the cell wall of woody, herbaceous or agricultural residues to release the simple sugar components of biomass polymers and lignin. A review of the progress in this area suggests that a 40% reduction in cost could be expected by 2025 from process improvements, which would bring down the estimated cost of pilot plant production from USD_{2005} 18 to 22/GJ to USD_{2005} 12 to 15/GJ (Hamelinck et al., 2005a; Foust et al., 2009; NRC, 2009a) and into a competitive range.

Photosynthetic organisms, such as algae, use CO_2, water, and sunlight to biologically produce a variety of carbohydrates and lipids, chemicals, fuels like H_2, other molecules and oxygen with high photosynthetic efficiency and possibly high potentials (Sections 2.6.1, 3.3.5 and 3.7.6). Estimates of potential bioenergy supply from aquatic plants are very uncertain because of the lack of sufficient data for their assessment (Kheshgi et al., 2000; Smeets et al., 2009). Nevertheless these species need to be explored further because their development can utilize brackish waters and heavily saline soils and thus represent a strategy for low LUC impacts (Chisti, 2007; Weyer et al., 2009). The prospects of algae-based fuels and chemicals are at this stage uncertain, with wide ranges for potential production costs reported in the literature.

Data availability is limited with respect to production of biomaterials; cost estimates for chemicals from biomass are rare in the peer-reviewed literature, and future projections and LRs are even rarer. This condition is linked, in part, to the fact that successful bio-based products are entering the market place either as partial components of otherwise fossil-derived products or as fully new synthetic polymers, such as polylactides based on lactic acid derived from sugar fermentation. Analyses indicate that, in addition to producing biomaterials to replace fossil fuels, cascaded use of biomaterials and subsequent use of waste material for energy can offer more effective and larger mitigation impacts per hectare or tonne of biomass used (e.g., Dornburg and Faaij, 2005).

The benefits of biomass gasification and CCS alone or with coal are significant (see Figures 2.10 and 2.11). Similarly, capturing CO_2 from fermentation processes offers a significant option in many regions of the world, and coupling with CCS may become an attractive medium-term mitigation option. However, such concepts are not deployed at present and cost trends are not available in the literature, making investments in biomass (or coal) gasification technologies risky. Also, geologic sequestration reliability and the uncertainty of the regulatory environment pose further barriers. More detailed analysis is desired in this field.

2.8.4.3 Social and environmental impacts

The effects of bioenergy on social and environmental issues—ranging from health and poverty to biodiversity and water quality—may be positive or negative depending upon local conditions, the specific feedstock production system and technology paths chosen, how criteria and the alternative scenarios are defined, and how actual projects are designed and implemented, among other variables (Sections 9.2 through 9.5). Perhaps most important is the overall management and governance of land use when biomass is produced for energy on top of meeting food and other demands from agricultural production (as well as livestock). In cases where increases in land use due to biomass production are balanced out by improvements in agricultural management, undesirable iLUC effects can be avoided, while if unmanaged, conflicts may emerge. The overall performance of bioenergy production systems is therefore interlinked with management of land use and water resources. Trade-offs between those dimensions exist and need to be resolved through appropriate strategies and decision making. Such strategies are currently emerging due to many efforts targeting the deployment of sustainability frameworks and certification systems for bioenergy production (see also Section 2.4.5), setting standards for GHG performance (including LUC effects), addressing environmental issues and taking into consideration a number of social aspects.

Most bioenergy systems can contribute to climate change mitigation if they replace fossil-based energy that was causing high GHG emissions and if the bioenergy production emissions—including those arising due to LUC or temporal imbalance of terrestrial carbon stocks—are kept low (examples given in Sections 2.3 and 2.6). High N_2O emissions from feedstock production and the use of high carbon intensity fossil fuels in the biomass conversion process can strongly impact the GHG savings. Best fertilizer management practices, process integration minimizing losses, surplus heat utilization, and biomass use as a process fuel can reduce GHG emissions. But in cold climates the displacement efficiency (see Section 2.5.3) can become low when biomass is used both as feedstock and as fuel in the conversion process.

Given the lack of studies on how biomass resources may be distributed over various demand sectors, no detailed allocation of the different biomass supplies for various applications is suggested here. Furthermore, the net avoidance costs per tonne of CO_2 for biomass usage depend on various factors, including the biomass resource and supply (logistics) costs, conversion costs (which in turn depend on availability of improved or advanced technologies) and fossil fuel prices, most notably of oil.

A GHG performance evaluation of key biofuel production systems deployed today and possible second-generation biofuels using different calculation methods is available (Sections 2.5.2, 2.5.3 and 9.3.4; Hoefnagels et al., 2010). Recent insights converge by concluding that well-managed bioenergy production and utilization chains can deliver high GHG mitigation percentages (80 to 90%) compared to their fossil counterparts, especially for lignocellulosic biomass used for power generation and heat and, when the technology would be commercially available, for lignocellulosic biofuels. The use of most residues and organic wastes, principally animal residues, for energy result in such good performance. Also, most current biofuel production systems have positive GHG balances, and for some of them this situation persists even when significant iLUC effects are incorporated (see below).

LUC can strongly affect those scores, and when conversion of land with large carbon stocks takes place for the purpose of biofuel production, emission benefits can shift to negative levels in the near term. This is most extreme for palm oil-based biodiesel production, where extreme carbon emissions are obtained if peatlands are drained and converted to oil palm (Wicke et al., 2008). The GHG mitigation effect of biomass use for energy (and materials) therefore strongly depends on location (in particular avoidance of converting carbon-rich lands to carbon-poor cropping systems), feedstock choice and avoiding iLUC (see below). In contrast, using perennial cropping systems can store large amounts of carbon and enhance sequestration on marginal and degraded soils, and biofuel production can replace fossil fuel use. Governance of land use, proper zoning and choice of biomass production systems are therefore key factors to achieve good performance.

The assessment of available iLUC literature (Figures 2.13, 9.10, and 9.11) indicated that initial models were lacking in geographic resolution, leading to higher proportions than necessary of land use assigned to deforestation, as the models did not have other kinds of lands (e.g., pastures in Brazil) for use. While the early paper of Searchinger et al. (2008) claimed an iLUC factor of 0.8 (losing 0.8 ha of forest land for each hectare of land used for bioenergy), later (2010) studies that coupled macro-economic to biophysical models tuned that down to 0.15 to 0.3 (see, e.g., Al-Riffai et al., 2010). Models used to estimate iLUC effects vary in their estimates of land displacement. Partial and general equilibrium models have different assumptions and reflect different time frames, and thus they incorporate more or less adjustment. More detailed evaluations (e.g., Al-Riffai et al., 2010; Lapola et al., 2010; see Section 2.5.3) do estimate significant iLUC impacts but also suggest that any iLUC effect strongly (up to fully) depends on the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. This balance in development is also the basis for the recent European biomass resource potential analysis, for which expected gradual productivity increments in agriculture are the basis for possible land availability (as reported in Fischer et al. (2010) and de Wit and Faaij (2010); see Figure 2.5(a)) minimizing competition with food (or nature) as a starting point. Increased model sophistication to adapt to the complex type of analysis required and improved data on the actual dynamics of land distribution in the major biofuel-producing countries are now producing results that show lower overall LUC impacts (Figure 9.11) and acknowledge that land use management at large is key (Berndes et al., 2010).

Bioenergy projects can result in gains or losses in associated biospheric stocks and in both direct and indirect LUC, the latter being inherently difficult to quantify. Even so, it can be concluded that LUC can affect GHG balances in several ways, with beneficial or detrimental outcomes for bioenergy's contribution to climate change mitigation, depending on conditions and context. When land high in carbon (notably forests and especially peat soil forests) is converted to bioenergy, upfront emissions may cause a time lag of decades to centuries before net emission savings are achieved. But the establishment of bioenergy plantations can also lead to assimilation of CO_2 into soils and aboveground biomass in the short term. Increased utilization of forest biomass can reduce forest carbon stocks. The longer-term net effect on forest carbon stocks can be positive or negative depending on natural conditions (including disturbances such as insect outbreaks and fires) and forest management practices. The use of post-consumer organic waste and by-products from the agricultural and forest industries does not cause LUC if these biomass sources were not utilized for alternative purposes. Bioenergy feedstocks can be produced in combination with food and fibre, avoiding land use displacement and improving the productive use of land. Lignocellulosic feedstocks for bioenergy can decrease the pressure on prime cropping land. Stimulation of increased productivity in all forms of land use reduces the LUC pressure.

Air pollution effects of bioenergy depend on both the bioenergy technology (including pollution control technologies) and the displaced energy technology (e.g., inefficient coal versus modern natural gas combustion) (Figure 9.12). Improved biomass cookstoves for traditional biomass use can provide large and cost-effective mitigation of GHG emissions with substantial co-benefits in terms of health and living conditions, particularly for the 2.7 billion people in the world that rely on traditional biomass for cooking and heating (Sections 2.5.4, 9.3.4, 9.3.4.2 and 9.3.4.3). Efficient technologies for cooking are even cost-effective compared to other major interventions in health, such as those addressing tobacco, undernourishment or tuberculosis (Figures 2.14 and 9.13).

Other key environmental impacts cover water use, biodiversity and other emissions (Sections 2.5.5 and 9.3.4). Just as for GHG impacts, proper management determines emission levels to water, air and soil. Development of standards or criteria (and continuous improvement processes) will push bioenergy production to lower emissions and higher efficiency than today's systems.

Water is a critical issue that needs to be better analyzed at a regional level to understand the full impact of changes in vegetation and land use management. Recent studies (Berndes, 2002; Dornburg et al., 2008; Rost et al., 2009; Wu et al., 2009) indicate that considerable improvements can be made in water use efficiency in conventional agriculture, bioenergy crops and, depending on location and climate, perennial cropping systems, by improving water retention and lowering direct evaporation from soils (Figure 9.14). Nevertheless, without proper management, increased biomass production could come with increased competition for water in critical areas, which is highly undesirable (Fingerman et al., 2010).

Similar remarks can be made with respect to biodiversity, although more scientific uncertainty exists due to ongoing debates about methods of biodiversity impacts assessment. Clearly, development of large-scale monocultures at the expense of natural areas is detrimental for biodiversity (for example, highlighted in UNEP. 2008b). However, as discussed in Section 2.5, bioenergy can also lead to positive effects by integrating different perennial grasses and woody crops into agricultural landscapes, which could also increase soil carbon and productivity, reduce shallow landslides and local 'flash floods', reduce wind and water erosion, and reduce sediment and nutrients transported into river systems. Forest residue harvesting improves forest site conditions for replanting, and thinning generally improves productivity and growth of the remaining stand. Removal of biomass from overly-dense stands can reduce wildfire risk.

The impact assessments for all these areas deserve considerably more research, data collection and proper monitoring, as exemplified by ongoing activities of governments (see footnote 64) and roundtables[78] for pilot studies.

78 See Roundtable on Sustainable Biofuels pilot studies at www2.epfl.ch/energycenter-jahia4/page65660.html.

Social impacts from a large expansion of bioenergy are very complex and difficult to quantify. Crops grown as biofuel feedstock currently use less than 1% of the world's agricultural land, but demand for biofuels has represented one driver of demand growth and therefore contributed to global food price increases. Increased demand for food and feed, increases in oil prices, speculation on international food markets, and incidental poor harvests due to extreme weather events are examples of events that have likely also had an impact on global food prices. Even considering the benefit of increased prices to poor farmers, increased food prices adversely affect the level of poverty, food security, and malnourishment of children. On the other hand, biofuels can also provide opportunities for developing countries to make progress in rural development and agricultural growth, especially when this growth is economically sustainable.

In general, bioenergy options have a much larger positive impact on job creation in rural areas than other energy sources, for example, 50 to 2,200 jobs/PJ (Section 2.5.7.3). Also when the intensification of conventional agriculture frees up land that could be used for bioenergy, the total job impact and added value generated in rural regions increases when bioenergy production increases. Effective pasture/agriculture land use management could increase the rain-fed production potential significantly (see Table 2.3; Wicke et al., 2009). For many developing countries, the potential of bioenergy to generate employment, economic activity in rural areas, and fuel supply security are key drivers. In addition, expenditures on fossil fuel (imports) can be (strongly) reduced. However, whether such benefits end up with rural farmers depends largely on the way production chains are organized and how land use is governed.

The bioenergy options that are developed, the way they are developed, and under what conditions will have a profound influence on whether impacts will largely be positive or negative (Argentina scenarios; van Dam et al., 2009a,b). The development of standards or criteria (and continuous improvement processes) can push bioenergy production to lower or positive impacts and higher efficiency than today's systems. Bioenergy has the opportunity to contribute to climate change mitigation, a secure and diverse energy supply, and economic development in developed and developing countries alike, but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, and how actual projects are designed and implemented, among many other factors.

2.8.5 Conclusions regarding deployment: Key messages about bioenergy

Bioenergy is currently the largest RE source and is likely to remain one of the largest RE sources for the first half of this century. There is considerable growth potential, but it requires active development.

- Assessments in the recent literature show that the technical potential of biomass for energy may be as large as 500 EJ/yr by 2050. However, large uncertainty exists about important factors such as market and policy conditions that affect this potential.

- The expert assessment in this chapter suggests potential deployment levels by 2050 in the range of 100 to 300 EJ/yr. Realizing this potential represents a major challenge but would make a substantial contribution to the world's primary energy demand in 2050—roughly equal to the equivalent heat content of today's worldwide biomass extraction in agriculture and forestry.

- Bioenergy has significant potential to mitigate GHGs if resources are sustainably developed and efficient technologies are applied. Certain current systems and key future options including perennial crops, forest products and biomass residues and wastes, and advanced conversion technologies, can deliver significant GHG mitigation performance—an 80 to 90% reduction compared to the fossil energy baseline. However, land conversion and forest management that lead to a large loss of carbon stocks and iLUC effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts.

- In order to achieve the high potential deployment levels of biomass for energy, increases in competing food and fibre demand must be moderate, land must be properly managed and agricultural and forestry yields must increase substantially. Expansion of bioenergy in the absence of monitoring and good governance of land use carries the risk of significant conflicts with respect to food supplies, water resources and biodiversity, as well as a risk of low GHG benefits. Conversely, implementation that follows effective sustainability frameworks could mitigate such conflicts and allow realization of positive outcomes, for example, in rural development, land amelioration and climate change mitigation, including opportunities to combine adaptation measures.

- The impacts and performance of biomass production and use are region- and site-specific. Therefore, as part of good governance of land use and rural development, bioenergy policies need to consider regional conditions and priorities along with the agricultural (crops and livestock) and forestry sectors. Biomass resource potentials are influenced by and interact with climate change impacts but the specific impacts are still poorly understood; there will be strong regional differences in this respect. Bioenergy and new (perennial) cropping systems also offer opportunities to combine adaptation measures (e.g., soil protection, water retention and modernization of agriculture) with production of biomass resources.

- Several important bioenergy options (i.e., sugarcane ethanol production in Brazil, select waste-to-energy systems, efficient biomass cookstoves, biomass-based CHP) are competitive today and can provide important synergies with longer-term options. Lignocellulosic biofuels replacing gasoline, diesel and jet fuels, advanced bioelectricity options and biorefinery concepts can offer competitive deployment of bioenergy for the 2020 to 2030 timeframe. Combining biomass conversion with CCS raises the possibility of achieving GHG removal from the atmosphere in the long term—a necessity for substantial GHG emission reductions. Advanced biomaterials are promising as well for the economics of bioenergy production and mitigation, though the potential is less well understood as is the potential role of aquatic biomass (algae), which is highly uncertain.

- Rapidly changing policy contexts, recent market-based activities, the increasing support for advanced biorefineries and lignocellulosic biofuel options, and in particular the development of sustainability criteria and frameworks, all have the potential to drive bioenergy systems and their deployment in sustainable directions. Achieving this goal will require sustained investments that reduce costs of key technologies, improved biomass production and supply infrastructure, and implementation strategies that can gain public and political acceptance.

In conclusion and for illustrating the interrelations between scenario variables (see Figure 2.26), key preconditions under which bioenergy production capacity is developed and what the resulting impacts may be, Figure 2.27 presents four different sketches for biomass deployment for energy on a global scale by 2050. The 100 to 300 EJ range that follows from the resource potential review delineates the lower and upper limit for deployment. The assumed storylines roughly follow the IPCC SRES definitions, applied to bioenergy and summarized in Figure 2.26 (Hoogwijk et al., 2005), that were also used to derive the technical potential shown on the stacked bar of Figure 2.25 (Dornburg et al., 2008, 2010).

Biomass and its multiple energy products can be developed alongside food, fodder, fibre and forest products in both sustainable and unsustainable ways. As viewed through the IPCC scenario storylines and sketches, high and low penetration levels can be reached with and without taking into account sustainable development and climate change mitigation pathways. Insights into bioenergy technology developments and integrated systems can be gleaned from these sketches.

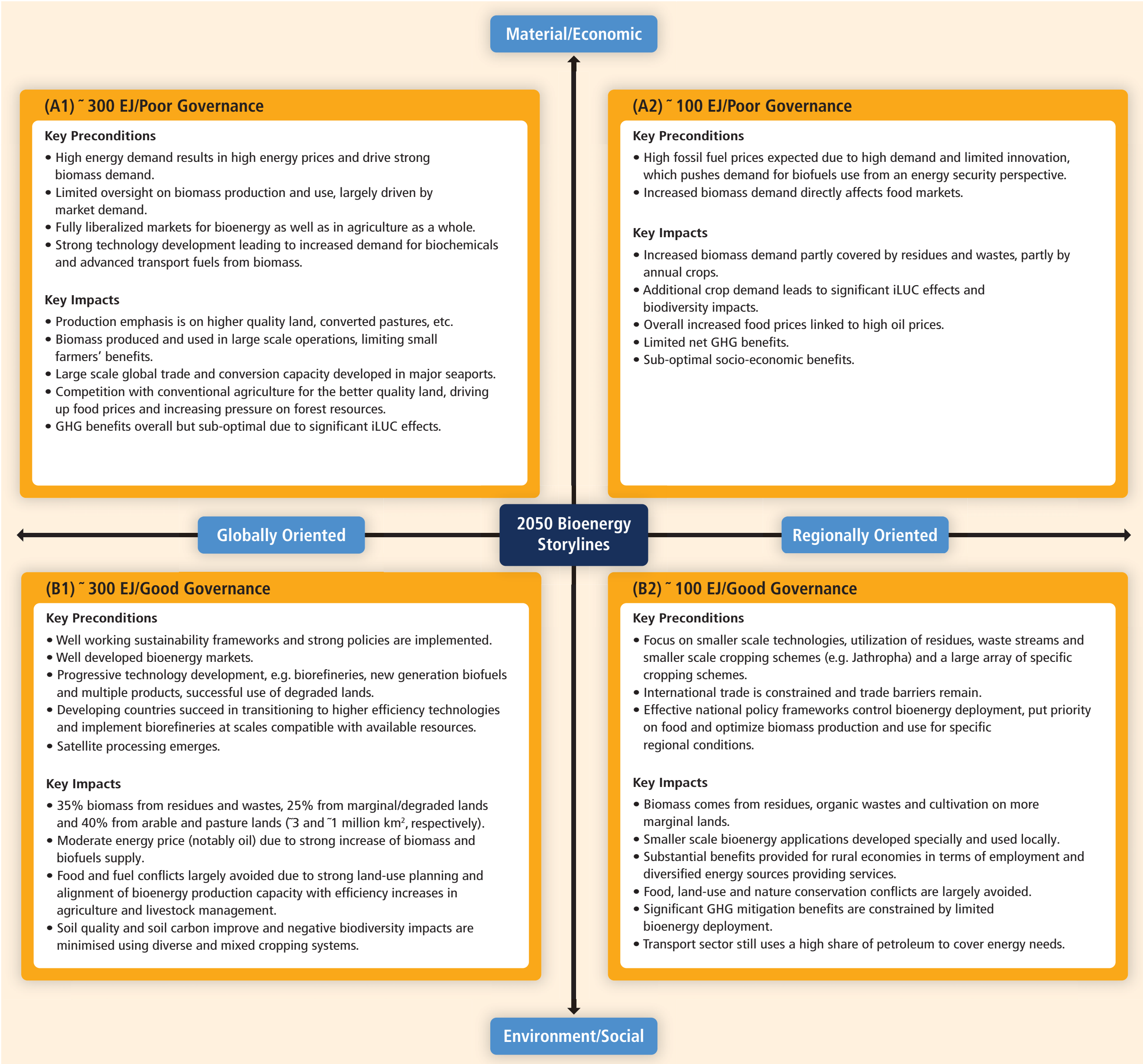


Figure 2.27 | Possible futures for 2050 biomass deployment for energy: Four illustrative contrasting sketches describing key preconditions and impacts following world conditions typical of the IPCC SRES storylines (IPCC, 2000) summarized in Figure 2.26.

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3

Direct Solar Energy

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Executive Summary

Solar energy is abundant and offers significant potential for near-term (2020) and long-term (2050) climate change mitigation. There are a wide variety of solar technologies of varying maturities that can, in most regions of the world, contribute to a suite of energy services. Even though solar energy generation still only represents a small fraction of total energy consumption, markets for solar technologies are growing rapidly. Much of the desirability of solar technology is its inherently smaller environmental burden and the opportunity it offers for positive social impacts. The cost of solar technologies has been reduced significantly over the past 30 years and technical advances and supportive public policies continue to offer the potential for additional cost reductions. Potential deployment scenarios range widely—from a marginal role of direct solar energy in 2050 to one of the major sources of energy supply. The actual deployment achieved will depend on the degree of continued innovation, cost reductions and supportive public policies.

Solar energy is the most abundant of all energy resources. Indeed, the rate at which solar energy is intercepted by the Earth is about 10,000 times greater than the rate at which humankind consumes energy. Although not all countries are equally endowed with solar energy, a significant contribution to the energy mix from direct solar energy is possible for almost every country. Currently, there is no evidence indicating a substantial impact of climate change on regional solar resources.

Solar energy conversion consists of a large family of different technologies capable of meeting a variety of energy service needs. Solar technologies can deliver heat, cooling, natural lighting, electricity, and fuels for a host of applications. Conversion of solar energy to *heat* (i.e., thermal conversion) is comparatively straightforward, because any material object placed in the sun will absorb thermal energy. However, maximizing that absorbed energy and stopping it from escaping to the surroundings can take specialized techniques and devices such as evacuated spaces, optical coatings and mirrors. Which technique is used depends on the application and temperature at which the heat is to be delivered. This can range from 25°C (e.g., for swimming pool heating) to 1,000°C (e.g., for dish/Stirling concentrating solar power), and even up to 3,000°C in solar furnaces.

Passive solar heating is a technique for maintaining comfortable conditions in buildings by exploiting the solar irradiance incident on the buildings through the use of glazing (windows, sun spaces, conservatories) and other transparent materials and managing heat gain and loss in the structure without the dominant use of pumps or fans. Solar *cooling* for buildings can also be achieved, for example, by using solar-derived heat to drive thermodynamic refrigeration absorption or adsorption cycles. Solar energy for lighting actually requires no conversion since solar lighting occurs naturally in buildings through windows. However, maximizing the effect requires specialized engineering and architectural design.

Generation of *electricity* can be achieved in two ways. In the first, solar energy is converted directly into electricity in a device called a photovoltaic (PV) cell. In the second, solar thermal energy is used in a concentrating solar power (CSP) plant to produce high-temperature heat, which is then converted to electricity via a heat engine and generator. Both approaches are currently in use. Furthermore, solar driven systems can deliver process heat and cooling, and other solar technologies are being developed that will deliver energy carriers such as hydrogen or hydrocarbon fuels—known as *solar fuels*.

The various solar technologies have differing maturities, and their applicability depends on local conditions and government policies to support their adoption. Some technologies are already competitive with market prices in certain locations, and in general, the overall viability of solar technologies is improving. Solar thermal can be used for a wide variety of applications, such as for domestic hot water, comfort heating of buildings, and industrial process heat. This is significant, as many countries spend up to one-third of their annual energy usage for heat. Service hot water heating for domestic and commercial buildings is now a mature technology growing at a rate of about 16% per year and employed in most countries of the world. The world installed capacity of solar thermal systems at the end of 2009 has been estimated to be 180 GW_{th}.

Passive solar and daylighting are conserving energy in buildings at a highly significant rate, but the actual amount is difficult to quantify. Well-designed passive solar systems decrease the need for additional comfort heating requirements by about 15% for existing buildings and about 40% for new buildings.

The generation of electricity using PV panels is also a worldwide phenomenon. Assisted by supportive pricing policies, the compound annual growth rate for PV production from 2003 to 2009 was more than 50%—making it one of the fastest-growing energy technologies in percentage terms. As of the end of 2009, the installed capacity for PV power production was about 22 GW. Estimates for 2010 give a consensus value of about 13 GW of newly added capacity. Most of those installations are roof-mounted and grid-connected. The production of electricity from CSP installations has seen a large increase in planned capacity in the last few years, with several countries beginning to experience significant new installations.

Integration of solar energy into broader energy systems involves both challenges and opportunities. Energy provided by PV panels and solar domestic water heaters can be especially valuable because the energy production often occurs at times of peak loads on the grid, as in cases where there is a large summer daytime load associated with air conditioning. PV and solar domestic water heaters also fit well with the needs of many countries because they are modular, quick to install, and can sometimes delay the need for costly construction or expansion of the transmission grid. At the same time, solar energy typically has a variable production profile with some degree of unpredictability that must be managed, and central-station solar electricity plants may require new transmission infrastructure. Because CSP can be readily coupled with thermal storage, the production profile can be controlled to limit production variability and enable dispatch capability.

Solar technologies offer opportunities for positive social impacts, and their environmental burden is small. Solar technologies have low lifecycle greenhouse gas emissions, and quantification of external costs has yielded favourable values compared to fossil fuel-based energy. Potential areas of concern include recycling and use of toxic materials in manufacturing for PV, water usage for CSP, and energy payback and land requirements for both. An important social benefit of solar technologies is their potential to improve the health and livelihood opportunities for many of the world's poorest populations—addressing some of the gap in availability of modern energy services for the roughly 1.4 billion people who do not have access to electricity and the 2.7 billion people who rely on traditional biomass for home cooking and heating needs. On the downside, some solar projects have faced public concerns regarding land requirements for centralized CSP and PV plants, perceptions regarding visual impacts, and for CSP, cooling water requirements. Land use impacts can be minimized by selecting areas with low population density and low environmental sensitivity. Similarly, water usage for CSP could be significantly reduced by using dry cooling approaches. Studies to date suggest that none of these issues presents a barrier against the widespread use of solar technologies.

Over the last 30 years, solar technologies have seen very substantial cost reductions. The current levelized costs of energy (electricity and heat) from solar technologies vary widely depending on the upfront technology cost, available solar irradiation as well as the applied discount rates. The levelized costs for solar thermal energy at a 7% discount rate range between less than USD_{2005} 10 and slightly more than USD_{2005} 20/GJ for solar hot water generation with a high degree of utilization in China to more than USD_{2005} 130/GJ for space heating applications in Organisation for Economic Co-operation and Development (OECD) countries with relative low irradiation levels of 800 kWh/m^2/yr. Electricity generation costs for utility-scale PV in regions of high solar irradiance in Europe and the USA are in the range of approximately 15 to 40 US $cents_{2005}$ /kWh at a 7% discount rate, but may be lower or higher depending on the available resource and on other framework conditions. Current cost data are limited for CSP and are highly dependent on other system factors such as storage. In 2009, the levelized costs of energy for large solar troughs with six hours of thermal storage ranged from below 20 to approximately 30 US $cents_{2005}$ /kWh. Technological improvements and cost reductions are expected, but the learning curves and subsequent cost reductions of solar technologies depend on production volume, research and development (R&D), and other factors such as access to capital, and not on the mere passage of time. Private capital is flowing into all the technologies, but government support and stable political conditions can lessen the risk of private investment and help ensure faster deployment.

Potential deployment scenarios for solar energy range widely—from a marginal role of direct solar energy in 2050 to one of the major sources of global energy supply. Although it is true that direct solar energy provides only a very small fraction of global energy supply today, it has the largest technical potential of all energy sources. In concert with technical improvements and resulting cost reductions, it could see dramatically expanded use in the decades to come. Achieving continued cost reductions is the central challenge that will influence the future deployment of solar energy. Moreover, as with some other forms of renewable energy, issues of variable production profiles and energy market integration as well as the possible need for new transmission infrastructure will influence the magnitude, type and cost of solar energy deployment. Finally, the regulatory and legal framework in place can also foster or hinder the uptake of direct solar energy applications.

3.1 Introduction

The aim of this chapter is to provide a synopsis of the state-of-the-art and possible future scenarios of the full realization of direct solar energy's potential for mitigating climate change. It establishes the resource base, describes the many and varied technologies, appraises current market development, outlines some methods for integrating solar into other energy systems, addresses its environmental and social impacts, and finally, evaluates the prospects for future deployment.

Some of the solar energy absorbed by the Earth appears later in the form of wind, wave, ocean thermal, hydropower and excess biomass energies. The scope of this chapter, however, does not include these other indirect forms. Rather, it deals with the *direct* use of solar energy.

Various books have been written on the history of solar technology (e.g., Butti and Perlin, 1980). This history began when early civilizations discovered that buildings with openings facing the Sun were warmer and brighter, even in cold weather. During the late 1800s, solar collectors for heating water and other fluids were invented and put into practical use for domestic water heating and solar industrial applications, for example, large-scale solar desalination. Later, mirrors were used (e.g., by Augustin Mouchot in 1875) to boost the available fluid temperature, so that heat engines driven by the Sun could develop motive power, and thence, electrical power. Also, the late 1800s brought the discovery of a device for converting sunlight directly into electricity. Called the photovoltaic (PV) cell, this device bypassed the need for a heat engine. The modern silicon solar cell, attributed to Russell Ohl working at American Telephone and Telegraph's (AT&T) Bell Labs, was discovered around 1940.

The modern age of solar research began in the 1950s with the establishment of the International Solar Energy Society (ISES) and increased research and development (R&D) efforts in many industries. For example, advances in the solar hot water heater by companies such as Miromit in Israel and the efforts of Harry Tabor at the National Physical Laboratory in Jerusalem helped to make solar energy the standard method for providing hot water for homes in Israel by the early 1960s. At about the same time, national and international networks of solar irradiance measurements were beginning to be established. With the oil crisis of the 1970s, most countries in the world developed programs for solar energy R&D, and this involved efforts in industry, government labs and universities. These policy support efforts, which have, for the most part, continued up to the present, have borne fruit: now one of the fastest-growing renewable energy (RE) technologies, solar energy is poised to play a much larger role on the world energy stage.

Solar energy is an abundant energy resource. Indeed, in just one hour, the solar energy intercepted by the Earth exceeds the world's energy consumption for the entire year. Solar energy's potential to mitigate climate change is equally impressive. Except for the modest amount of carbon dioxide (CO_2) emissions produced in the manufacture of conversion devices (see Section 3.6.1) the direct use of solar energy produces very little greenhouse gases, and it has the potential to displace large quantities of non-renewable fuels (Tsilingiridis et al., 2004).

Solar energy conversion is manifest in a family of technologies having a broad range of energy service applications: lighting, comfort heating, hot water for buildings and industry, high-temperature solar heat for electric power and industry, photovoltaic conversion for electrical power, and production of solar fuels, for example, hydrogen or synthesis gas (syngas). This chapter will further detail all of these technologies.

Several solar technologies, such as domestic hot water heating and pool heating, are already competitive and used in locales where they offer the least-cost option. And in jurisdictions where governments have taken steps to actively support solar energy, very large solar electricity (both PV and CSP) installations, approaching 100 MW of power, have been realized, in addition to large numbers of rooftop PV installations. Other applications, such as solar fuels, require additional R&D before achieving significant levels of adoption.

In pursuing any of the solar technologies, there is the need to deal with the variability and the cyclic nature of the Sun. One option is to store excess collected energy until it is needed. This is particularly effective for handling the lack of sunshine at night. For example, a 0.1-m thick slab of concrete in the floor of a home will store much of the solar energy absorbed during the day and release it to the room at night. When totalled over a long period of time such as one year, or over a large geographical area such as a continent, solar energy can offer greater service. The use of both these concepts of time and space, together with energy storage, has enabled designers to produce more effective solar systems. But much more work is needed to capture the full value of solar energy's contribution.

Because of its inherent variability, solar energy is most useful when integrated with another energy source, to be used when solar energy is not available. In the past, that source has generally been a non-renewable one. But there is great potential for integrating direct solar energy with other RE technologies.

The rest of this chapter will include the following topics. Section 3.2 summarizes research that characterizes this solar resource and discusses the global and regional technical potential for direct solar energy as well as the possible impacts of climate change on this resource. Section 3.3 describes the five different technologies and their applications: passive solar heating and lighting for buildings (Section 3.3.1), active solar heating and cooling for buildings and industry (Section 3.3.2), PV electricity generation (Section 3.3.3), CSP electricity generation (Section 3.3.4), and solar fuel production (Section 3.3.5). Section 3.4 reviews the current status of market development, including installed capacity and energy currently being generated (Section 3.4.1), and the industry capacity and supply chain (Section 3.4.2). Following this are sections on the integration of solar technologies into other energy systems (Section 3.5), the environmental and social impacts (Section 3.6), and the prospects for future technology innovations (Section 3.7). The two final sections cover cost trends (Section 3.8) and the policies needed to achieve the goals for deployment (Section 3.9). Many of the sections, such as Section 3.3, are segmented into subsections, one for each of the five solar technologies.

3.2 Resource potential

The solar resource is virtually inexhaustible, and it is available and able to be used in all countries and regions of the world. But to plan and design appropriate energy conversion systems, solar energy technologists must know how much irradiation will fall on their collectors.

Iqbal (1984), among others, has described the character of solar irradiance, which is the electromagnetic radiation emitted by the Sun. Outside the Earth's atmosphere, the solar irradiance on a surface perpendicular to the Sun's rays at the mean Earth-Sun distance is practically constant throughout the year. Its value is now accepted to be 1,367 W/m^2 (Bailey et al., 1997). With a clear sky on Earth, this figure becomes roughly 1,000 W/m^2 at the Earth's surface. These rays are actually electromagnetic waves—travelling fluctuations in electric and magnetic fields. With the Sun's surface temperature being close to 5800 Kelvin, solar irradiance is spread over wavelengths ranging from 0.25 to 3 μm. About 40% of solar irradiance is visible light, while another 10% is ultraviolet radiation, and 50% is infrared radiation. However, at the Earth's surface, evaluation of the solar irradiance is more difficult because of its interaction with the atmosphere, which contains clouds, aerosols, water vapour and trace gases that vary both geographically and temporally. Atmospheric conditions typically reduce the solar irradiance by roughly 35% on clear, dry days and by about 90% on days with thick clouds, leading to lower average solar irradiance. On average, solar irradiance on the ground is 198 W/m^2 (Solomon et al., 2007), based on ground surface area (Le Treut et al., 2007).

The solar irradiance reaching the Earth's surface (Figure 3.1) is divided into two primary components: beam solar irradiance on a horizontal surface, which comes directly from the Sun's disk, and diffuse irradiance, which comes from the whole of the sky except the Sun's disk. The term 'global solar irradiance' refers to the sum of the beam and the diffuse components.

There are several ways to assess the global resource potential of solar energy. The *theoretical* potential, which indicates the amount of irradiance at the Earth's surface (land and ocean) that is theoretically available for energy purposes, has been estimated at 3.9×10^6 EJ/yr (Rogner et al., 2000; their Table 5.18). *Technical potential* is the amount of solar irradiance output obtainable by full deployment of demonstrated and likely-to-develop technologies or practices (see Annex I, Glossary).

3.2.1 Global technical potential

The amount of solar energy that could be put to human use depends significantly on local factors such as land availability and meteorological conditions and demands for energy services. The technical potential varies over the different regions of the Earth, as do the assessment methodologies. As described in a comparative literature study (Krewitt et al., 2009) for the German Environment Agency, the solar electricity technical potential of PV and CSP depends on the available solar irradiance, land use exclusion factors and the future development of technology improvements. Note that this study used different assumptions for the land use factors for PV and CSP. For PV, it assumed that 98% of the technical potential comes from centralized PV power plants and that the suitable land area in the world for PV deployment averages 1.67% of total land area. For CSP, all land areas with high direct-normal irradiance (DNI)—a minimum DNI of 2,000 kWh/m^2/yr (7,200 MJ/m^2/yr)—were defined as suitable, and just 20% of that land was excluded for other uses. The

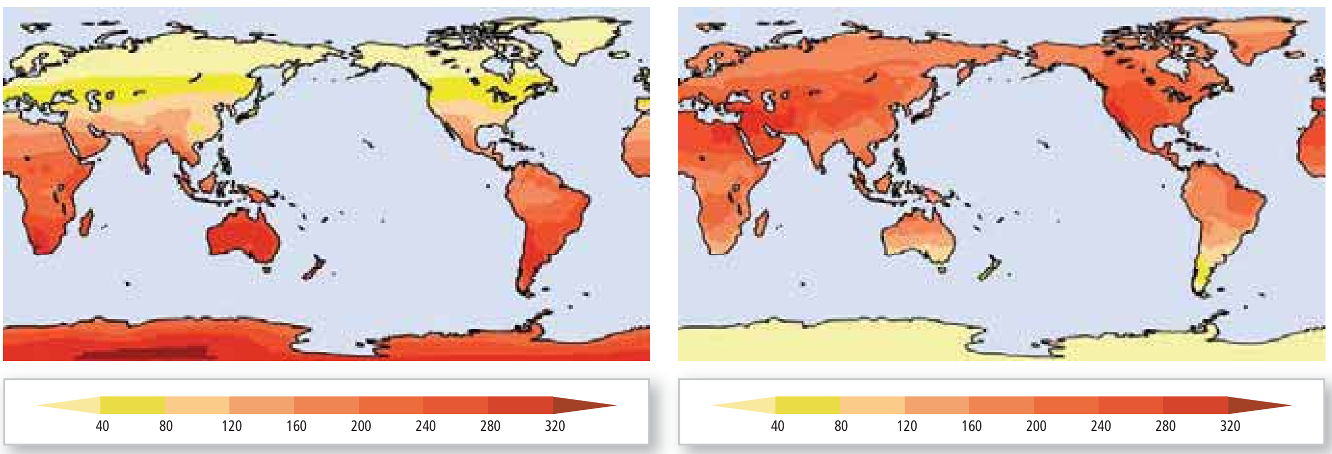


Figure 3.1 | The global solar irradiance (W/m^2) at the Earth's surface obtained from satellite imaging radiometers and averaged over the period 1983 to 2006. Left panel: December, January, February. Right panel: June, July, August (ISCCP Data Products, 2006).

resulting technical potentials for 2050 are 1,689 EJ/yr for PV and 8,043 EJ/yr for CSP.

Analyzing the PV studies (Hofman et al., 2002; Hoogwijk, 2004; de Vries et al., 2007) and the CSP studies (Hofman et al., 2002; Trieb, 2005; Trieb et al., 2009a) assessed by Krewitt et al. (2009), the technical potential varies significantly between these studies, ranging from 1,338 to 14,778 EJ/yr for PV and 248 and 10,791 EJ/yr for CSP. The main difference between the studies arises from the allocated land area availabilities and, to some extent, on differences in the power conversion efficiency used.

The technical potential of solar energy for heating purposes is vast and difficult to assess. The deployment potential is mainly limited by the demand for heat. Because of this, the technical potential is not assessed in the literature except for REN21 (Hoogwijk and Graus, 2008) to which Krewitt et al. (2009) refer. In order to provide a reference, REN21 has made a rough assessment of the technical potential of solar water heating by taking the assumed available rooftop area for solar PV applications from Hoogwijk (2004) and the irradiation for each of the regions. Therefore, the range given by REN21 is a lower bound only.

3.2.2 Regional technical potential

Table 3.1 shows the minimum and maximum estimated range for total solar energy technical potential for different regions, not differentiating the ways in which solar irradiance might be converted to secondary energy forms. For the minimum estimates, minimum annual clear-sky irradiance, sky clearance and available land used for installation of solar collectors are assumed. For the maximum estimates, maximum annual clear-sky irradiance and sky clearance are adopted with an assumption of maximum available land used. As Table 3.1 also indicates, the worldwide solar energy technical potential is considerably larger than the current primary energy consumption.

3.2.3 Sources of solar irradiance data

The calculation and optimization of the energy output and economical feasibility of solar energy systems such as buildings and power plants requires detailed solar irradiance data measured at the site of the solar installation. Therefore, it is essential to know the overall global solar energy available, as well as the relative magnitude of its two primary components: direct-beam irradiation and diffuse irradiation from the sky including clouds. Additionally, sometimes it is necessary to account for irradiation received by reflection from the ground and other surfaces. The details on how solar irradiance is measured and calculated can be found in the *Guide to Meteorological Instruments and Methods of Observation* (WMO, 2008). Also important are the patterns of seasonal availability, variability of irradiation, and daytime temperature onsite. Due to significant interannual variability of regional climate conditions in different parts of the world, such measurements must be generated over several years for many applications to provide sufficient statistical validity.

In regions with a high density of well-maintained ground measurements of solar irradiance, sophisticated gridding of these measurements can be expected to provide accurate information about the local solar irradiance. However, many parts of the world have inadequate ground-based sites (e.g., central Asia, northern Africa, Mexico, Brazil, central South America). In these regions, satellite-based irradiance measurements are

Table 3.1 | Annual total technical potential of solar energy for various regions of the world, not differentiated by conversion technology (Rogner et al., 2000; their Table 5.19).

REGIONS	Range of Estimates	
	Minimum, EJ	Maximum, EJ
North America	181	7,410
Latin America and Caribbean	113	3,385
Western Europe	25	914
Central and Eastern Europe	4	154
Former Soviet Union	199	8,655
Middle East and North Africa	412	11,060
Sub-Saharan Africa	372	9,528
Pacific Asia	41	994
South Asia	39	1,339
Centrally planned Asia	116	4,135
Pacific OECD	73	2,263
TOTAL	**1,575**	**49,837**
Ratio of technical potential to primary energy supply in 2008 (492 EJ)	*3.2*	*101*

Note: Basic assumptions used in assessing minimum and maximum technical potentials of solar energy are given in Rogner et al. (2000):

- Annual minimum clear-sky irradiance relates to horizontal collector plane, and annual maximum clear-sky irradiance relates to two-axis-tracking collector plane; see Table 2.2 in WEC (1994).
- Maximum and minimum annual sky clearance assumed for the relevant latitudes; see Table 2.2 in WEC (1994).

the primary source of information, but their accuracy is inherently lower than that of a well-maintained and calibrated ground measurement. Therefore, satellite radiation products require validation with accurate ground-based measurements (e.g., the Baseline Surface Radiation Network). Presently, the solar irradiance at the Earth's surface is estimated with an accuracy of about 15 W/m^2 on a regional scale (ISCCP Data Products, 2006). The Satellite Application Facility on Climate Monitoring project, under the leadership of the German Meteorological Service and in partnership with the Finnish, Belgian, Dutch, Swedish and Swiss National Meteorological Services, has developed methodologies for irradiance data from satellite measurements.

Various international and national institutions provide information on the solar resource, including the World Radiation Data Centre (Russia), the National Renewable Energy Laboratory (USA), the National Aeronautics and Space Administration (NASA, USA), the Brasilian Spatial Institute (Brazil), the German Aerospace Center (Germany), the Bureau of Meteorology Research Centre (Australia), and the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Spain), National Meteorological Services, and certain commercial companies. Table 3.2 gives references to some international and national projects that are collecting, processing and archiving information on solar irradiance resources at the Earth's surface and subsequently distributing it in easily accessible formats with understandable quality metrics.

3.2.4 Possible impact of climate change on resource potential

Climate change due to an increase of greenhouse gases (GHGs) in the atmosphere may influence atmospheric water vapour content, cloud cover, rainfall and turbidity, and this can impact the resource potential of solar energy in different regions of the globe. Changes in major climate variables, including cloud cover and solar irradiance at the Earth's surface, have been evaluated using climate models and considering anthropogenic forcing for the 21st century (Meehl et al., 2007; Meleshko et al., 2008). These studies found that the pattern of variation of monthly mean global solar irradiance does not exceed 1% over some regions of the globe, and it varies from model to model. Currently, there is no other evidence indicating a substantial impact of global warming on regional solar resources. Although some research on global dimming and global brightening indicates a probable impact on irradiance, no current evidence is available. Uncertainty in pattern changes seems to be rather large, even for large-scale areas of the Earth.

3.3 Technology and applications

This section discusses technical issues for a range of solar technologies, organized under the following categories: passive solar and daylighting,

Table 3.2 | International and national projects that collect, process and archive information on solar irradiance resources at the Earth's surface.

Available Data Sets	Responsible Institution/Agency
Ground-based solar irradiance from 1,280 sites for 1964 to 2009 provided by national meteorological services around the world.	World Radiation Data Centre, Saint Petersburg, Russian Federation (wrdc.mgo.rssi.ru)
National Solar Radiation Database that includes 1,454 ground locations for 1991 to 2005. The satellite-modelled solar data for 1998 to 2005 provided on 10-km grid. The hourly values of solar data can be used to determine solar resources for collectors.	National Renewable Energy Laboratory, USA (www.nrel.gov)
European Solar Radiation Database that includes measured solar radiation complemented with other meteorological data necessary for solar engineering. Satellite images from METEOSAT help in improving accuracy in spatial interpolation. Test Reference Years were also included.	Supported by Commission of the European Communities, National Weather Services and scientific institutions of the European countries
The Solar Radiation Atlas of Africa contains information on surface radiation over Europe, Asia Minor and Africa. Data covering 1985 to 1986 were derived from measurements by METEOSAT 2.	Supported by the Commission of the European Communities
The solar data set for Africa based on images from METEOSAT processed with the Heliosat-2 method covers the period 1985 to 2004 and is supplemented with ground-based solar irradiance.	Ecole des Mines de Paris, France
Typical Meteorological Year (Test Reference Year) data sets of hourly values of solar radiation and meteorological parameters derived from individual weather observations in long-term (up to 30 years) data sets to establish a typical year of hourly data. Used by designers of heating and cooling systems and large-scale solar thermal power plants.	National Renewable Energy Laboratory, USA. National Climatic Data Center, National Oceanic and Atmospheric Administration, USA. (www.ncdc.noaa.gov)
The solar radiation data for solar energy applications. IEA/SHC Task36 provides a wide range of users with information on solar radiation resources at Earth's surface in easily accessible formats with understandable quality metrics. The task focuses on development, validation and access to solar resource information derived from surface- and satellite-based platforms.	International Energy Agency (IEA) Solar Heating and Cooling Programme (SHC). (swera.unep.net)
Solar and Wind Energy Resource Assessment (SWERA) project aimed at developing information tools to simulate RE development. SWERA provides easy access to high-quality RE resource information and data for users. Covered major areas of 13 developing countries in Latin America, the Caribbean, Africa and Asia. SWERA produced a range of solar data sets and maps at better spatial scales of resolution than previously available using satellite- and ground-based observations.	Global Environment Facility-sponsored project. United Nations Environment Programme (swera.unep.net)

active heating and cooling, PV electricity generation, CSP electricity generation and solar fuel production. Each section also describes applications of these technologies.

3.3.1 Passive solar and daylighting technologies

Passive solar energy technologies absorb solar energy, store and distribute it in a natural manner (e.g., natural ventilation), without using mechanical elements (e.g., fans) (Hernandez Gonzalvez, 1996). The term 'passive solar building' is a qualitative term describing a building that makes significant use of solar gain to reduce heating energy consumption based on the natural energy flows of radiation, conduction and convection. The term 'passive building' is often employed to emphasize use of passive energy flows in both heating and cooling, including redistribution of absorbed direct solar gains and night cooling (Athienitis and Santamouris, 2002).

Daylighting technologies are primarily passive, including windows, skylights and shading and reflecting devices. A worldwide trend, particularly in technologically advanced regions, is for an increased mix of passive and active systems, such as a forced-air system that redistributes passive solar gains in a solar house or automatically controlled shades that optimize daylight utilization in an office building (Tzempelikos et al., 2010).

The basic elements of passive solar design are windows, conservatories and other glazed spaces (for solar gain and daylighting), thermal mass, protection elements, and reflectors (Ralegaonkar and Gupta, 2010). With the combination of these basic elements, different systems are obtained: direct-gain systems (e.g., the use of windows in combination with walls able to store energy, solar chimneys, and wind catchers), indirect-gain systems (e.g., Trombe walls), mixed-gain systems (a combination of direct-gain and indirect-gain systems, such as conservatories, sunspaces and greenhouses), and isolated-gain systems. Passive technologies are integrated with the building and may include the following components:

- Windows with high solar transmittance and a high thermal resistance facing towards the Equator as nearly as possible can be employed to maximize the amount of direct solar gains into the living space while reducing heat losses through the windows in the heating season and heat gains in the cooling season. Skylights are also often used for daylighting in office buildings and in solaria/sunspaces.

- Building-integrated thermal storage, commonly referred to as thermal mass, may be sensible thermal storage using concrete or brick materials, or latent thermal storage using phase-change materials (Mehling and Cabeza, 2008). The most common type of thermal storage is the direct-gain system in which thermal mass is adequately distributed in the living space, absorbing the direct solar gains. Storage is particularly important because it performs two essential functions: storing much of the absorbed direct solar energy for slow release, and maintaining satisfactory thermal comfort conditions by limiting the maximum rise in operative (effective) room temperature (ASHRAE, 2009). Alternatively, a collector-storage wall, known as a Trombe wall, may be used, in which the thermal mass is placed directly next to the glazing, with possible air circulation between the cavity of the wall system and the room. However, this system has not gained much acceptance because it limits views to the outdoor environment through the fenestration. Hybrid thermal storage with active charging and passive heat release can also be employed in part of a solar building while direct-gain mass is also used (see, e.g., the EcoTerra demonstration house (Figure 3.2, left panel), which uses solar-heated air from a building-integrated photovoltaic/thermal system to heat a ventilated concrete slab). Isolated thermal storage passively coupled to a fenestration system or solarium/sunspace is another option in passive design.

- Well-insulated opaque envelope appropriate for the climatic conditions can be used to reduce heat transfer to and from the outdoor environment. In most climates, this energy efficiency aspect must be integrated with the passive design. A solar technology that may be used with opaque envelopes is transparent insulation (Hollands et al., 2001) combined with thermal mass to store solar gains in a wall, turning it into an energy-positive element.

- Daylighting technologies and advanced solar control systems, such as automatically controlled shading (internal, external) and fixed shading devices, are particularly suited for daylighting applications in the workplace (Figure 3.2, right panel). These technologies include electrochromic and thermochromic coatings and newer technologies such as transparent photovoltaics, which, in addition to a passive daylight transmission function, also generate electricity. Daylighting is a combination of energy conservation and passive solar design. It aims to make the most of the natural daylight that is available. Traditional techniques include: shallow-plan design, allowing daylight to penetrate all rooms and corridors; light wells in the centre of buildings; roof lights; tall windows, which allow light to penetrate deep inside rooms; task lighting directly over the workplace, rather than lighting the whole building interior; and deep windows that reveal and light room surfaces to cut the risk of glare (Everett, 1996).

- Solariums, also called sunspaces, are a particular case of the direct-gain passive solar system, but with most surfaces transparent, that is, made up of fenestration. Solariums are becoming increasingly attractive both as a retrofit option for existing houses and as an integral part of new buildings (Athienitis and Santamouris, 2002). The major driving force for this growth is the development of new advanced energy-efficient glazing.

Some basic rules for optimizing the use of passive solar heating in buildings are the following: buildings should be well insulated to reduce overall heat losses; they should have a responsive, efficient heating system; they should face towards the Equator, that is, the glazing should

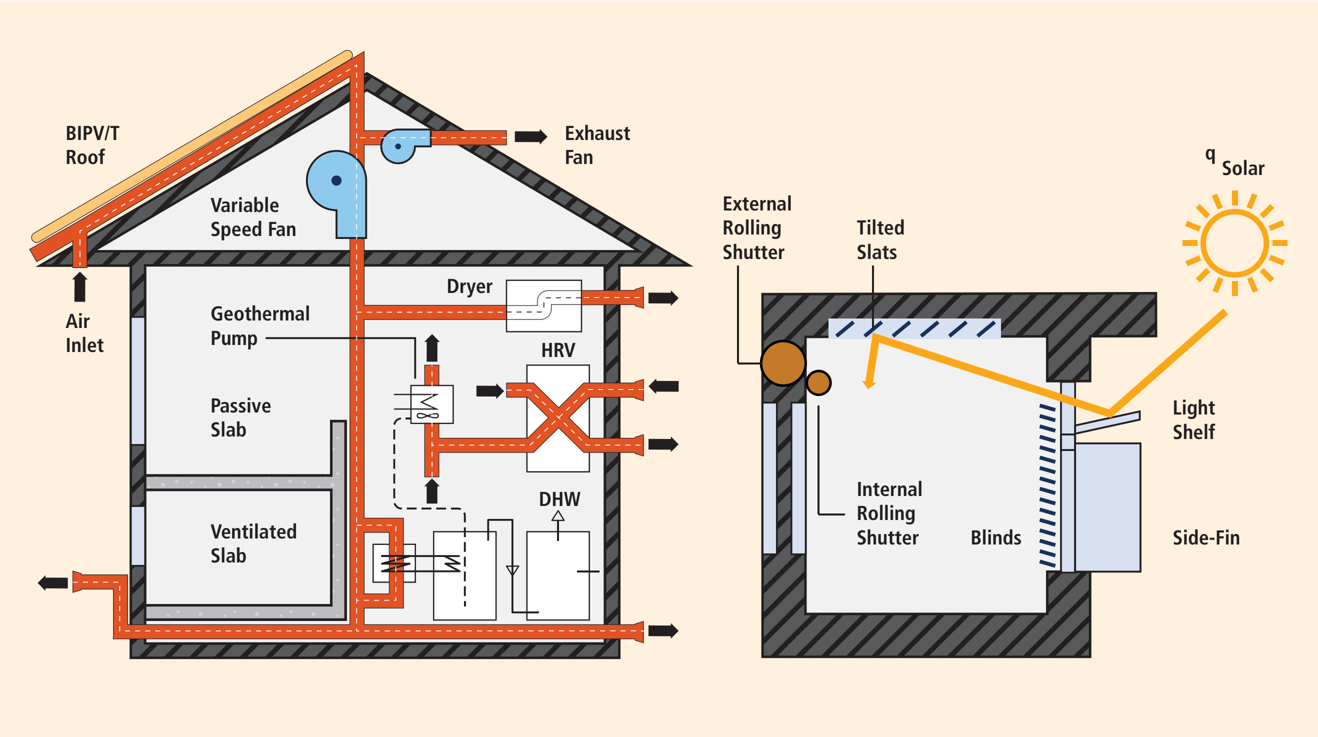


Figure 3.2 | Left: Schematic of thermal mass placement and passive-active systems in a house; solar-heated air from building-integrated photovoltaic/thermal (BIPV/T) roof heats ventilated slab or domestic hot water (DHW) through heat exchanger; HRV is heat recovery ventilator. Right: Schematic of several daylighting concepts designed to redistribute daylight into the office interior space (Athienitis, 2008).

be concentrated on the equatorial side, as should the main living rooms, with rooms such as bathrooms on the opposite side; they should avoid shading by other buildings to benefit from the essential mid-winter sun; and they should be 'thermally massive' to avoid overheating in the summer and on certain sunny days in winter (Everett, 1996).

Clearly, passive technologies cannot be separated from the building itself. Thus, when estimating the contribution of passive solar gains, the following must be distinguished: 1) buildings specifically designed to harness direct solar gains using passive systems, defined here as solar buildings, and 2) buildings that harness solar gains through near-equatorial facing windows; this orientation is more by chance than by design. Few reliable statistics are available on the adoption of passive design in residential buildings. Furthermore, the contribution of passive solar gains is missing in existing national statistics. Passive solar is reducing the demand and is not part of the supply chain, which is what is considered by the energy statistics.

The passive solar design process itself is in a period of rapid change, driven by the new technologies becoming affordable, such as the recently available highly efficient fenestration at the same prices as ordinary glazing. For example, in Canada, double-glazed low-emissivity argon-filled windows are presently the main glazing technology used; but until a few years ago, this glazing was about 20 to 40% more expensive than regular double glazing. These windows are now being used in retrofits of existing homes as well. Many homes also add a solarium during retrofit. The new glazing technologies and solar control systems allow the design of a larger window area than in the recent past.

In most climates, unless effective solar gain control is employed, there may be a need to cool the space during the summer. However, the need for mechanical cooling may often be eliminated by designing for passive cooling. Passive cooling techniques are based on the use of heat and solar protection techniques, heat storage in thermal mass and heat dissipation techniques. The specific contribution of passive solar and energy conservation techniques depends strongly on the climate (UNEP, 2007). Solar-gain control is particularly important during the 'shoulder' seasons when some heating may be required. In adopting larger window areas—enabled by their high thermal resistance—active solar-gain control becomes important in solar buildings for both thermal and visual considerations.

The potential of passive solar cooling in reducing CO_2 emissions has been shown recently (Cabeza et al., 2010; Castell et al., 2010). Experimental work demonstrates that adequate insulation can reduce by up to 50% the cooling energy demand of a building during the hot season. Moreover, including phase-change materials in the already-insulated building envelope can reduce the cooling energy demand in such buildings further by up to 15%—about 1 to 1.5 kg/yr/m^2 of CO_2 emissions would be saved in these buildings due to reducing the energy consumption compared to the insulated building without phase-change material.

Passive solar system applications are mainly of the direct-gain type, but they can be further subdivided into the following main application categories: multi-story residential buildings and two-story detached or semi-detached solar homes (see Figure 3.2, left panel), designed to have a large equatorial-facing façade to provide the potential for a large solar capture area (Athienitis, 2008). Perimeter zones and their fenestration systems in office buildings are designed primarily based on daylighting performance. In this application, the emphasis is usually on reducing cooling loads, but passive heat gains may be desirable as well during the heating season (see Figure 3.2, right panel, for a schematic of shading devices).

In addition, residential or commercial buildings may be designed to use natural or hybrid ventilation systems and techniques for cooling or fresh air supply, in conjunction with designs for using daylight throughout the year and direct solar gains during the heating season. These buildings may profit from low summer night temperatures by using night hybrid ventilation techniques that utilize both mechanical and natural ventilation processes (Santamouris and Asimakopoulos, 1996; Voss et al., 2007).

In 2010, passive technologies played a prominent role in the design of net-zero-energy solar homes—homes that produce as much electrical and thermal energy as they consume in an average year. These houses are primarily demonstration projects in several countries currently collaborating in the International Energy Agency (IEA) Task 40 of the Solar Heating and Cooling (SHC) Programme (IEA, 2009b)—Energy Conservation in Buildings and Community Systems Annex 52—which focuses on net-zero-energy solar buildings. Passive technologies are essential in developing affordable net-zero-energy homes. Passive solar gains in homes based on the Passive House Standard are expected to reduce the heating load by about 40%. By extension, systematic passive solar design of highly insulated buildings at a community scale, with optimal orientation and form of housing, should easily result in a similar energy saving of 40%. In Europe, according to the Energy Performance of Buildings Directive recast, Directive 2010/31/EC (The European Parliament and the Council of the European Union, 2010), all new buildings must be nearly zero-energy buildings by 31 December 2020, while EU member states should set intermediate targets for 2015. New buildings occupied and owned by public authorities have to be nearly zero-energy buildings after 31 December 2018. The nearly zero or very low amount of energy required should to a very significant level be covered by RE sources, including onsite energy production using combined heat and power generation or district heating and cooling, to satisfy most of their demand. Measures should also be taken to stimulate building refurbishments into nearly zero-energy buildings.

Low-energy buildings are known under different names. A survey carried out by Concerted Action Energy Performance of Buildings (EPBD) identified 17 different terms to describe such buildings across Europe, including: low-energy house, high-performance house, passive house ('Passivhaus'), zero-carbon house, zero-energy house, energy-savings house, energy-positive house and 3-litre house. Concepts that take into account more parameters than energy demand again use special terms such as eco-building or green building.

Another IEA Annex—Energy Conservation through Energy Storage Implementing Agreement (ECES IA) Annex 23—was initiated in November 2009 (IEA ECES, 2004). The general objective of the Annex is to ensure that energy storage techniques are properly applied in ultra-low-energy buildings and communities. The proper application of energy storage is expected to increase the likelihood of sustainable building technologies.

Another passive solar application is natural drying. Grains and many other agricultural products have to be dried before being stored so that insects and fungi do not render them unusable. Examples include wheat, rice, coffee, copra (coconut flesh), certain fruits and timber (Twidell and Weir, 2006). Solar energy dryers vary mainly as to the use of the solar heat and the arrangement of their major components. Solar dryers constructed from wood, metal and glass sheets have been evaluated extensively and used quite widely to dry a full range of tropical crops (Imre, 2007).

3.3.2 Active solar heating and cooling

Active solar heating and cooling technologies use the Sun and mechanical elements to provide either heating or cooling; various technologies are discussed here, as well as thermal storage.

3.3.2.1 Solar heating

In a solar heating system, the solar collector transforms solar irradiance into heat and uses a carrier fluid (e.g., water, air) to transfer that heat to a well-insulated storage tank, where it can be used when needed. The two most important factors in choosing the correct type of collector are the following: 1) the service to be provided by the solar collector, and 2) the related desired range of temperature of the heat-carrier fluid. An uncovered absorber, also known as an unglazed collector, is likely to be limited to low-temperature heat production (Duffie and Beckman, 2006).

A solar collector can incorporate many different materials and be manufactured using a variety of techniques. Its design is influenced by the system in which it will operate and by the climatic conditions of the installation location.

Flat-plate collectors are the most widely used solar thermal collectors for residential solar water- and space-heating systems. They are also used in air-heating systems. A typical flat-plate collector consists of an absorber, a header and riser tube arrangement or a single serpentine tube, a transparent cover, a frame and insulation (Figure 3.3a). For low-temperature applications, such as the heating of swimming pools, only a single plate is used as an absorber (Figure 3.3b). Flat-plate collectors demonstrate a good price/performance ratio, as well as a broad range of mounting possibilities (e.g., on the roof, in the roof itself, or unattached).

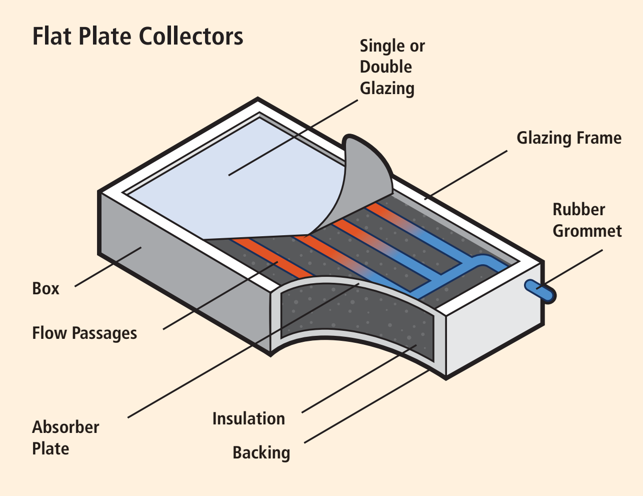


Figure 3.3a | Schematic diagram of thermal solar collectors: Glazed flat-plate.

Evacuated-tube collectors are usually made of parallel rows of transparent glass tubes, in which the absorbers are enclosed, connected to a header pipe (Figure 3.3c). To reduce heat loss within the frame by convection, the air is pumped out of the collector tubes to generate a vacuum. This makes it possible to achieve high temperatures, useful

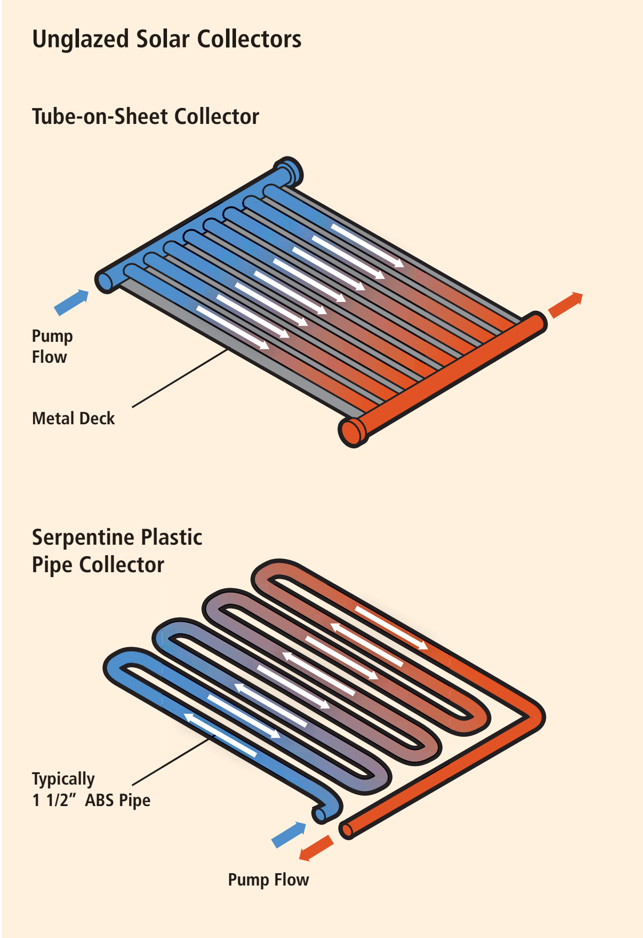


Figure 3.3b | Schematic diagram of thermal solar collectors: Unglazed tube-on-sheet and serpentine plastic pipe.

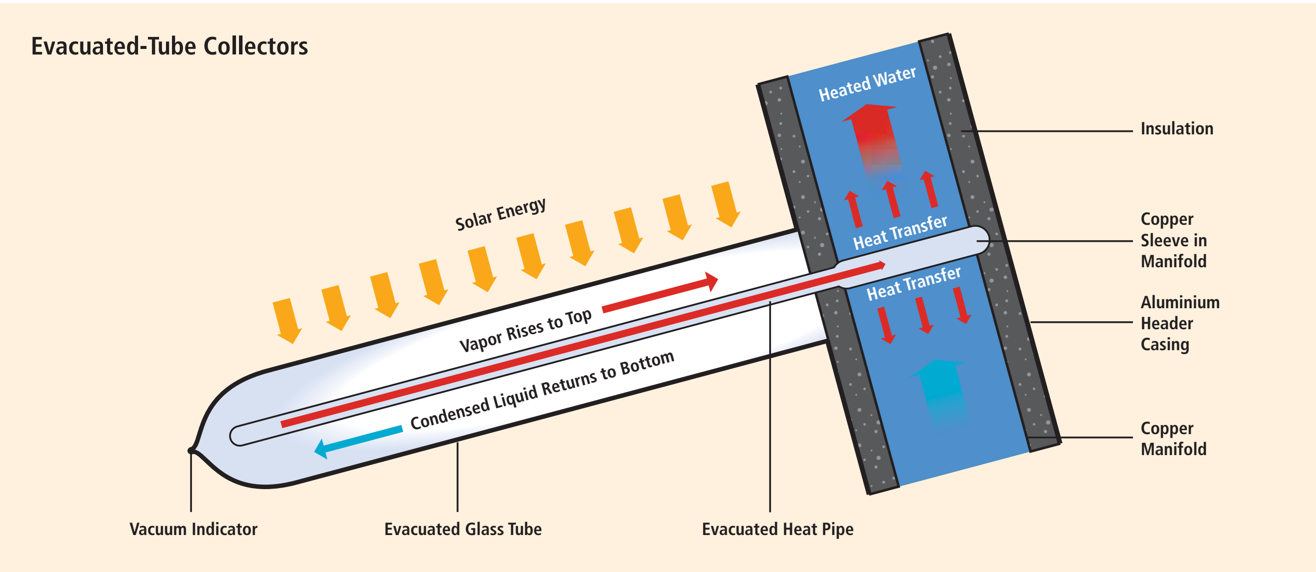


Figure 3.3c | Schematic diagram of thermal solar collectors: Evacuated-tube collectors.

for cooling (see below) or industrial applications. Most vacuum tube collectors use heat pipes for their core instead of passing liquid directly through them. Evacuated heat-pipe tubes are composed of multiple evacuated glass tubes, each containing an absorber plate fused to a heat pipe. The heat from the hot end of the heat pipes is transferred to the transfer fluid of a domestic hot water or hydronic space-heating system.

Solar water-heating systems used to produce hot water can be classified as passive or active solar water heaters (Duffie and Beckman, 2006). Also of interest are active solar cooling systems, which transform the hot water produced by solar energy into cold water.

Passive solar water heaters are of two types (Figure 3.4). Integral collector-storage (ICS) or 'batch' systems include black tanks or tubes in an insulated glazed box. Cold water is preheated as it passes through the solar collector, with the heated water flowing to a standard backup water heater. The heated water is stored inside the collector itself. In thermosyphon (TS) systems, a separate storage tank is directly above the collector. In direct (open-loop) TS systems, the heated water rises from the collector to the tank and cool water from the tank sinks back into the collector. In indirect (closed-loop) TS systems (Figure 3.4, left), heated fluid (usually a glycol-water mixture) rises from the collector to an outer tank that surrounds the water storage tank and acts as a heat exchanger (double-wall heat exchangers) for separation from potable water. In climates where freezing temperatures are unlikely, many collectors include an integrated storage tank at the top of the collector. This design has many cost and user-friendly advantages compared to a system that uses a separate standalone heat-exchanger tank. It is also appropriate in households with significant daytime and evening hot water needs; but it does not work well in households with predominantly morning draws because sometimes the tanks can lose most of the collected energy overnight.

Active solar water heaters rely on electric pumps and controllers to circulate the carrier fluid through the collectors. Three types of active solar water-heating systems are available. Direct circulation systems use pumps to circulate pressurized potable water directly through the collectors. These systems are appropriate in areas that do not freeze for long periods and do not have hard or acidic water. Antifreeze indirect-circulation systems pump heat-transfer fluid, which is usually a glycol-water mixture, through collectors. Heat exchangers transfer the heat from the fluid to the water for use (Figure 3.4, right). Drainback indirect-circulation systems use pumps to circulate water through the collectors. The water in the collector and the piping system drains into a reservoir tank when the pumps stop, eliminating the risk of freezing in cold climates. This system should be carefully designed and installed to ensure that the piping always slopes downward to the reservoir tank. Also, stratification should be carefully considered in the design of the water tank (Hadorn, 2005).

A *solar combisystem* provides both solar space heating and cooling as well as hot water from a common array of solar thermal collectors, usually backed up by an auxiliary non-solar heat source (Weiss, 2003). Solar combisystems may range in size from those installed in individual properties to those serving several in a block heating scheme. A large number of different types of solar combisystems are produced. The systems on the market in a particular country may be more restricted, however, because different systems have tended to evolve in different countries.

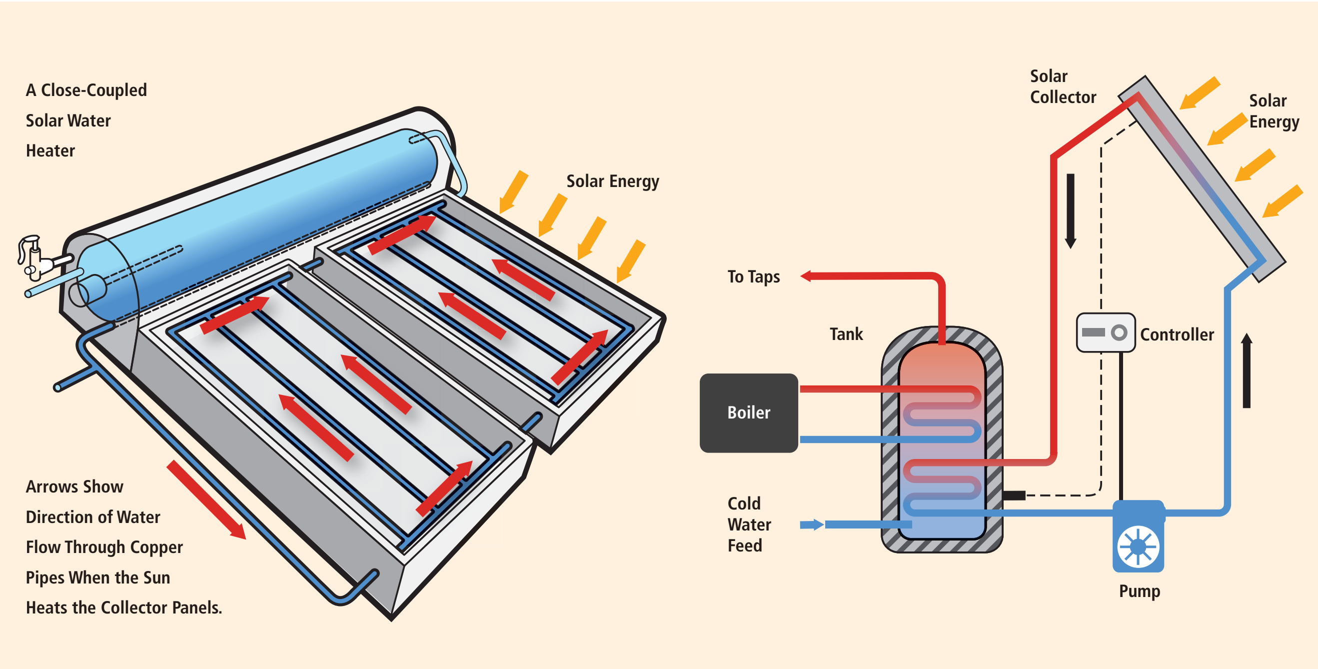


Figure 3.4 | Generic schematics of thermal solar systems. Left: Passive (thermosyphon). Right: Active system.

Depending on the size of the combisystem installed, the annual space heating contribution can range from 10 to 60% or more in ultra-low energy Passivhaus-type buildings, and even up to 100% where a large seasonal thermal store or concentrating solar thermal heat is used.

3.3.2.2 Solar cooling

Solar cooling can be broadly categorized into solar electric refrigeration, solar thermal refrigeration, and solar thermal air-conditioning. In the first category, the solar electric compression refrigeration uses PV panels to power a conventional refrigeration machine (Fong et al., 2010). In the second category, the refrigeration effect can be produced through solar thermal gain; solar mechanical compression refrigeration, solar absorption refrigeration, and solar adsorption refrigeration are the three common options. In the third category, the conditioned air can be directly provided through the solar thermal gain by means of desiccant cooling. Both solid and liquid sorbents are available, such as silica gel and lithium chloride, respectively.

Solar electrical air-conditioning, powered by PV panels, is of minor interest from a systems perspective, unless there is an off-grid application (Henning, 2007). This is because in industrialized countries, which have a well-developed electricity grid, the maximum use of photovoltaics is achieved by feeding the produced electricity into the public grid.

Solar thermal air-conditioning consists of solar heat powering an absorption chiller and it can be used in buildings (Henning, 2007). Deploying such a technology depends heavily on the industrial deployment of low-cost small-power absorption chillers. This technology is being studied within the IEA Task 25 on solar-assisted air-conditioning of buildings, SHC program and IEA Task 38 on solar air-conditioning and refrigeration, SHC program.

Closed heat-driven cooling systems using these cycles have been known for many years and are usually used for large capacities of 100 kW and greater. The physical principle used in most systems is based on the sorption phenomenon. Two technologies are established to produce thermally driven low- and medium-temperature refrigeration: absorption and adsorption.

Open cooling cycle (or desiccant cooling) systems are mainly of interest for the air conditioning of buildings. They can use solid or liquid sorption. The central component of any open solar-assisted cooling system is the dehumidification unit. In most systems using solid sorption, this unit is a desiccant wheel. Various sorption materials can be used, such as silica gel or lithium chloride. All other system components are found in standard air-conditioning applications with an air-handling unit and include the heat recovery units, heat exchangers and humidifiers. Liquid sorption techniques have been demonstrated successfully.

3.3.2.3 Thermal storage

Thermal storage within thermal solar systems is a key component to ensure reliability and efficiency. Four main types of thermal energy storage technologies can be distinguished: sensible, latent, sorption and thermochemical heat storage (Hadorn, 2005; Paksoy, 2007; Mehling and Cabeza, 2008; Dincer and Rosen, 2010).

Sensible heat storage systems use the heat capacity of a material. The vast majority of systems on the market use water for heat storage. Water heat storage covers a broad range of capacities, from several hundred litres to tens of thousands of cubic metres.

Latent heat storage systems store thermal energy during the phase change, either melting or evaporation, of a material. Depending on the temperature range, this type of storage is more compact than heat storage in water. Melting processes have energy densities of the order of 100 kWh/m^3 (360 MJ/m^3), compared to 25 kWh/m^3 (90 MJ/m^3) for sensible heat storage. Most of the current latent heat storage technologies for low temperatures store heat in building structures to improve thermal performance, or in cold storage systems. For medium-temperature storage, the storage materials are nitrate salts. Pilot storage units in the 100-kW range currently operate using solar-produced steam.

Sorption heat storage systems store heat in materials using water vapour taken up by a sorption material. The material can either be a solid (adsorption) or a liquid (absorption). These technologies are still largely in the development phase, but some are on the market. In principle, sorption heat storage densities can be more than four times higher than sensible heat storage in water.

Thermochemical heat storage systems store heat in an endothermic chemical reaction. Some chemicals store heat 20 times more densely than water (at a $\Delta T \approx 100°C$); but more typically, the storage densities are 8 to 10 times higher. Few thermochemical storage systems have been demonstrated. The materials currently being studied are the salts that can exist in anhydrous and hydrated form. Thermochemical systems can compactly store low- and medium-temperature heat. Thermal storage is discussed with specific reference to higher-temperature CSP in Section 3.3.4.

Underground thermal energy storage is used for seasonal storage and includes the various technologies described below. The most frequently used storage technology that makes use of the underground is *aquifer* *thermal energy storage*. This technology uses a natural underground layer (e.g., sand, sandstone or chalk) as a storage medium for the temporary storage of heat or cold. The transfer of thermal energy is realized by extracting groundwater from the layer and by re-injecting it at the modified temperature level at a separate location nearby. Most applications are for the storage of winter cold to be used for the cooling of large office buildings and industrial processes. Aquifer cold storage is gaining interest because savings on electricity bills for chillers are about 75%, and in many cases, the payback time for additional investments is shorter than five years. A major condition for the application of this technology is the availability of a suitable geologic formation.

3.3.2.4 Active solar heating and cooling applications

For active solar heating and cooling applications, the amount of hot water produced depends on the type and size of the system, amount of sun available at the site, seasonal hot-water demand pattern, and installation characteristics of the system (Norton, 2001).

Solar heating for industrial processes is at a very early stage of development in 2010 (POSHIP, 2001). Worldwide, less than 100 operating solar thermal systems for process heat are reported, with a total capacity of about 24 MW_{th} (34,000 m^2 collector area). Most systems are at an experimental stage and relatively small scale. However, significant potential exists for market and technological developments, because 28% of the overall energy demand in the EU27 countries originates in the industrial sector, and much of this demand is for heat below 250°C. Education and knowledge dissemination are needed to deploy this technology.

In the short term, solar heating for industrial processes will mainly be used for low-temperature processes, ranging from 20°C to 100°C. With technological development, an increasing number of medium-temperature applications—up to 250°C—will become feasible within the market. According to Werner (2006), about 30% of the total industrial heat demand is required at temperatures below 100°C, which could theoretically be met with solar heating using current technologies. About 57% of this demand is required at temperatures below 400°C, which could largely be supplied by solar in the foreseeable future.

In several specific industry sectors—such as food, wine and beverages, transport equipment, machinery, textiles, and pulp and paper—the share of heat demand at low and medium temperatures (below 250°C) is around 60% (POSHIP, 2001). Tapping into this low- and medium-temperature heat demand with solar heat could provide a significant opportunity for solar contribution to industrial energy requirements. A substantial opportunity for solar thermal systems also exists in chemical industries and in washing processes.

Among the industrial processes, desalination and water treatment (e.g., sterilization) are particularly promising applications for solar thermal energy, because these processes require large amounts of medium-temperature heat and are often necessary in areas with high solar irradiance and high energy costs.

Some process heat applications can be met with temperatures delivered by 'ordinary' low-temperature collectors, namely, from 30°C to 80°C. However, the bulk of the demand for industrial process heat requires temperatures from 80°C to 250°C.

Process heat collectors are another potential application for solar thermal heat collectors. Typically, these systems require a large capacity (hence, large collector areas), low costs, and high reliability and quality. Although low- and high-temperature collectors are offered in a dynamically growing market, process heat collectors are at a very early stage of development and no products are available on an industrial scale. In addition to 'concentrating' collectors, improved flat collectors with double and triple glazing are currently being developed, which could meet needs for process heat in the range of up to 120°C. Concentrating-type solar collectors are described in Section 3.3.4.

Solar refrigeration is used, for example, to cool stored vaccines. The need for such systems is greatest in peripheral health centres in rural communities in the developing world, where no electrical grid is available.

Solar cooling is a specific area of application for solar thermal technology. High-efficiency flat plates, evacuated tubes or parabolic troughs can be used to drive absorption cycles to provide cooling. For a greater coefficient of performance (COP), collectors with low concentration levels can provide the temperatures (up to around 250°C) needed for double-effect absorption cycles. There is a natural match between solar energy and the need for cooling.

A number of closed heat-driven cooling systems have been built, using solar thermal energy as the main source of heat. These systems often have large cooling capacities of up to several hundred kW. Since the early 2000s, a number of systems have been developed in the small-capacity range, below 100 kW, and, in particular, below 20 kW and down to 4.5 kW. These small systems are single-effect machines of different types, used mainly for residential buildings and small commercial applications.

Although open-cooling cycles are generally used for air conditioning in buildings, closed heat-driven cooling cycles can be used for both air conditioning and industrial refrigeration.

Other solar applications are listed below. The production of potable water using solar energy has been readily adopted in remote or isolated regions (Narayan et al., 2010). Solar stills are widely used in some parts of the world (e.g., Puerto Rico) to supply water to households of up to 10 people (Khanna et al., 2008). In appropriate isolation conditions, solar detoxification can be an effective low-cost treatment for low-contaminant waste (Gumy et al., 2006). Multiple-effect humidification (MEH) desalination units indirectly use heat from highly efficient solar thermal collectors to induce evaporation and condensation inside a thermally isolated, steam-tight container. These MEH systems are now beginning to appear in the market. Also see the report on water desalination by CSP (DLR, 2007) and the discussion of SolarPACES Task VI (SolarPACES, 2009b).

In solar drying, solar energy is used either as the sole source of the required heat or as a supplemental source, and the air flow can be generated by either forced or free (natural) convection (Fudholi et al., 2010). Solar cooking is one of the most widely used solar applications in developing countries (Lahkar and Samdarshi, 2010) though might still be considered an early stage commercial product due to limited overall deployment in comparison to other cooking methods. A solar cooker uses sunlight as its energy source, so no fuel is needed and operating costs are zero. Also, a reliable solar cooker can be constructed easily and quickly from common materials.

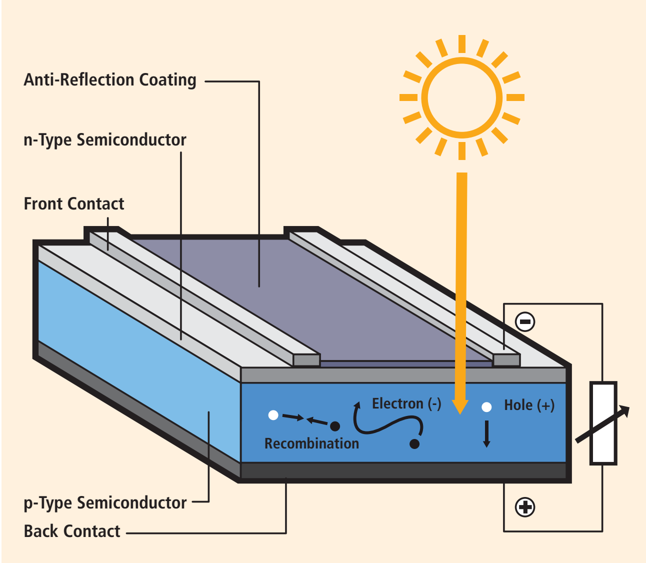


Figure 3.5 | Generic schematic cross-section illustrating the operation of an illuminated solar cell.

3.3.3 Photovoltaic electricity generation

Photovoltaic (PV) solar technologies generate electricity by exploiting the photovoltaic effect. Light shining on a semiconductor such as silicon (Si) generates electron-hole pairs that are separated spatially by an internal electric field created by introducing special impurities into the semiconductor on either side of an interface known as a p-n junction. This creates negative charges on one side of the interface and positive charges are on the other side (Figure 3.5). This resulting charge separation creates a voltage. When the two sides of the illuminated cell are connected to a load, current flows from one side of the device via the load to the other side of the cell. The conversion efficiency of a solar cell is defined as a ratio of output power from the solar cell with unit area (W/cm^2) to the incident solar irradiance. The maximum potential efficiency of a solar cell depends on the absorber material properties and device design. One technique for increasing solar cell efficiency is with a multijunction approach that stacks specially selected absorber materials that can collect more of the solar spectrum since each different material can collect solar photons of different wavelengths.

PV cells consist of organic or inorganic matter. Inorganic cells are based on silicon or non-silicon materials; they are classified as wafer-based cells or thin-film cells. Wafer-based silicon is divided into two different types: monocrystalline and multicrystalline (sometimes called 'polycrystalline').

3.3.3.1 Existing photovoltaic technologies

Existing PV technologies include wafer-based crystalline silicon (c-Si) cells, as well as thin-film cells based on copper indium/gallium disulfide/diselenide ($CuInGaSe_2$; CIGS), cadmium telluride (CdTe), and thin-film silicon (amorphous and microcrystalline silicon). Mono- and multicrystalline silicon wafer PV (including ribbon technologies) are the dominant technologies on the PV market, with a 2009 market share of about 80%; thin-film PV (primarily CdTe and thin-film Si) has the remaining 20% share. Organic PV (OPV) consists of organic absorber materials and is an emerging class of solar cells.

Wafer-based silicon technology includes solar cells made of monocrystalline or multicrystalline wafers with a current thickness of around 200 µm, while the thickness is decreasing down to 150 µm. Single-junction wafer-based c-Si cells have been independently verified to have record energy conversion efficiencies of 25.0% for monocrystalline silicon cells and 20.3% for multicrystalline cells (Green et al., 2010b) under standard test conditions (i.e., irradiance of 1,000 W/m^2, air-mass 1.5, 25°C). The theoretical Shockley-Queisser limit of a single-junction cell with an energy bandgap of crystalline silicon is 31% energy conversion efficiency (Shockley and Queisser, 1961).

Several variations of wafer-based c-Si PV for higher efficiency have been developed, for example, heterojunction solar cells and interdigitated back-contact (IBC) solar cells. Heterojunction solar cells consist of a crystalline silicon wafer base sandwiched by very thin (~5 nm) amorphous silicon layers for passivation and emitter. The highest-efficiency heterojunction solar cell is 23.0% for a 100.4-cm^2 cell (Taguchi et al., 2009). Another advantage is a lower temperature coefficient. The efficiency of conventional c-Si solar cells declines with elevating ambient temperature at a rate of -0.45%/°C, while the heterojunction cells show a lower rate of -0.25%/°C (Taguchi et al., 2009). An IBC solar cell, where both the base and emitter are contacted at the back of the cell, has the advantage of no shading of the front of the cell by a top electrode. The highest efficiency of such a back-contact silicon wafer cell is 24.2% for 155.1 cm^2 (Bunea et al., 2010). Commercial module efficiencies for wafer-based silicon PV range from 12 to 14% for multi-crystalline Si and from 14 to 20% for monocrystalline Si.

Commercial thin-film PV technologies include a range of absorber material systems: amorphous silicon (a-Si), amorphous silicon-germanium, microcrystalline silicon, CdTe and CIGS. These thin-film cells have an absorber layer thickness of a few µm or less and are deposited on glass, metal or plastic substrates with areas of up to 5.7 m^2 (Stein et al., 2009).

The a-Si solar cell, introduced in 1976 (Carlson and Wronski, 1976) with initial efficiencies of 1 to 2%, has been the first commercially successful thin-film PV technology. Because a-Si has a higher light absorption coefficient than c-Si, the thickness of an a-Si cell can be less than 1 µm—that is, more than 100 times thinner than a c-Si cell. Developing higher efficiencies for a-Si cells has been limited by inherent material quality and by light-induced degradation identified as the Staebler-Wronski effect (Staebler and Wronski, 1977). However, research efforts have successfully lowered the impact of the Staebler-Wronski effect to around 10% or less by controlling the microstructure of the film. The highest stabilized efficiency—the efficiency after the light-induced degradation—is reported as 10.1% (Benagli et al., 2009).

Higher efficiency has been achieved by using multijunction technologies with alloy materials, e.g., germanium and carbon or with microcrystalline silicon, to form semiconductors with lower or higher bandgaps, respectively, to cover a wider range of the solar spectrum (Yang and Guha, 1992; Yamamoto et al., 1994; Meier et al., 1997). Stabilized efficiencies of 12 to 13% have been measured for various laboratory devices (Green et al., 2010b).

CdTe solar cells using a heterojunction with cadmium sulphide (CdS) have a suitable energy bandgap of 1.45 electron-volt (eV) (0.232 aJ) with a high coefficient of light absorption. The best efficiency of this cell is 16.7% (Green et al., 2010b) and the best commercially available modules have an efficiency of about 10 to 11%.

The toxicity of metallic cadmium and the relative scarcity of tellurium are issues commonly associated with this technology. Although several assessments of the risk (Fthenakis and Kim, 2009; Zayed and Philippe, 2009) and scarcity (Green et al., 2009; Wadia et al., 2009) are available, no consensus exists on these issues. It has been reported that this potential hazard can be mitigated by using a glass-sandwiched module design and by recycling the entire module and any industrial waste (Sinha et al., 2008).

The CIGS material family is the basis of the highest-efficiency thin-film solar cells to date. The copper indium diselenide ($CuInSe_2$)/CdS solar cell was invented in the early 1970s at AT&T Bell Labs (Wagner et al., 1974). Incorporating Ga and/or S to produce $CuInGa(Se,S)_2$ results in the benefit of a widened bandgap depending on the composition (Dimmler and Schock, 1996). CIGS-based solar cells have been validated at an efficiency of 20.1% (Green et al., 2010b). Due to higher efficiencies and lower manufacturing energy consumptions, CIGS cells are currently in the industrialization phase, with best commercial module efficiencies of up to 13.1% (Kushiya, 2009) for $CuInGaSe_2$ and 8.6% for $CuInS_2$ (Meeder et al., 2007). Although it is acknowledged that the scarcity of In might be an issue, Wadia et al. (2009) found that the current known economic indium reserves would allow the installation of more than 10 TW of CIGS-based PV systems.

High-efficiency solar cells based on a multijunction technology using III-V semiconductors (i.e., based on elements from the III and V columns of the periodic chart), for example, gallium arsenide (GaAs) and gallium indium phosphide (GaInP) , can have superior efficiencies. These cells were originally developed for space use and are already commercialized. An economically feasible terrestrial application is the use of these cells in concentrating PV (CPV) systems, where concentrating optics are used to focus sunlight onto high efficiency solar cells (Bosi and Pelosi, 2007). The most commonly used cell is a triple-junction device based on GaInP/GaAs/germanium (Ge), with a record efficiency of 41.6% for a lattice-matched cell (Green et al., 2010b) and 41.1% for a metamorphic or lattice-mismatched device (Bett et al., 2009). Sub-module efficiencies have reached 36.1% (Green et al., 2010b). Another advantage of the concentrator system is that cell efficiencies increase under higher irradiance (Bosi and Pelosi, 2007), and the cell area can be decreased in proportion to the concentration level. Concentrator applications, however, require direct-normal irradiation, and are thus suited for specific climate conditions with low cloud coverage.

3.3.3.2 Emerging photovoltaic technologies

Emerging PV technologies are still under development and in laboratory or (pre-) pilot stage, but could become commercially viable within the next decade. They are based on very low-cost materials and/or processes and include technologies such as dye-sensitized solar cells, organic solar cells and low-cost (printed) versions of existing inorganic thin-film technologies.

Electricity generation by dye-sensitized solar cells (DSSCs) is based on light absorption in dye molecules (the 'sensitizers') attached to the very large surface area of a nanoporous oxide semiconductor electrode (usually titanium dioxide), followed by injection of excited electrons from the dye into the oxide. The dye/oxide interface thus serves as the separator of negative and positive charges, like the p-n junction in other devices. The negatively charged electrons are then transported through the semiconductor electrode and reach the counter electrode through the load, thus generating electricity. The injected electrons from the dye molecules are replenished by electrons supplied through a liquid electrolyte that penetrates the pores of the semiconductor electrode, providing the electrical path from the counter electrode (Graetzel, 2001). State-of-the-art DSSCs have achieved a top conversion efficiency of 10.4% (Chiba et al., 2005). Despite the gradual improvements since its discovery in 1991 (O'Regan and Graetzel, 1991), long-term stability against ultraviolet light irradiation, electrolyte leakage and high ambient temperatures continue to be key issues in commercializing these PV cells.

Organic PV (OPV) cells use stacked solid organic semiconductors, either polymers or small organic molecules. A typical structure of a small-molecule OPV cell consists of a stack of p-type and n-type organic semiconductors forming a planar heterojunction. The short-lived nature of the tightly bound electron-hole pairs (excitons) formed upon light absorption limits the thickness of the semiconductor layers that can be used—and therefore, the efficiency of such devices. Note that excitons need to move to the interface where positive and negative charges can be separated before they recombine. If the travel distance is short, the 'active' thickness of material is small and not all light can be absorbed within that thickness.

The efficiency achieved with single-junction OPV cells is about 5% (Li et al., 2005), although predictions indicate about twice that value or higher can be achieved (Forrest, 2005; Koster et al., 2006). To decouple exciton transport distances from optical thickness (light absorption), so-called bulk-heterojunction devices have been developed. In these devices, the absorption layer is made of a nanoscale mixture of p- and n-type materials to allow excitons to reach the interface within their lifetime, while also enabling a sufficient macroscopic layer thickness. This bulk-heterojunction structure plays a key role in improving the efficiency, to a record value of 7.9% in 2009 (Green et al., 2010a). The developments in cost and processing (Brabec, 2004; Krebs, 2005) of materials have caused OPV research to advance further. Also, the main development challenge is to achieve a sufficiently high stability in combination with a reasonable efficiency.

3.3.3.3 Novel photovoltaic technologies

Novel technologies are potentially disruptive (high-risk, high-potential) approaches based on new materials, devices and conversion concepts. Generally, their practically achievable conversion efficiencies and cost structure are still unclear. Examples of these approaches include intermediate-band semiconductors, hot-carrier devices, spectrum converters, plasmonic solar cells, and various applications of quantum dots (Section 3.7.3). The emerging technologies described in the previous section primarily aim at very low cost, while achieving a sufficiently high efficiency and stability. However, most of the novel technologies aim at reaching very high efficiencies by making better use of the entire solar spectrum from infrared to ultraviolet.

3.3.3.4 Photovoltaic systems

A photovoltaic system is composed of the PV module, as well as the balance of system (BOS) components, which include an inverter, storage devices, charge controller, system structure, and the energy network. The system must be reliable, cost effective, attractive and match with the electric grid in the future (US Photovoltaic Industry Roadmap Steering Committee, 2001; Navigant Consulting Inc., 2006; EU PV European Photovoltaic Technology Platform, 2007; Kroposki et al., 2008; NEDO, 2009).

At the component level, BOS components for grid-connected applications are not yet sufficiently developed to match the lifetime of PV modules. Additionally, BOS component and installation costs need to be reduced. Moreover, devices for storing large amounts of electricity (over 1 MWh or 3,600 MJ) will be adapted to large PV systems in the new energy network. As new module technologies emerge in the future, some of the ideas relating to BOS may need to be revised. Furthermore, the quality of the system needs to be assured and adequately maintained according to defined standards, guidelines and procedures. To ensure system quality, assessing performance is important, including on-line analysis (e.g., early fault detection) and off-line analysis of PV systems. The knowledge gathered can help to validate software for predicting the energy yield of future module and system technology designs.

To increasingly penetrate the energy network, PV systems must use technology that is compatible with the electric grid and energy supply and demand. System designs and operation technologies must also be developed in response to demand patterns by developing technology to forecast the power generation volume and to optimize the storage function. Moreover, inverters must improve the quality of grid electricity by controlling reactive power or filtering harmonics with communication in a new energy network that uses a mixture of inexpensive and effective communications systems and technologies, as well as smart meters (see Section 8.2.1).

3.3.3.5 Photovoltaic applications

Photovoltaic applications include PV power systems classified into two major types: those not connected to the traditional power grid (i.e., off-grid applications) and those that are connected (i.e., grid-connected applications). In addition, there is a much smaller, but stable, market segment for consumer applications.

Off-grid PV systems have a significant opportunity for economic application in the un-electrified areas of developing countries. Figure 3.6 shows the ratio of various off-grid and grid-connected systems in the Photovoltaic Power Systems (PVPS) Programme countries. Of the total capacity installed in these countries during 2009, only about 1.2% was installed in off-grid systems that now make up 4.2% of the cumulative installed PV capacity of the IEA PVPS countries (IEA, 2010e).

Off-grid centralized PV mini-grid systems have become a reliable alternative for village electrification over the last few years. In a PV mini-grid system, energy allocation is possible. For a village located in an isolated area and with houses not separated by too great a distance, the power may flow in the mini-grid without considerable losses. Centralized systems for local power supply have different technical advantages concerning electrical performance, reduction of storage needs, availability

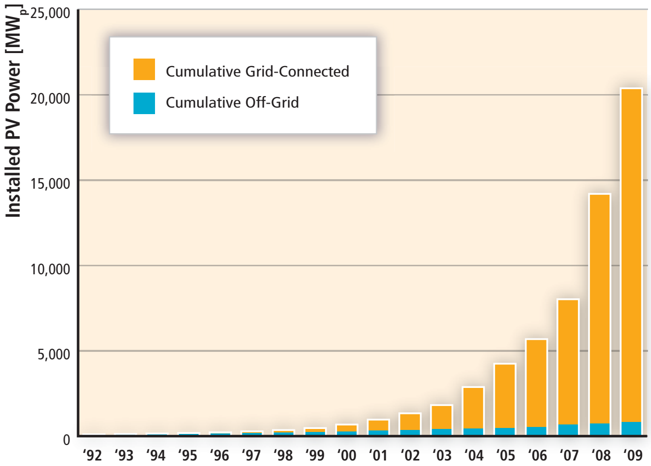


Figure 3.6 | Historical trends in cumulative installed PV power of off-grid and grid-connected systems in the OECD countries (IEA, 2010e). Vertical axis is in peak megawatts.

of energy, and dynamic behaviour. Centralized PV mini-grid systems could be the least-cost options for a given level of service, and they may have a diesel generator set as an optional balancing system or operate as a hybrid PV-wind-diesel system. These kinds of systems are relevant for reducing and avoiding diesel generator use in remote areas (Munoz et al., 2007; Sreeraj et al., 2010).

Grid-connected PV systems use an inverter to convert electricity from direct current (DC)—as produced by the PV array—to alternating current (AC), and then supply the generated electricity to the electricity network. Compared to an off-grid installation, system costs are lower because energy storage is not generally required, since the grid is used as a buffer. The annual output yield ranges from 300 to 2,000 kWh/kW (Clavadetscher and Nordmann, 2007; Gaiddon and Jedliczka, 2007; Kurokawa et al., 2007; Photovoltaic Geographic Information System, 2008) for several installation conditions in the world. The average annual performance ratio—the ratio between average AC system efficiency and standard DC module efficiency—ranges from 0.7 to 0.8 (Clavadetscher and Nordmann, 2007) and gradually increases further to about 0.9 for specific technologies and applications.

Grid-connected PV systems are classified into two types of applications: distributed and centralized. Grid-connected *distributed* PV systems are installed to provide power to a grid-connected customer or directly to the electricity network. Such systems may be: 1) on or integrated into the customer's premises, often on the demand side of the electricity meter; 2) on public and commercial buildings; or 3) simply in the built environment such as on motorway sound barriers. Typical sizes are 1 to 4 kW for residential systems, and 10 kW to several MW for rooftops on public and industrial buildings.

These systems have a number of advantages: distribution losses in the electricity network are reduced because the system is installed at the point of use; extra land is not required for the PV system, and costs for mounting the systems can be reduced if the system is mounted on an existing structure; and the PV array itself can be used as a cladding or roofing material, as in building-integrated PV (Eiffert, 2002; Ecofys Netherlands BV, 2007; Elzinga, 2008).

An often-cited disadvantage is the greater sensitivity to grid interconnection issues, such as overvoltage and unintended islanding (Kobayashi and Takasaki, 2006; Cobben et al., 2008; Ropp et al., 2008). However, much progress has been made to mitigate these effects, and today, by Institute of Electrical and Electronics Engineers (IEEE) and Underwriter Laboratories standards (IEEE 1547 (2008), UL 1741), all inverters must have the function of the anti-islanding effect.

Grid-connected *centralized* PV systems perform the functions of centralized power stations. The power supplied by such a system is not associated with a particular electricity customer, and the system is not located to specifically perform functions on the electricity network other than the supply of bulk power. Typically, centralized systems are mounted on the ground, and they are larger than 1 MW.

The economical advantage of these systems is the optimization of installation and operating cost by bulk buying and the cost effectiveness of the PV components and balance of systems at a large scale. In addition, the reliability of centralized PV systems can be greater than distributed PV systems because they can have maintenance systems with monitoring equipment, which can be a smaller part of the total system cost.

Multi-functional PV, daylighting and solar thermal components involving PV or solar thermal that have already been introduced into the built environment include the following: shading systems made from PV and/or solar thermal collectors; hybrid PV/thermal (PV/T) systems that generate electricity and heat from the same 'panel/collector' area; semi-transparent PV windows that generate electricity and transmit daylight from the same surface; façade collectors; PV roofs; thermal energy roof systems; and solar thermal roof-ridge collectors. Currently, fundamental and applied R&D activities are also underway related to developing other products, such as transparent solar thermal window collectors, as well as façade elements that consist of vacuum-insulation panels, PV panels, heat pump, and a heat-recovery system connected to localized ventilation.

Solar energy can be integrated within the building envelope and with energy conservation methods and smart-building operating strategies. Much work over the last decade or so has gone into this integration, culminating in the 'net-zero' energy building.

Much of the early emphasis was on integrating PV systems with thermal and daylighting systems. Bazilian et al. (2001) and Tripanagnostopoulos (2007) listed methods for doing this and reviewed case studies where the methods had been applied. For example, PV cells can be laid on the absorber plate of a flat-plate solar collector. About 6 to 20% of the solar energy absorbed on the cells is converted to electricity; the remaining roughly 80% is available as low-temperature heat to be transferred to the fluid being heated. The resulting unit produces both heat and electricity and requires only slightly more than half the area used if the two conversion devices had been mounted side by side and worked independently. PV cells have also been developed to be applied to windows to allow daylighting and passive solar gain. Reviews of recent work in this area are provided by Chow (2010) and Arif Hasan and Sumathy (2010).

Considerable work has also been done on architecturally integrating the solar components into the building. Any new solar building should be very well insulated, well sealed, and have highly efficient windows and heat recovery systems. Probst and Roecker (2007), surveying the opinions of more than 170 architects and engineers who examined numerous existing solar buildings, concluded the following: 1) best integration is achieved when the solar component is integrated as a construction element, and 2) appearance—including collector colour, orientation and jointing—must sometimes take precedence over performance in the overall design. In describing 16 case studies of building-integrated photovoltaics, Eiffert and Kiss (2000) identified two main products available on the architectural market: façade systems and roof systems. Façade systems include curtain wall products, spandrel panels and glazings; roofing products include tiles, shingles, standing-seam products and skylights. These can be integrated as components or constitute the entire structure (as in the case of a bus shelter).

The idea of the net-zero-energy solar building has sparked recent interest. Such buildings send as much excess PV-generated electrical energy to the grid as the energy they draw over the year. An IEA Task is considering how to achieve this goal (IEA NZEB, 2009). Recent examples for the Canadian climate are provided by Athienitis (2008). Starting from a building that meets the highest levels of conservation, these homes use hybrid air-heating/PV panels on the roof; the heated air is used for space heating or as a source for a heat pump. Solar water-heating collectors are included, as is fenestration permitting a large passive gain through equatorial-facing windows. A key feature is a ground-source heat pump, which provides a small amount of residual heating in the winter and cooling in the summer.

Smart solar-building control strategies may be used to manage the collection, storage and distribution of locally produced solar electricity and heat to reduce and shift peak electricity demand from the grid. An example of a smart solar-building design is given by Candanedo and Athienitis (2010), where predictive control based on weather forecasts one day ahead and real-time prediction of building response are used to optimize energy performance while reducing peak electricity demand.

3.3.4 Concentrating solar power electricity generation

Concentrating solar power (CSP) technologies produce electricity by concentrating direct-beam solar irradiance to heat a liquid, solid or gas that is then used in a downstream process for electricity generation. The majority of the world's electricity today—whether generated by coal, gas, nuclear, oil or biomass—comes from creating a hot fluid. CSP simply provides an alternative heat source. Therefore, an attraction of this technology is that it builds on much of the current know-how on power generation in the world today. And it will benefit not only from ongoing advances in solar concentrator technology, but also as improvements continue to be made in steam and gas turbine cycles.

Any concentrating solar system depends on direct-beam irradiation as opposed to global horizontal irradiation as for flat-plate systems. Thus, sites must be chosen accordingly, and the best sites for CSP are in near-equatorial cloud-free regions such as the North African desert. The average capacity factor of a solar plant will depend on the quality of the solar resource.

Some of the key advantages of CSP include the following: 1) it can be installed in a range of capacities to suit varying applications and conditions, from tens of kW (dish/Stirling systems) to multiple MWs (tower and trough systems); 2) it can integrate thermal storage for peaking loads (less than one hour) and intermediate loads (three to six hours); 3) it has modular and scalable components; and 4) it does not require exotic materials. This section discusses various types of CSP systems and thermal storage for these systems.

Large-scale CSP plants most commonly concentrate sunlight by reflection, as opposed to refraction with lenses. Concentration is either to a line (linear focus) as in trough or linear Fresnel systems or to a point (point focus) as in central-receiver or dish systems. The major features of each type of CSP system are illustrated in Figure 3.7 and are described below.

In trough concentrators, long rows of parabolic reflectors concentrate the solar irradiance by the order of 70 to 100 times onto a heat collection element (HCE) mounted along the reflector's focal line. The troughs track the Sun around one axis, with the axis typically being oriented north-south. The HCE comprises a steel inner pipe (coated with a solar-selective surface) and a glass outer tube, with an evacuated space in between. Heat-transfer oil is circulated through the steel pipe and heated to about 390°C. The hot oil from numerous rows of troughs is passed through a heat exchanger to generate steam for a conventional steam turbine generator (Rankine cycle). Land requirements are of the order of 2 km^2 for a 100-MW_e plant, depending on the collector technology and assuming no storage. Alternative heat transfer fluids to the synthetic oil commonly used in trough receivers, such as steam and molten salt, are being developed to enable higher temperatures and overall efficiencies, as well as integrated thermal storage in the case of molten salt.

Linear Fresnel reflectors use long lines of flat or nearly flat mirrors, which allow the moving parts to be mounted closer to the ground, thus reducing structural costs. (In contrast, large trough reflectors presently use thermal bending to achieve the curve required in the glass surface.) The receiver is a fixed inverted cavity that can have a simpler construction than evacuated tubes and be more flexible in sizing. The attraction of

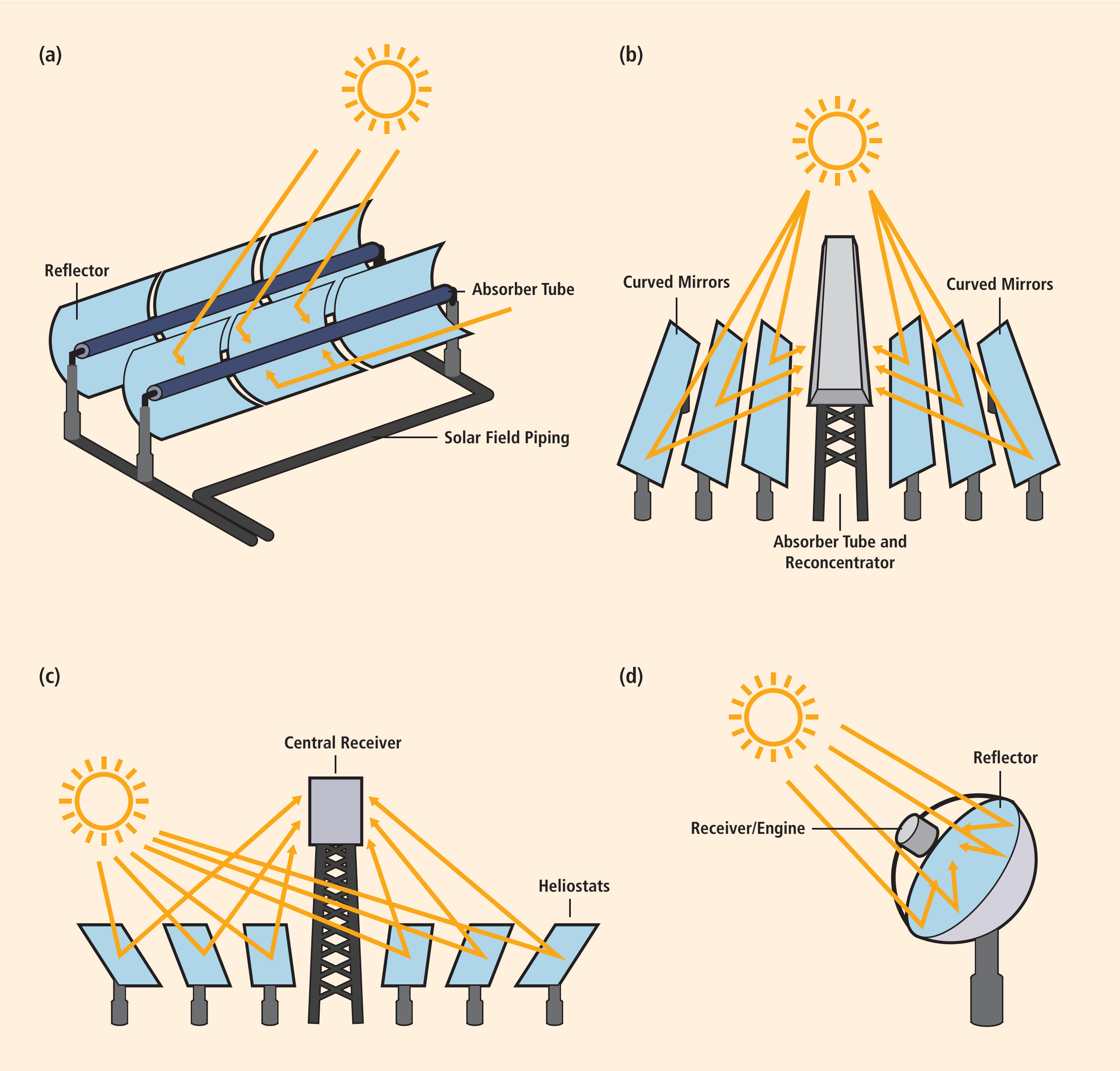


Figure 3.7 | Schematic diagrams showing the underlying principles of four basic CSP configurations: (a) parabolic trough, (b) linear Fresnel reflector, (c) central receiver/power tower, and (d) dish systems (Richter et al., 2009).

linear Fresnel reflectors is that the installed costs on a per square metre basis can be lower than for trough systems. However, the annual optical performance is less than that for a trough.

Central receivers (or power towers), which are one type of point-focus collector, are able to generate much higher temperatures than troughs and linear Fresnel reflectors, although requiring two-axis tracking as the Sun moves through solar azimuth and solar elevation. This higher temperature is a benefit because higher-temperature thermodynamic cycles used for generating electricity are more efficient. This technology uses an array of mirrors (heliostats), with each mirror tracking the Sun and reflecting the light onto a fixed receiver atop a tower. Temperatures of more than 1,000°C can be reached. Central receivers can easily generate the maximum temperatures of advanced steam turbines, can use high-temperature molten salt as the heat transfer fluid, and can be used to power gas turbine (Brayton) cycles.

Dish systems include an ideal optical reflector and therefore are suitable for applications requiring high temperatures. Dish reflectors are paraboloid and concentrate the solar irradiation onto a receiver mounted at the focal point, with the receiver moving with the dish. Dishes have been used to power Stirling engines at 900°C, and also for steam generation. There is now significant operational experience with dish/Stirling engine systems, and commercial rollout is planned. In 2010, the capacity of each Stirling engine is small—on the order of 10 to 25 $kW_{electric}$. The largest solar dishes have a 485-m^2 aperture and are in research facilities or demonstration plants.

In *thermal storage*, the heat from the solar field is stored prior to reaching the turbine. Thermal storage takes the form of sensible or latent heat storage (Gil et al., 2010; Medrano et al., 2010). The solar field needs to be oversized so that enough heat can be supplied to both operate the turbine during the day and, in parallel, charge the thermal storage. The term 'solar multiple' refers to the total solar field area installed divided by the solar field area needed to operate the turbine at design point without storage. Thermal storage for CSP systems needs to be at a temperature higher than that needed for the working fluid of the turbine. As such, system temperatures are generally between 400°C and 600°C, with the lower end for troughs and the higher end for towers. Allowable temperatures are also dictated by the limits of the media available. Examples of storage media include molten salt (presently comprising separate hot and cold tanks), steam accumulators (for short-term storage only), solid ceramic particles, high-temperature phase-change materials, graphite, and high-temperature concrete. The heat can then be drawn from the storage to generate steam for a turbine, as and when needed. Another type of storage associated with high-temperature CSP is thermochemical storage, where solar energy is stored chemically. This is discussed more fully in Sections 3.3.5 and 3.7.5.

Thermal energy storage integrated into a system is an important attribute of CSP. Until recently, this has been primarily for operational purposes, providing 30 minutes to 1 hour of full-load storage. This eases the impact of thermal transients such as clouds on the plant, assists start-up and shut-down, and provides benefits to the grid. Trough plants are now designed for 6 to 7.5 hours of storage, which is enough to allow operation well into the evening when peak demand can occur and tariffs are high. Trough plants in Spain are now operating with molten-salt storage. In the USA, Abengoa Solar's 280-MW Solana trough project, planned to be operational by 2013, intends to integrate six hours of thermal storage. Towers, with their higher temperatures, can charge and store molten salt more efficiently. Gemasolar, a 17-MW_e solar tower project under construction in Spain, is designed for 15 hours of storage, giving a 75% annual capacity factor (Arce et al., 2011).

Thermal storage is a means of providing dispatchability. Hybridization with non-renewable fuels is another way in which CSP can be designed to be dispatchable. Although the back-up fuel itself may not be renewable (unless it is biomass-derived), it provides significant operational benefits for the turbine and improves solar yield.

CSP applications range from small distributed systems of tens of kW to large centralized power stations of hundreds of MW.

Stirling and Brayton cycle generation in CSP can be installed in a wide range from small distributed systems to clusters forming medium- to large-capacity power stations. The dish/Stirling technology has been under development for many years, with advances in dish structures, high-temperature receivers, use of hydrogen as the circulating working fluid, as well as some experiments with liquid metals and improvements in Stirling engines—all bringing the technology closer to commercial deployment. Although the individual unit size may only be of the order of tens of kW_e, power stations having a large capacity of up to 800 MW_e have been proposed by aggregating many modules. Because each dish represents a stand-alone electricity generator, from the perspective of distributed generation there is great flexibility in the capacity and rate at which units are installed. However, the dish technology is less likely to integrate thermal storage.

An alternative to the Stirling engine is the Brayton cycle, as used by gas turbines. The attraction of these engines for CSP is that they are already in significant production, being used for distributed generation fired with landfill gas or natural gas. In the solarized version, the air is instead heated by concentrated solar irradiance from a tower or dish reflector. It is also possible to integrate with a biogas or natural gas combustor to back up the solar. Several developments are currently underway based on solar tower and micro-turbine combinations.

Centralized CSP benefits from the economies of scale offered by large-scale plants. Based on conventional steam and gas turbine cycles, much of the technological know-how of large power station design and practice is already in place. However, although larger capacity has significant cost benefits, it has also tended to be an inhibitor until recently because of the much larger investment commitment required from investors. In addition, larger power stations require strong infrastructural support, and new or augmented transmission capacity may be needed.

The earliest commercial CSP plants were the 354 MW of Solar Electric Generating Stations in California—deployed between 1985 and 1991—that continue to operate commercially today. As a result of the positive experiences and lessons learned from these early plants, the trough systems tend to be the technology most often applied today as the CSP industry grows. In Spain, regulations to date have mandated that the largest capacity unit that can be installed is 50 MW_e to help stimulate industry competition. In the USA, this limitation does not exist, and proposals are in place for much larger plants—280 MW_e in the case of troughs and 400-MW_e plants (made up of four modules) based on towers. There are presently two operational solar towers of 10 and 20 MW_e, and all tower developers plan to increase capacity in line with technology development, regulations and investment capital. Multiple dishes have also been proposed as a source of aggregated heat, rather than distributed-generation Stirling or Brayton units.

CSP or PV electricity can also be used to power reverse-osmosis plants for desalination. Dedicated CSP desalination cycles based on pressure and temperature are also being developed for desalination (see Section 3.3.2).

3.3.5 Solar fuel production

Solar fuel technologies convert solar energy into chemical fuels, which can be a desirable method of storing and transporting solar energy. They can be used in a much wider variety of higher-efficiency applications than just electricity generation cycles. Solar fuels can be processed into liquid transportation fuels or used directly to generate electricity in fuel cells; they can be employed as fuels for high-efficiency gas-turbine cycles or internal combustion engines; and they can serve for upgrading fossil fuels, CO_2 synthesis, or for producing industrial or domestic heat. The challenge is to produce large amounts of chemical fuels directly from sunlight in cost-effective ways and to minimize adverse effects on the environment (Steinfeld and Meier, 2004).

Solar fuels that can be produced include synthesis gas (syngas, i.e., mixed gases of carbon monoxide and hydrogen), pure hydrogen (H_2) gas, dimethyl ether (DME) and liquids such as methanol and diesel. The high energy density of H_2 (on a mass basis) and clean conversion give it attractive properties as a future fuel and it is also used as a feedstock for many industrial processes. H_2 has a higher energy density than batteries, although batteries have a higher round-trip efficiency. However, its very low energy density on a volumetric basis poses economic challenges associated with its storage and transport. It will require significant new distribution infrastructure and either new designs of internal combustion engine or a move to fuel cells. Additionally, the synthesis of hydrogen with CO_2 can produce hydrocarbon fuels that are compatible with existing infrastructures. DME gas is similar to liquefied petroleum gas (LPG) and easily stored. Methanol is liquid and can replace gasoline without significant changes to the engine or the fuel distribution infrastructure. Methanol and DME can be used for fuel cells after reforming, and DME can also be used in place of LPG. Fischer-Tropsch processes can produce hydrocarbon fuels and electricity (see Sections 2.6 and 8.2.4).

There are three basic routes, alone or in combination, for producing storable and transportable fuels from solar energy: 1) the electrochemical route uses solar electricity from PV or CSP systems followed by an electrolytic process; 2) the photochemical/photobiological route makes direct use of solar photon energy for photochemical and photobiological processes; and 3) the thermochemical route uses solar heat at moderate and/or high temperatures followed by an endothermic thermochemical process (Steinfeld and Meier, 2004). Note that the electrochemical and thermochemical routes apply to any RE technology, not exclusively to solar technologies.

Figure 3.8 illustrates possible pathways to produce H_2 or syngas from water and/or fossil fuels using concentrated solar energy as the source of high-temperature process heat. Feedstocks include *inorganic* compounds such as water and CO_2, and *organic* sources such as coal, biomass and natural gas (NG). See Chapter 2 for parallels with biomass-derived syngas.

Electrolysis of water can use solar electricity generated by PV or CSP technology in a conventional (alkaline) electrolyzer, considered a benchmark for producing solar hydrogen. With current technologies, the overall solar-to-hydrogen energy conversion efficiency ranges between 10 and 14%, assuming electrolyzers working at 70% efficiency and solar electricity being produced at 15% (PV) and 20% (CSP) annual efficiency. The electricity demand for electrolysis can be significantly reduced if the electrolysis of water proceeds at higher temperatures (800° to 1,000°C) via solid-oxide electrolyzer cells (Jensen et al., 2007). In this case, concentrated solar energy can be applied to provide both the high-temperature process heat and the electricity needed for the high-temperature electrolysis.

Thermolysis and thermochemical cycles are a long-term sustainable and carbon-neutral approach for hydrogen production from water. This route involves energy-consuming (endothermic) reactions that make use of concentrated solar irradiance as the energy source for high-temperature process heat (Abanades et al., 2006). Solar thermolysis requires temperatures above 2,200°C and raises difficult challenges for reactor materials and gas separation. Water-splitting thermochemical cycles allow operation at lower temperature, but require several chemical reaction steps and also raise challenges because of inefficiencies associated with heat transfer and product separation at each step.

Decarbonization of fossil fuels is a near- to mid-term transition pathway to solar hydrogen that encompasses the carbothermal reduction of metal oxides (Epstein et al., 2008) and the decarbonization of fossil fuels via solar cracking (Spath and Amos, 2003; Rodat et al., 2009), reforming (Möller et al., 2006) and gasification (Z'Graggen and Steinfeld, 2008; Piatkowski et al., 2009). These routes are being pursued by European, Australian and US academic and industrial research consortia. Their technical feasibility has been demonstrated in concentrating solar chemical pilot plants at the power level of 100 to 500 kW_{th}. Solar hybrid fuel can be produced by supplying concentrated solar thermal energy to the endothermic processes of methane and biomass reforming—that is, solar heat is used for process energy only, and fossil fuels are still a required input. Some countries having vast solar and natural gas resources, but a relatively small domestic energy market (e.g., the Middle East and Australia) are in a position to produce and export solar energy in the form of liquid fuels.

Solar fuel synthesis from solar hydrogen and CO_2 produces hydrocarbons that are compatible with existing energy infrastructures such as the natural gas network or existing fuel supply structures. The renewable methane process combines solar hydrogen with CO_2 from the

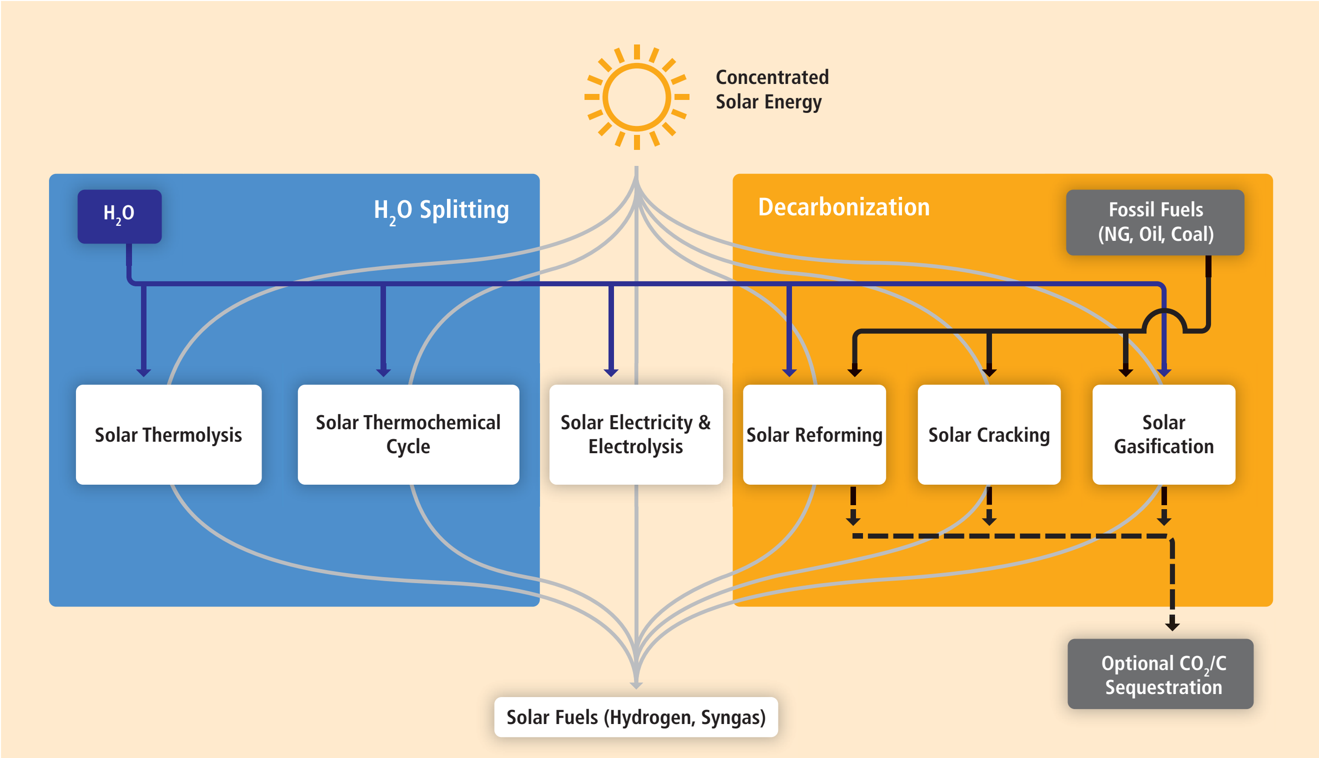


Figure 3.8 | Thermochemical routes for solar fuels production, indicating the chemical source of H_2: water (H_2O) for solar thermolysis and solar thermochemical cycles to produce H_2 only; fossil or biomass fuels as feedstock for solar cracking to produce H_2 and carbon (C); or a combination of fossil/biomass fuels and H_2O/CO_2 for solar reforming and gasification to produce syngas, H_2 and carbon monoxide (CO). For the solar decarbonization processes, sequestration of the CO_2/C may be considered (from Steinfeld and Meier, 2004; Steinfeld, 2005).

atmosphere or other sources in a synthesis reactor with a nickel catalyst. In this way, a substitute for natural gas is produced that can be stored, transported and used in gas power plants, heating systems and gas vehicles (Sterner, 2009).

Solar methane can be produced using water, air, solar energy and a source of CO_2. Possible CO_2 sources are biomass, industry processes or the atmosphere. CO_2 is regarded as the carrier for hydrogen in this energy system. By separating CO_2 from the combustion process of solar methane, CO_2 can be recycled in the energy system or stored permanently. Thus, carbon sink energy systems powered by RE can be created (Sterner, 2009). The first pilot plants at the kW scale with atmospheric CO_2 absorption have been set up in Germany, proving the technical feasibility. Scaling up to the utility MW scale is planned in the next few years (Specht et al., 2010).

In an alternative conversion step, liquid fuels such as Fischer-Tropsch diesel, DME, methanol or solar kerosene (jet fuel) can be produced from solar energy and CO_2/water (H_2O) for long-distance transportation. The main advantages of these solar fuels are the same range as fossil fuels (compared to the generally reduced range of electric vehicles), less competition for land use, and higher per-hectare yields compared to biofuels. Solar energy can be harvested via natural photosynthesis in biofuels with an efficiency of 0.5%, via PV power and solar fuel conversion (technical photosynthesis) with an efficiency of 10% (Sterner, 2009) and via solar-driven thermochemical dissociation of CO_2 and H_2O using metal oxide redox reactions, yielding a syngas mixture of carbon monoxide (CO) and H_2, with a solar-to-fuel efficiency approaching 20% (Chueh et al., 2010). This approach would provide a solution to the issues and controversy surrounding existing biofuels, although the cost of this technology is a possible constraint.

3.4 Global and regional status of market and industry development

This section looks at the five key solar technologies, first focusing on installed capacity and generated energy, then on industry capacity and supply chains, and finally on the impact of policies specific to these technologies.

3.4.1 Installed capacity and generated energy

This subsection discusses the installed capacity and generated energy within the five technology areas of passive solar, active solar heating and cooling, PV electricity generation, CSP electricity generation, and solar fuel production.

For *passive solar technologies*, no estimates are available at this time for the installed capacity of passive solar or the energy generated or saved through this technology.

For *active solar heating*, the total installed capacity worldwide was about 149 GW_{th} in 2008 and 180 GW_{th} in 2009 (Weiss and Mauthner, 2010; REN21, 2010).

In 2008, new capacity of 29.1 GW_{th}, corresponding to 41.5 million m^2 of solar collectors, was installed worldwide (Weiss and Mauthner, 2010). In 2008, China accounted for about 79% of the installations of glazed collectors, followed by the EU with 14.5%.

The overall new installations grew by 34.9% compared to 2007. The growth rate in 2006/2007 was 18.8%. The main reasons for this growth were the high growth rates of glazed water collectors in China, Europe and the USA.

In 2008, the global market had high growth rates for evacuated-tube collectors and flat-plate collectors, compared to 2007. The market for unglazed air collectors also increased significantly, mainly due to the installation of 23.9 MW_{th} of new systems in Canada.

Compared to 2007, the 2008 installation rates for new unglazed, glazed flat-plate, and evacuated-tube collectors were significantly up in Jordan, Cyprus, Canada, Ireland, Germany, Slovenia, Macedonia (FYROM), Tunisia, Poland, Belgium and South Africa.

New installations in China, the world's largest market, again increased significantly in 2008 compared to 2007, reaching 21.7 GW_{th}. After a market decline in Japan in 2007, the growth rate was once again positive in 2008.

Market decreases compared to 2007 were reported for Israel, the Slovak Republic and the Chinese province of Taiwan.

The main markets for unglazed water collectors are still found in the USA (0.8 GW_{th}), Australia (0.4 GW_{th}), and Brazil (0.08 GW_{th}). Notable markets are also in Austria, Canada, Mexico, The Netherlands, South Africa, Spain, Sweden and Switzerland, with values between 0.07 and 0.01 GW_{th} of new installed unglazed water collectors in 2008.

Comparison of markets in different countries is difficult due to the wide range of designs used for different climates and different demand requirements. In Scandinavia and Germany, a solar heating system will typically be a combined water-heating and space-heating system, known as a solar combisystem, with a collector area of 10 to 20 m^2. In Japan, the number of solar domestic water-heating systems is large, but most installations are simple integral preheating systems. The market in Israel is large due to a favourable climate, as well as regulations mandating installation of solar water heaters. The largest market is in China, where there is widespread adoption of advanced evacuated-tube solar collectors. In terms of per capita use, Cyprus is the leading country in the world, with an installed capacity of 527 kW_{th} per 1,000 inhabitants.

The type of application of solar thermal energy varies greatly in different countries (Weiss and Mauthner, 2010). In China (88.7 GW_{th}), Europe (20.9 GW_{th}) and Japan (4.4 GW_{th}), flat-plate and evacuated-tube collectors mainly prepare hot water and provide space heating. However, in the USA and Canada, swimming pool heating is still the dominant application, with an installed capacity of 12.9 GW_{th} of unglazed plastic collectors.

The biggest reported solar thermal system for industrial process heat was installed in China in 2007. The 9 MW_{th} plant produces heat for a textile company. About 150 large-scale plants (>500 m^2; 350 kW_{th})[1] with a total capacity of 160 MW_{th} are in operation in Europe. The largest plants for solar-assisted district heating are located in Denmark (13 MW_{th}) and Sweden (7 MW_{th}).

In Europe, the market size more than tripled between 2002 and 2008. However, even in the leading European solar thermal markets of Austria, Greece, and Germany, only a minor portion of residential homes use solar thermal. For example, in Germany, only about 5% of one- and two-family homes are using solar thermal energy.

The European market has the largest variety of different solar thermal applications, including systems for hot-water preparation, plants for space heating of single- and multi-family houses and hotels, large-scale plants for district heating, and a growing number of systems for air-conditioning, cooling and industrial applications.

Advanced applications such as solar cooling and air conditioning (Henning, 2004, 2007), industrial applications (POSHIP, 2001) and desalination/water treatment are in the early stages of development. Only a few hundred first-generation systems are in operation.

For *PV electricity generation*, newly installed capacity in 2009 was about 7.5 GW, with shipments to first point in the market at 7.9 GW (Jäger-Waldau, 2010a; Mints, 2010). This addition brought the cumulative installed PV capacity worldwide to about 22 GW—a capacity able to generate up to 26 TWh (93,600 TJ) per year. More than 90% of this capacity is installed in three leading markets: the EU27 with 16 GW (73%), Japan with 2.6 GW (12%), and the USA with 1.7 GW (8%) (Jäger-Waldau, 2010b). These markets are dominated by grid-connected PV systems, and growth within PV markets has been stimulated by various government programmes around the world. Examples of such programmes include feed-in tariffs in Germany and Spain, and various mechanisms in the USA, such as buy-down incentives, investment tax credits, performance-based incentives and RE quota systems. For 2010,

1 To enable comparison, the IEA's Solar Heating and Cooling Programme, together with the European Solar Thermal Industry Federation and other major solar thermal trade associations, publish statistics in kW_{th} (kilowatt thermal) and use a factor of 0.7 kW_{th}/m^2 to convert square metres of collector area into installed thermal capacity (kW_{th}).

the market is estimated between 9 and 24 GW of additional installed PV systems, with a consensus value in the 13 GW range (Jäger-Waldau, 2010a).

Figure 3.9 illustrates the cumulative installed capacity for the top eight PV markets through 2009, including Germany (9,800 MW), Spain (3,500 MW), Japan (2,630 MW), the USA (1,650 MW), Italy (1,140 MW), Korea (460 MW), France (370 MW) and the People's Republic of China (300 MW). By far, Spain and Germany have seen the largest amounts of growth in installed PV capacity in recent years, with Spain seeing a huge surge in 2008 and Germany having experienced steady growth over the last five years.

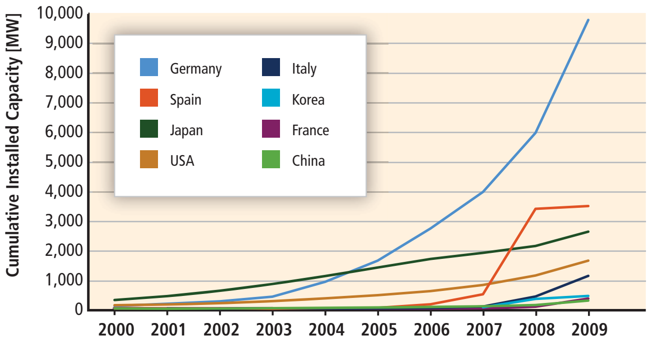


Figure 3.9 | Installed PV capacity in eight markets. Data sources: EurObserv'ER (2009); IEA (2009c); REN21 (2009); and Jäger-Waldau (2010b).

Concentrating photovoltaics (CPV) is an emerging market with about 17 MW of cumulative installed capacity at the end of 2008. The two main tracks are high-concentration PV (>300 times or 300 suns) and low- to medium-concentration PV with a concentration factor of 2 to about 300 (2 to ~300 suns). To maximize the benefits of CPV, the technology requires high direct-beam irradiance, and these areas have a limited geographical range—the 'Sun Belt' of the Earth. The market share of CPV is still small, but an increasing number of companies are focusing on CPV. In 2008, about 10 MW of CPV were installed, and market estimates for 2009 are in the 20 to 30 MW range; for 2010, about 100 MW are expected.

Regarding CSP *electricity generation*, at the beginning of 2009, more than 700 MW_e of grid-connected CSP plants were installed worldwide, with another 1,500 MW_e under construction (Torres et al., 2010). The majority of installed plants use parabolic trough technology. Central-receiver technology comprises a growing share of plants under construction and those announced. The bulk of the operating capacity is installed in Spain and the south-western United States.

In 2007, after a hiatus of more than 15 years, the first major CSP plants came on line with Nevada Solar One (64 MW_e, USA) and PS10 (11 MW_e, Spain). In Spain, successive Royal Decrees have been in place since 2004 and have stimulated the CSP industry in that country. Royal Decree 661/2007 has been a major driving force for CSP plant construction and expansion plans. As of November 2009, 2,340 MW_e of CSP projects had been preregistered for the tariff provisions of the Royal Decree. In the USA, more than 4,500 MW_e of CSP are currently under power purchase agreement contracts. The different contracts specify when the projects must start delivering electricity between 2010 and 2015 (Bloem et al., 2010). More than 10,000 MW_e of new CSP plants have been proposed in the USA. More than 50 CSP electricity projects are currently in the planning phase, mainly in North Africa, Spain and the USA. In Australia, the federal government has called for 1,000 MW_e of new solar plants, covering both CSP and PV, under the Solar Flagships programme. Figure 3.10 shows the current and planned deployment to add more CSP capacity in the near future.

Hybrid solar/fossil plants have received increasing attention in recent years, and several integrated solar combined-cycle (ISCC) projects have been either commissioned or are under construction in the Mediterranean region and the USA. The first plant in Morocco (Ain Beni Mathar: 470 MW total, 22 MW solar) began operating in June 2010, and two additional plants in Algeria (Hassi R'Mel: 150 MW total, 30 MW solar) and Egypt (Al Kuraymat: 140 MW total, 20 MW solar) are under construction. In Italy, another example of an ISCC project is Archimede; however, the plant's 31,000-m^2 parabolic trough solar field will be the first to use molten salt as the heat transfer fluid (SolarPACES, 2009a).

Solar fuel production technologies are in an earlier stage of development. The high-temperature solar reactor technology is typically being developed at a laboratory scale of 1 to 10 kW_{th} solar power input.

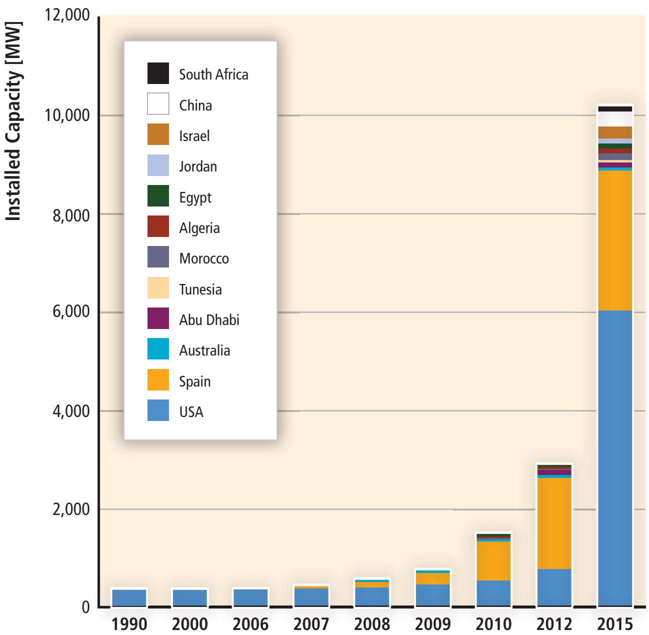


Figure 3.10 | Installed and planned concentrated solar power plants by country (Bloem et al., 2010).

Scaling up thermochemical processes for hydrogen production to the 100-kW_{th} power level is reported for a medium-temperature mixed iron oxide cycle (800°C to 1,200°C) (Roeb et al., 2006, 2009) and for the high-temperature zinc oxide (ZnO) dissociation reaction at above 1,700°C (Schunk et al., 2008, 2009). Pilot plants in the power range of 300 to 500 kW_{th} have been built for the carbothermic reduction of ZnO (Epstein et al., 2008), the steam reforming of methane (Möller et al., 2006), and the steam gasification of petcoke (Z'Graggen and Steinfeld, 2008). Solar-to-gas has been demonstrated at a 30-kW scale to drive a commercial natural gas vehicle, applying a nickel catalyst (Specht et al., 2010). Demonstration at the MW scale should be warranted before erecting commercial solar chemical plants for fuels production, which are expected to be available only after 2020 (Pregger et al., 2009).

Direct conversion of solar energy to fuel is not yet widely demonstrated or commercialized. But two options appear commercially feasible in the near to medium term: 1) the solar hybrid fuel production system (including solar methane reforming and solar biomass reforming), and 2) solar PV or CSP electrolysis.

Australia's Commonwealth Scientific and Industrial Research Organisation is running a 250-kW_{th} reactor and plans to build a MW-scale demonstration plant using solar steam-reforming technology, with an eventual move to CO_2 reforming for higher performance and less water usage. With such a system, liquid solar fuels can be produced in sunbelts such as Australia and solar energy shipped on a commercial basis to Asia and beyond.

Oxygen gas produced by solar (PV or CSP) electrolysis can be used for coal gasification and partial oxidation of natural gas. With the combined process of solar electrolysis and partial oxidation of coal or methane, theoretically 10 to 15% of solar energy is incorporated into the methanol or DME. Also, the production cost of the solar hybrid fuel can be lower than the solar hydrogen produced by the solar electrolysis process only.

3.4.2 Industry capacity and supply chain

This subsection discusses the industry capacity and supply chain within the five technology areas of passive solar, active solar heating and cooling, PV electricity generation, CSP electricity generation and solar fuel production.

In passive solar technologies, people make up part of the industry capacity and the supply chain: namely, the engineers and architects who collaborate to produce passively heated buildings. Close collaboration between the two disciplines has often been missing in the past, but the dissemination of systematic design methodologies issued by different countries has improved the design capabilities (Athienitis and Santamouris, 2002).

The integration of passive solar systems with the active heating/cooling air-conditioning systems both in the design and operation stages of the building is essential to achieve good comfort conditions while saving energy. However, this is often overlooked because of inadequate collaboration for integrating building design between architects and engineers. Thus, the architect often designs the building envelope based solely on qualitative passive solar design principles, and the engineer often designs the heating-ventilation-air-conditioning system based on extreme design conditions without factoring in the benefits due to solar gains and natural cooling. The result may be an oversized system and inappropriate controls incompatible with the passive system and that can cause overheating and discomfort (Athienitis and Santamouris, 2002). Collaboration between the disciplines involved in building design is now improving with the adoption of computer tools for integrated analysis and design.

The design of high-mass buildings with significant near-equatorial-facing window areas is common in some areas of the world such as Southern Europe. However, a systematic approach to designing such buildings is still not widely employed. This is changing with the introduction of the passive house standard in Germany and other countries (PHPP, 2004), the deployment of the European Directives, and new national laws such as China's standard based on the German one.

Glazing and window technologies have made substantial progress in the last 20 years (Hollands et al., 2001). New-generation windows result in low energy losses, high daylight efficiency, solar shading, and noise reduction. New technologies such as transparent PV and electrochromic and thermochromic windows provide many possibilities for designing solar houses and offices with abundant daylight. The change from regular double-glazed to double-glazed low-emissivity argon windows is presently occurring in Canada and is accelerated by the rapid drop in prices of these windows.

The primary materials for low-temperature thermal storage in passive solar systems are concrete, bricks and water. A review of thermal storage materials is given by Hadorn (2008) under IEA SHC Task 32, focusing on a comparison of the different technologies. Phase-change material (PCM) thermal storage (Mehling and Cabeza, 2008) is particularly promising in the design, control and load management of solar buildings because it reduces the need for structural reinforcement required for heavier traditional sensible storage in concrete-type construction. Recent developments facilitating integration include microencapsulated PCM that can be mixed with plaster and applied to interior surfaces (Schossig et al., 2005). PCM in microencapsulated polymers is now on the market and can be added to plaster, gypsum or concrete to enhance the thermal capacity of a room. For renovation, this provides a good alternative to new heavy walls, which would require additional structural support (Hadorn, 2008).

In spite of the advances in PCM, concrete has certain advantages for thermal storage when a massive building design approach is used, as in many of the Mediterranean countries. In this approach, the concrete also serves as the structure of the building and is thus likely more cost effective than thermal storage without this added function.

For active solar heating and cooling, a number of different collector technologies and system approaches have been developed due to different applications—including domestic hot water, heating, preheating and combined systems—and varying climatic conditions.

In some parts of the production process, such as selective coatings, large-scale industrial production levels have been attained. A number of different materials, including copper, aluminium and stainless steel, are applied and combined with different welding technologies to achieve a highly efficient heat-exchange process in the collector. The materials used for the cover glass are structured or flat, low-iron glass. The first antireflection coatings are coming onto the market on an industrial scale, leading to efficiency improvements of about 5%.
In general, vacuum-tube collectors are well-suited for higher-temperature applications. The production of vacuum-tube collectors is currently dominated by the Chinese Dewar tubes, where a metallic heat exchanger is integrated to connect them with the conventional hot-water systems. In addition, some standard vacuum-tube collectors, with metallic heat absorbers, are on the market.

The largest exporters of solar water-heating systems are Australia, Greece and the USA. The majority of exports from Greece are to Cyprus and the near-Mediterranean area. France also sends a substantial number of systems to its overseas territories. The majority of US exports are to the Caribbean region. Australian companies export about 50% of production (mainly thermosyphon systems with external horizontal tanks) to most of the areas of the world that do not have hard-freeze conditions.

PV electricity generation is discussed under the areas of overall solar cell production, thin-film module production and polysilicon production. The development characteristic of the PV sector is much different than the traditional power sector, more closely resembling the semiconductor market, with annual growth rates between 40 to 50% and a high learning rate. Therefore, scientific and peer-reviewed papers can be several years behind the actual market developments due to the nature of statistical time delays and data consolidation. The only way to keep track of such a dynamic market is to use commercial market data. Global PV cell production[2] reached more than 11.5 GW in 2009.

2 Solar cell production capacities mean the following: for wafer-silicon-based solar cells, only the cells; for thin films, the complete integrated module. Only those companies that actually produce the active circuit (solar cell) are counted; companies that purchase these circuits and then make modules are not counted.

Figure 3.11 plots the increase in production from 2000 through 2009, showing regional contributions (Jäger-Waldau, 2010a). The compound annual growth rate in production from 2003 to 2009 was more than 50%.

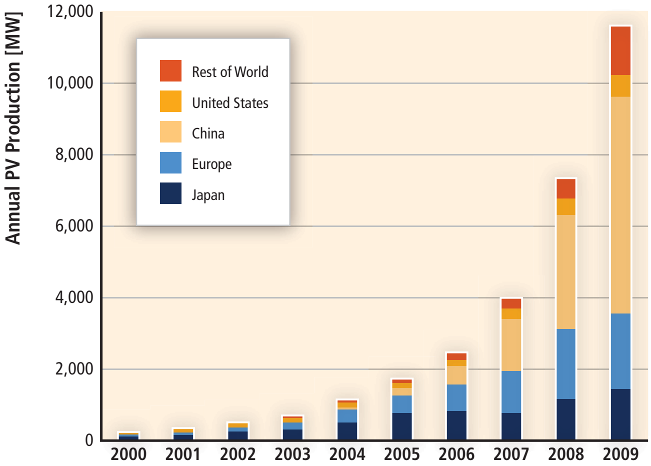


Figure 3.11 | Worldwide PV production from 2000 to 2009 (Jäger-Waldau, 2010b).

The announced production capacities—based on a survey of more than 300 companies worldwide—increased despite very difficult economic conditions in 2009 (Figure 3.12) (Jäger-Waldau, 2010b). Only published announcements from the respective companies, not third-party information, were used. April 2010 was the cut-off date for the information included. This method has the drawback that not all companies announce their capacity increases in advance; also, in times of financial tightening, announcements of scale-backs in expansion plans are often delayed to prevent upsetting financial markets. Therefore, the capacity figures provide a trend, but do not represent final numbers.

In 2008 and 2009, Chinese production capacity increased over-proportionally. In actual production, China surpassed all other countries,

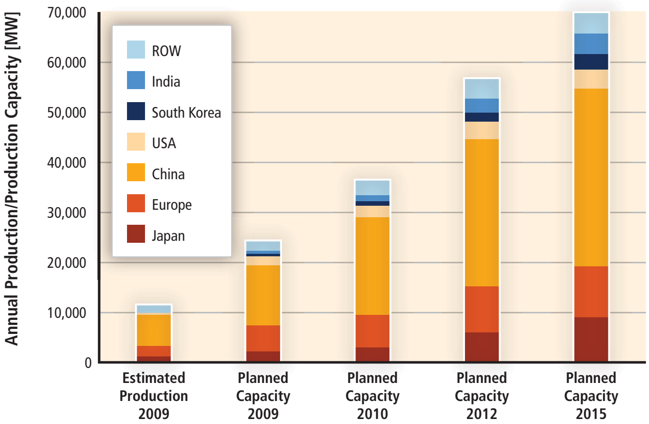


Figure 3.12 | Worldwide annual PV production in 2009 compared to the announced production capacities (Jäger-Waldau, 2010a).

estimated in 2009 at between 5.4 and 6.1 GW (including 1.5 to 1.7 GW production in the Chinese province of Taiwan), Europe had 2.0 to 2.2 GW, and was followed by Japan, with 1.5 to 1.7 GW (Jäger-Waldau, 2010b). In terms of production, First Solar (USA/Germany/France/Malaysia) was number one (1,082 MW), followed by Suntech (China) estimated at 750 MW and Sharp (Japan) estimated at 580 MW.

If all these ambitious plans can be realized by 2015, then China will have about 51% (including 16% in the Chinese province of Taiwan) of the worldwide production capacity of 70 GW, followed by Europe (15%) and Japan (13%).

Worldwide, more than 300 companies produce solar cells. In 2009, *silicon-based solar cells and modules* represented about 80% of the worldwide market (Figure 3.13). In addition to a massive increase in production capacities, the current development predicts that thin-film-based solar cells will increase their market share to over 30% by 2012.

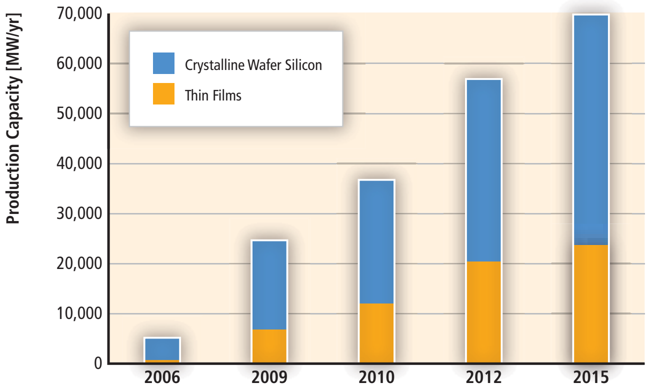


Figure 3.13 | Actual (2006) and announced (2009 to 2015) production capacities of thin-film and crystalline silicon-based solar modules (Jäger-Waldau, 2010b).

In 2005, production of *thin-film PV modules* grew to more than 100 MW per year. Since then, the compound annual growth rate of thin-film PV module production was higher than that of the industry—thus increasing the market share of thin-film products from 6% in 2005 to about 20% in 2009. Most of this thin-film share comes from the largest PV company.

More than 150 companies are involved in the thin-film solar cell production process, ranging from R&D activities to major manufacturing plants. The first 100-MW thin-film factories became operational in 2007, and the announcements of new production capacities accelerated again in 2008. If all expansion plans are realized in time, thin-film production capacity could be 20.0 GW, or 35% of the total 56.7 GW in 2012, and 23.5 GW, or 34% of a total of 70 GW in 2015 (Jäger-Waldau, 2009, 2010b). The first thin-film factories with GW production capacity are already under construction for various thin-film technologies.

The rapid growth of the PV industry since 2000 led to the situation between 2004 and early 2008 where the demand for polysilicon outstripped the supply from the semiconductor industry. This led to a silicon shortage, which resulted in silicon spot-market prices as high as USD_{2005} 450/kg (USD_{2005}, assumed 2008 base) in 2008 compared to USD_{2005} 25.5/kg in 2003 and consequently higher prices for PV modules. This extreme price hike triggered the massive capacity expansion, not only of established companies, but of many new entrants as well.

The six companies that reported shipment figures delivered together about 43,900 tonnes of polysilicon in 2008, as reported by Semiconductor Equipment and Materials International (SEMI, 2009a). In 2008, these companies had a production capacity of 48,200 tonnes of polysilicon (Service, 2009). However, all polysilicon producers, including new entrants with current and alternative technologies, had a production capacity of more than 90,000 tonnes of polysilicon in 2008. Considering that not all new capacity actually produced polysilicon at nameplate capacity in 2008, it was estimated that 62,000 tonnes of polysilicon could be produced. Subtracting the needs of the semiconductor industry and adding recycling and excess production, the available amount of silicon for the PV industry was estimated at 46,000 tonnes of polysilicon. With an average material need of 8.7 g/W_p (p = peak), this would have been sufficient for the production of 5.3 GW of crystalline silicon PV cells.

The drive to reduce costs and secure key markets has led to the emergence of two interesting trends. One is the move to large original design manufacturing units, similar to the developments in the semiconductor industry. A second is that an increasing number of solar manufacturers move part of their module production close to the final market to demonstrate the local job creation potential and ensure the current policy support. This may also be a move to manufacture in low-cost or subsidized markets.

The regional distribution of polysilicon production capacities is as follows: China 20,000 tonnes, Europe 17,500 tonnes, Japan 12,000 tonnes, and USA 37,000 tonnes (Service, 2009).

In 2009, solar-grade silicon production of about 88,000 tonnes was reported, sufficient for about 11 GW of PV assuming an average materials need of 8 g/W_p (Displaybank, 2010). China produced about 18,000 tonnes or 20% of world demand, fulfilling about half of its domestic demand (Baoshan, 2010).

Projections of silicon production capacities for solar applications in 2012 span a range between 140,000 tonnes from established polysilicon producers, up to 250,000 tonnes including new producers (e.g., Bernreuther and Haugwitz, 2010; Ruhl et al., 2010). The possible solar cell production will also depend on the material use per W_p. Material consumption could decrease from the current 8 g/W_p to 7 g/W_p or even 6 g/W_p (which could increase delivered PV capacity from 31 to 36 to 42 GW, respectively), but this may not be achieved by all manufacturers.

Forecasts of the future costs of vital materials have a high-profile history, and there is ongoing public debate about possible material shortages and competition regarding some (semi-)metals (e.g., In and Te) used in thin-film cell production. In a recent study, Wadia et al. (2009) explored material limits for PV expansion by examining the dual constraints of material supply and least cost per watt for the most promising semiconductors as active photo-generating materials. Contrary to the commonly assumed scarcity of indium and tellurium, the study concluded that the currently known economic reserves of these materials would allow about 10 TW of CdTe or $CuInS_2$ solar cells to be installed.

In CSP electricity generation, the solar collector field is readily scalable, and the power block is based on adapted knowledge from the existing power industry such as steam and gas turbines. The collectors themselves benefit from a range of existing skill sets such as mechanical, structural and control engineers, and metallurgists. Often, the materials or components used in the collectors are already mass-produced, such as glass mirrors.

By the end of 2010, strong competition had emerged and an increasing number of companies had developed industry-level capability to supply materials such as high-reflectivity glass mirrors and manufactured components. Nonetheless, the large evacuated tubes designed specifically for use in trough/oil systems for power generation remain a specialized component, and only two companies (Schott and Solel) have been capable of supplying large orders of tubes, with a third company (Archimedes) now emerging. The trough concentrator itself comprises know-how in both structures and thermally sagged glass mirrors. Although more companies are now offering new trough designs and considering alternatives to conventional rear-silvered glass (e.g., polymer-based reflective films), the essential technology of concentration remains unchanged. Direct steam generation in troughs is under demonstration, as is direct heating of molten salt, but these designs are not yet commercially available. As a result of its successful operational history, the trough/oil technology comprised most of the CSP installed capacity in 2010.

Linear Fresnel and central-receiver systems comprise a high level of know-how, but the essential technology is such that there is the potential for a greater variety of new industry participants. Although only a couple of companies have historically been involved with central receivers, new players have entered the market over the last few years. There are also technology developers and projects at the demonstration level (China, USA, Israel, Australia, Spain). Central-receiver developers are aiming for higher temperatures, and, in some cases, alternative heat transfer fluids such as molten salts. The accepted standard to date has been to use large heliostats, but many of the new entrants are pursuing much smaller heliostats to gain potential cost reductions through high-volume mass production. The companies now interested in heliostat development range from optics companies to the automotive industry looking to diversify. High-temperature steam receivers will benefit from existing knowledge in the boiler industry. Similarly, with linear Fresnel, a range of new developments are occurring, although not yet as developed as the central-receiver technology.

Dish technology is much more specialized, and most effort presently has been towards developing the dish/Stirling concept as a commercial product. Again, the technology can be developed as specialized components through specific industry know-how such as the Stirling engine mass-produced through the automotive industry.

Within less than 10 years prior to 2010, the CSP industry has gone from negligible activity to over 2,400 MW_e either commissioned or under construction. A list of new CSP plants and their characteristics can be found at the IEA SolarPACES web site.[3] More than ten different companies are now active in building or preparing for commercial-scale plants, compared to perhaps only two or three who were in a position to build a commercial-scale plant three years ago. These companies range from large organizations with international construction and project management expertise who have acquired rights to specific technologies, to start-ups based on their own technology developed in-house. In addition, major independent power producers and energy utilities are playing a role in the CSP market.

The supply chain does not tend to be limited by raw materials, because the majority of required materials are bulk commodities such as glass, steel/aluminium, and concrete. The sudden new demand for the specific solar salt mixture material for molten-salt storage is claimed to have impacted supply. At present, evacuated tubes for trough plants can be produced at a sufficient rate to service several hundred MW per year. However, expanded capacity can be introduced readily through new factories with an 18-month lead time.

Solar fuel technology is still at an emerging stage—thus, there is no supply chain in place at present for commercial applications. However, solar fuels will comprise much of the same solar-field technology being deployed for other high-temperature CSP systems, with solar fuels requiring a different receiver/reactor at the focus and different downstream processing and control. Much of the downstream technology, such as Fischer-Tropsch liquid fuel plants, would come from existing expertise in the petrochemical industry. The scale of solar fuel demonstration plants is being ramped up to build confidence for industry, which will eventually expand operations.

3 See: www.solarpaces.org.

Hydrogen has been touted as a future transportation fuel due to its versatility, pollutant-free end use and storage capability. The key is a sustainable, CO_2-free source of hydrogen such as solar, cost-effective storage and appropriate distribution infrastructure. The production of solar hydrogen, in and of itself, does not produce a hydrogen economy because many factors are needed in the chain. The suggested path to solar hydrogen is to begin with solar enhancement of existing steam reforming processes, with a second generation involving solar electricity and advanced electrolysis, and a third generation using thermolysis or advanced thermochemical cycles, with many researchers aiming for the production of fuels from concentrated solar energy, water, and CO_2. In terms of making a transition, solar hydrogen can be mixed with natural gas and transported together in existing pipelines and distribution networks to customers, thus enhancing the solar portion of the global energy mix.

Steam reforming of natural gas for hydrogen production is a conventional industrial-scale process that produces most of the world's hydrogen today, with the heat for the process derived from burning a significant proportion of the fossil fuel feedstock. Using concentrated solar power, instead, as the source of the heat embodies solar energy in the fuel. The solar steam-reforming of natural gas and other hydrocarbons, and the solar steam-gasification of coal and other carbonaceous materials yields a high-quality syngas, which is the building block for a wide variety of synthetic fuels including Fischer-Tropsch-type chemicals, hydrogen, ammonia and methanol (Steinfeld and Meier, 2004).

The solar cracking route refers to the thermal decomposition of natural gas and other hydrocarbons. Besides H_2 and carbon, other compounds may also be formed, depending on the reaction kinetics and on the presence of impurities in the raw materials. The thermal decomposition yields a carbon-rich condensed phase and a hydrogen-rich gas phase. The carbonaceous solid product can either be sequestered without CO_2 release or used as material commodity (carbon black) under less severe CO_2 restraints. It can also be applied as reducing agent in metallurgical processes. The hydrogen-rich gas mixture can be further processed to high-purity hydrogen that is not contaminated with oxides of carbon; thus, it can be used in proton-exchange-membrane fuel cells without inhibiting platinum electrodes. From the perspective of carbon sequestration, it is easier to separate, handle, transport and store solid carbon than gaseous CO_2. Further, thermal cracking removes and separates carbon in a single step. The major drawback of thermal cracking is the energy loss associated with the sequestration of carbon. Thus, solar cracking may be the preferred option for natural gas and other hydrocarbons with a high H_2/C ratio (Steinfeld and Meier, 2004).

3.4.3 Impact of policies[4]

Direct solar energy technologies support a broad range of applications, and their deployment is confronted by many of the barriers outlined in Chapter 1. Solar technologies differ in levels of maturity, and although some applications are already competitive in localized markets, they generally face one common barrier: the need to achieve cost reductions (see Section 3.8). Utility-scale CSP and PV systems face different barriers than distributed PV and solar heating and cooling technologies. Important barriers include: 1) siting, permitting and financing challenges to develop land with favourable solar resources for utility-scale projects; 2) lack of access to transmission lines for large projects far from electric load centres; 3) complex access laws, permitting procedures and fees for smaller-scale projects; 4) lack of consistent interconnection standards and time-varying utility rate structures that capture the value of distributed generated electricity; 5) inconsistent standards and certifications and enforcement of these issues; and 6) lack of regulatory structures that capture environmental and risk mitigation benefits across technologies (Denholm et al., 2009).

Through appropriate policy designs (see Chapter 11), governments have shown that they can support solar technologies by funding R&D and by providing incentives to overcome economic barriers. Price-driven instruments (see Section 11.5.2), for example, were popularized after feed-in tariff (FIT) policies boosted levels of PV deployment in Germany and Spain. In 2009, various forms of FIT policies were implemented in more than 50 countries (REN21, 2010) and some designs offer premiums for building-integrated PV. Quota-driven frameworks such as renewable portfolio standards (RPS) and government bidding are common in the USA and China, respectively (IEA, 2009a). Traditional RPS frameworks are designed to be technology-neutral, and this puts at a disadvantage many solar applications that are more costly than alternatives such as wind power. In response, features of RPS frameworks (set-asides and credits) increasingly are including solar-specific policies, and such programs have led to increasing levels of solar installations (Wiser et al., 2010). In addition to these regulatory frameworks, fiscal policies and financing mechanisms (e.g., tax credits, soft loans and grants) are often employed to support the manufacturing of solar goods and to increase consumer demand (Rickerson et al., 2009). The challenge for solar projects to secure financing is a critical barrier, especially for developing technologies in market structures dominated by short-term transactions and planning.

Most successful solar policies are tailored to the barriers posed by specific applications. Across technologies, there is a need to offset relatively high upfront investment costs (Denholm et al., 2009). Yet, in the case of utility-scale CSP and PV projects, substantial and long-term investments are required at levels that exceed solar applications in distributed markets. Solar heating and cooling technologies are included in many policies, yet the characteristics of their applications differ from electricity-generating technologies. Policies based on energy yield rather than collector surface area are generally preferred for various types of solar thermal collectors (IEA, 2007). See Section 1.5 for further discussion.

Similar to other renewable sources, there is ongoing discussion about the merits of existing solar policies to spur innovation and accelerate deployment using cost-effective measures. Generally—and as discussed

4 Non-technology-specific policy issues are covered in Chapter 11 of this report.

in Chapter 11—the most successful policies are those that send clear, long-term and consistent signals to the market. In addition to targeted economic policies, government action through educationally based schemes (e.g., workshops, workforce training programs and seminars) and engagement of regulatory organizations are helping to overcome many of the barriers listed in this section.

3.5 Integration into the broader energy system[5]

This section discusses how direct solar energy technologies are part of the broader energy framework, focusing specifically on the following: low-capacity energy demand; district heating and other thermal loads; PV generation characteristics and the smoothing effect; and CSP generation characteristics and grid stabilization. Chapter 8 addresses the broader technical and institutional options for managing the unique characteristics, production variability, limited predictability and locational dependence of some RE technologies, including solar, as well as existing experience with and studies associated with the costs of that integration.

3.5.1 Low-capacity electricity demand

There can be comparative advantages for using solar energy rather than non-renewable fuels in many developing countries. Within a country, the advantages can be higher in un-electrified rural areas compared to urban areas. Indeed, solar energy has the advantage, due to being modular, of being able to provide small and decentralized supplies, as well as large centralized ones. For more on integrated buildings and households, see Section 8.3.2.

In a wide range of countries, particularly those that are not oil producers, solar energy and other forms of RE can be the most appropriate energy source. If electricity demand exceeds supply, the lack of electricity can prevent development of many economic sectors. Even in countries with high solar energy sustainable development potential, RE is often only considered to satisfy high-power requirements such as the industrial sector. However, large-scale technologies such as CSP are often not available to them due, for example, to resource conditions or suitable land area availability. In such cases, it is reasonable to keep the electricity generated near the source to provide high amounts of power to cover industrial needs.
Applications that have low power consumption, such as lighting in rural areas, can primarily be satisfied using onsite PV—even if the business plan for electrification of the area indicates that a grid connection would be more profitable. Furthermore, the criteria to determine the most suitable technological option for electrifying a rural area should include benefits such as local economic development, exploiting natural resources, creating jobs, reducing the country's dependence on imports, and protecting the environment.

5 Non-technology-specific issues related to integration of RE sources in current and future energy systems are covered in Chapter 8 of this report.

3.5.2 District heating and other thermal loads

Highly insulated buildings can be heated easily with relatively low-temperature district-heating systems, where solar energy is ideal, or quite small quantities of renewable-generated electricity (Boyle, 1996). A district cooling and heating system (DCS) can provide both cooling and heating for blocks of buildings. Since the district heating system already makes the outdoor pipe network available, a district cooling system becomes a viable solution to the cooling demand of buildings. There are already many DCS installations in the USA, Europe, Japan and other Asian countries because this system has many advantages compared to a decentralized cooling system. For example, it takes full advantage of economy of scale and diversity of cooling demand of different buildings, reduces noise and structure load, and saves considerable equipment area. It also allows greater flexibility in designing the building by removing the cooling tower on the roof and chiller plant in the building or on the roof, and it can provide more reliable and flexible services through a specialized professional team in cold-climate areas (Shu et al., 2010). For more on RE integration in district heating and cooling networks, see Section 8.2.2.3.

In China, Greece, Cyprus and Israel, solar water heaters make a significant contribution to supplying residential energy demand. In addition, solar water heating is widely used for pool heating in Australia and the USA. In countries where electricity is a major resource for water heating (e.g., Australia, Canada and the USA), the impact of numerous solar domestic water heaters on the operation of the power grid depends on the utility's load management strategy. For a utility that uses centralized load switching to manage electric water heater load, the impact is limited to fuel savings. Without load switching, the installation of many solar water heaters may have the additional benefit of reducing peak demand on the grid. For a utility that has a summer peak, the time of maximum solar water heater output corresponds with peak electrical demand, and there is a capacity benefit from load displacement of electric water heaters. Large-scale deployment of solar water heating can benefit both the customer and the utility. Another benefit to utilities is emissions reduction, because solar water heating can displace the marginal and polluting generating plant used to produce peak-load power.

Combining biomass and low-temperature solar thermal energy could provide zero emissions and high capacity factors to areas with less frequent direct-beam solar irradiance. In the short term, local tradeoffs exist for areas that have high biomass availability due to increased cloud cover and rainfall. However, solar technology is more land-efficient for energy production and greatly reduces the need for biomass growing area and biomass transport cost. Some optimum ratio of CSP and biomass supply is likely to exist at each site. Research is being conducted on tower and dish systems to develop technologies—such as solar-driven gasification of biomass—that optimally combine both these renewable resources. In the longer term, greater interconnectedness across different climate regimes may provide more stability of supply as a total grid system; this situation could reduce the need for occasional fuel supply for each individual CSP system.

3.5.3 Photovoltaic generation characteristics and the smoothing effect

At a specific location, the generation of electricity by a PV system varies systematically during a day and a year, but also randomly according to weather conditions. The variation of PV generation can, in some instances, have a large impact on voltage and power flow of the local transmission/distribution system from the early penetration stage, and on supply-demand balance in a total power system operation in the high-penetration stage (see also Section 8.2.1 for a further discussion of solar electricity characteristics, and the implications of those characteristics for electricity market planning, operations, and infrastructure).

Various studies have been published on the impact of supply-demand balance for a power system with a critical constraint of PV systems integration (Lee and Yamayee, 1981; Chalmers et al., 1985; Chowdhury and Rahman, 1988; Jewell and Unruh, 1990; Bouzguenda and Rahman, 1993; Asano et al., 1996). These studies generally conclude that the economic value of PV systems is significantly reduced at increasing levels of system penetration due to the high variability of PV. Today's base-load generation has a limited ramp rate—the rate at which a generator can change its output—which limits the feasible penetration of PV systems. However, these studies generally lack high-time-resolution PV system output data from multiple sites. The total electricity generation of numerous PV systems in a broad area should have less random and fast variation—because the generation output variations of numerous PV systems have low correlation and cancel each other in a 'smoothing effect'. The critical impact on supply-demand balance of power comes from the total generation of the PV systems within a power system (Piwko et al., 2007, 2010; Ogimoto et al., 2010).

Some approaches for analyzing the smoothing effect use modelling and measured data from around the world. Cloud models have been developed to estimate the smoothing effect of geographic diversity by considering regions ranging in size from 10 to 100,000 km^2 (Jewell and Ramakumar, 1987) and down to 0.2 km^2 (Kern and Russell, 1988). Using measured data, Kitamura (1999) proposed a set of specifications for describing fluctuations, considering three parameters: magnitude, duration of a transition between clear and cloudy, and speed of the transition, defined as the ratio of magnitude and duration; he evaluated the smoothing effect in a small area (0.1 km by 0.1 km). A similar approach, 'ramp analysis', was proposed by Beyer et al. (1991) and Scheffler (2002).

In a statistical approach, Otani et al. (1997) characterized irradiance data by the fluctuation factor using a high-pass filtered time series of solar irradiance. Woyte et al. (2001, 2007) analyzed the fluctuations of the instantaneous clearness index by means of a wavelet transform. To demonstrate the smoothing effect, Otani et al. (1998) demonstrated that the variability of sub-hourly irradiance even within a small area of 4 km by 4 km can be reduced due to geographic diversity. They analyzed the non-correlational irradiation/generation characteristics of several PV systems/sites that are dispersed spatially.

Wiemken et al. (2001) used data from actual PV systems in Germany to demonstrate that five-minute ramps in normalized PV power output at one site may exceed ±50%, but that five-minute ramps in the normalized PV power output from 100 PV systems spread throughout the country never exceed ±5%. Ramachandran et al. (2004) analyzed the reduction in power output fluctuation for spatially dispersed PV systems and for different time periods, and they proposed a cluster model to represent very large numbers of small, geographically dispersed PV systems. Results from Curtright and Apt (2008) based on three PV systems in Arizona indicate that 10-minute step changes in output can exceed 60% of PV capacity at individual sites, but that the maximum of the aggregate of three sites is reduced. Kawasaki et al. (2006) similarly analyzed the smoothing effect within a small (4 km by 4 km) network of irradiance sensors and concluded that the smoothing effect is most effective during times when the irradiance variability is most severe—particularly days characterized as partly cloudy.

Murata et al. (2009) developed and validated a method for estimating the variability of power output from PV plants dispersed over a wide area that is very similar to the methods used for wind by Ilex Energy Consulting Ltd et al. (2004) and Holttinen (2005). Mills and Wiser (2010) measured one-minute solar insolation for 23 sites in the USA and characterized the variability of PV with different degrees of geographic diversity, comparing the variability of PV to the variability of similarly sited wind. They determined that the relative aggregate variability of PV plants sited in a dense ten by ten array with 20-km spacing is six times less than the variability of a single site for variability on time scales of less than 15 minutes. They also found that for PV and wind plants similarly sited in a five by five grid with 50-km spacing, the variability of PV is only slightly more than the variability of wind on time scales of 5 to 15 minutes.

Oozeki et al. (2010) quantitatively evaluated the smoothing effect in a load-dispatch control area in Japan to determine the importance of data accumulation and analysis. The study also proposed a methodology to calculate the total PV output from a limited number of measurement data using Voronoi Tessellation. Marcos et al. (2010) analyzed one-second data collected throughout a year from six PV systems in Spain, ranging from 1 to 9.5 MW_p, totalling 18 MW. These studies concluded that over shorter and longer time scales, the level of variability is nearly identical because the aggregate fluctuation of PV systems spread over the large area depends on the correlation of the fluctuation between PV systems. The correlation of fluctuation, in turn, is a function both of the time scale and distance between PV systems. Variability is less correlated for PV systems that are further apart and for variability over shorter time scales.

Currently, however, not enough data on generation characteristics exist to evaluate the smoothing effect. Data collection from a sufficiently large number of sites (more than 1,000 sites and at distances of 2 to 200 km), periods and time resolution (one minute or less) had just begun in mid-2010 in several areas in the world. The smoothed generation characteristics of PV penetration considering area and multiple sites will be analyzed precisely after collecting reliable measurement data with sufficient time resolution and time synchronization. The results will contribute to the economic and reliable integration of PV into the energy system.

3.5.4 Concentrating solar power generation characteristics and grid stabilization

In a CSP plant, even without integrated storage, the inherent thermal mass in the collector system and spinning mass in the turbine tend to significantly reduce the impact of rapid solar transients on electrical output, and thus, lead to less impact on the grid (also see Section 8.2.1). By including integrated thermal storage systems, base-load capacity factors can be achieved (IEA, 2010b). This and the ability to dispatch power on demand during peak periods are key characteristics that have motivated regulators in the Mediterranean region, starting with Spain, to support large-scale deployment of this technology with tailored FITs. CSP is suitable for large-scale 10- to 300-MW_e plants replacing non-renewable thermal power capacity. With thermal storage or onsite thermal backup (e.g., fossil or biogas), CSP plants can also produce power at night or when irradiation is low. CSP plants can reliably deliver firm, scheduled power while the grid remains stable.

CSP plants may also be integrated with fossil fuel-fired plants such as displacing coal in a coal-fired power station or contributing to gas-fired integrated solar combined-cycle (ISCC) systems. In ISCC power plants, a solar parabolic trough field is integrated in a modern gas and steam power plant; the waste heat boiler is modified and the steam turbine is oversized to provide additional steam from a solar steam generator. Better fuel efficiency and extended operating hours make combined solar/fossil power generation much more cost-effective than separate CSP and combined-cycle plants. However, without including thermal storage, solar steam could only be supplied for some 2,000 of the 6,000 to 8,000 combined-cycle operating hours of a plant in a year. Furthermore, because the solar steam is only feeding the combined-cycle turbine—which supplies only one-third of its power—the maximum solar share obtainable is under 10%. Nonetheless, this concept is of special interest for oil- and gas-producing sunbelt countries, where solar power technologies can be introduced to their fossil-based power market (SolarPACES, 2008).

3.6 Environmental and social impacts[6]

This section first discusses the environmental impacts of direct solar technologies, and then describes potential social impacts. However, an overall issue identified at the start is the small number of peer-reviewed studies on impacts, indicating the need for much more work in this area.

6 A comprehensive assessment of social and environmental impacts of all RE sources covered in this report can be found in Chapter 9.

3.6.1 Environmental impacts

No consensus exists on the premium, if any, that society should pay for cleaner energy. However, in recent years, there has been progress in analyzing environmental damage costs, thanks to several major projects to evaluate the externalities of energy in the USA and Europe (Gordon, 2001; Bickel and Friedrich, 2005; NEEDS, 2009; NRC, 2010). Solar energy has been considered desirable because it poses a much smaller environmental burden than non-renewable sources of energy. This argument has almost always been justified by qualitative appeals, although this is changing.
Results for damage costs per kilogram of pollutant and per kWh were presented by the International Solar Energy Society in Gordon (2001). The results of studies such as NEEDS (2009), summarized in Table 3.3 for PV and in Table 3.4 for CSP, confirm that RE is usually comparatively beneficial, though impacts still exist. In comparison to the figures presented for PV and CSP here, the external costs associated with fossil generation options, as summarized in Chapter 10.6, are considerably higher, especially for coal-fired generation.

Considering passive solar technology, higher insulation levels provide many benefits, in addition to reducing heating loads and associated costs (Harvey, 2006). The small rate of heat loss associated with high levels of insulation, combined with large internal thermal mass, creates a more comfortable dwelling because temperatures are more uniform. This can indirectly lead to higher efficiency in the equipment supplying the heat. It also permits alternative heating systems that would not

Table 3.3 | Quantifiable external costs for photovoltaic, tilted-roof, single-crystalline silicon, retrofit, average European conditions; in US_{2005} cents/kWh (NEEDS, 2009).

	2005	2025	2050
Health Impacts	0.17	0.14	0.10
Biodiversity	0.01	0.01	0.01
Crop Yield Losses	0.00	0.00	0.00
Material Damage	0.00	0.00	0.00
Land Use	N/A	0.01	0.01
Total	**0.18**	**0.17**	**0.12**

Table 3.4 | Quantifiable external costs for concentrating solar power; in US_{2005} cents/kWh (NEEDS, 2009).

	2005	2025	2050
Health Impacts	0.65	0.10	0.06
Biodiversity	0.03	0.00	0.00
Crop Yield Losses	0.00	0.00	0.00
Material Damage	0.01	0.00	0.00
Land Use	N/A	N/A	N/A
Total	**0.69**	**0.10**	**0.06**

otherwise be viable, but which are superior to conventional heating systems in many respects. Better-insulated houses eliminate moisture problems associated, for example, with thermal bridges and damp basements. Increased roof insulation also increases the attenuation of outside sounds such as from aircraft.

For active solar heating and cooling, the environmental impact of solar water-heating schemes in the UK would be very small according to Boyle (1996). For example, in the UK, the materials used are those of everyday building and plumbing. Solar collectors are installed to be almost indistinguishable visually from normal roof lights. In Mediterranean countries, the use of free-standing thermosyphon systems on flat roofs can be visually intrusive. However, the collector is not the problem, but rather, the storage tank above it. A study of the lifecycle environmental impact of a thermosyphon domestic solar hot water system in comparison with electrical and gas water heating shows that these systems have improved LCA indices over electrical heaters, but the net gain is reduced by a factor of four when the primary energy source is natural gas instead of electricity (Tsilingiridis et al., 2004).

With regard to complete solar domestic hot water systems, the energy payback time requires accounting for any difference in the size of the hot water storage tank compared to the non-solar system and the energy used to manufacture the tank (Harvey, 2006). It is reported that the energy payback time for a solar/gas system in southern Australia is 2 to 2.5 years, despite the embodied energy being 12 times that of a tankless system. For an integrated thermosyphon flat-plate solar collector and storage device operating in Palermo (Italy), a payback time of 1.3 to 4.0 years is reported (Harvey, 2006).

PV systems do not generate any type of solid, liquid or gaseous by-products when producing electricity. Also, they do not emit noise or use non-renewable resources during operation. However, two topics are often considered: 1) the emission of pollutants and the use of energy during the full lifecycle of PV manufacturing, installation, operation and maintenance (O&M) and disposal; and 2) the possibility of recycling the PV module materials when the systems are decommissioned.

Starting with the latter concern, the PV industry uses some toxic, explosive gases, GHGs, as well as corrosive liquids, in its production lines. The presence and amount of those materials depend strongly on the cell type (see Section 3.3.3). However, the intrinsic needs of the production process of the PV industry force the use of quite rigorous control methods that minimize the emission of potentially hazardous elements during module production.

Recycling the material in PV modules is already economically viable, mainly for concentrated and large-scale applications. Projections are that between 80 and 96% of the glass, ethylene vinyl acetate, and metals (Te, selenium and lead) will be recycled. Other metals, such as Cd, Te, tin, nickel, aluminium and Cu, should be saved or they can be recycled by other methods. For discussions of Cd, for example, see Sinha et al. (2008), Zayed and Philippe (2009) and Wadia et al. (2009).

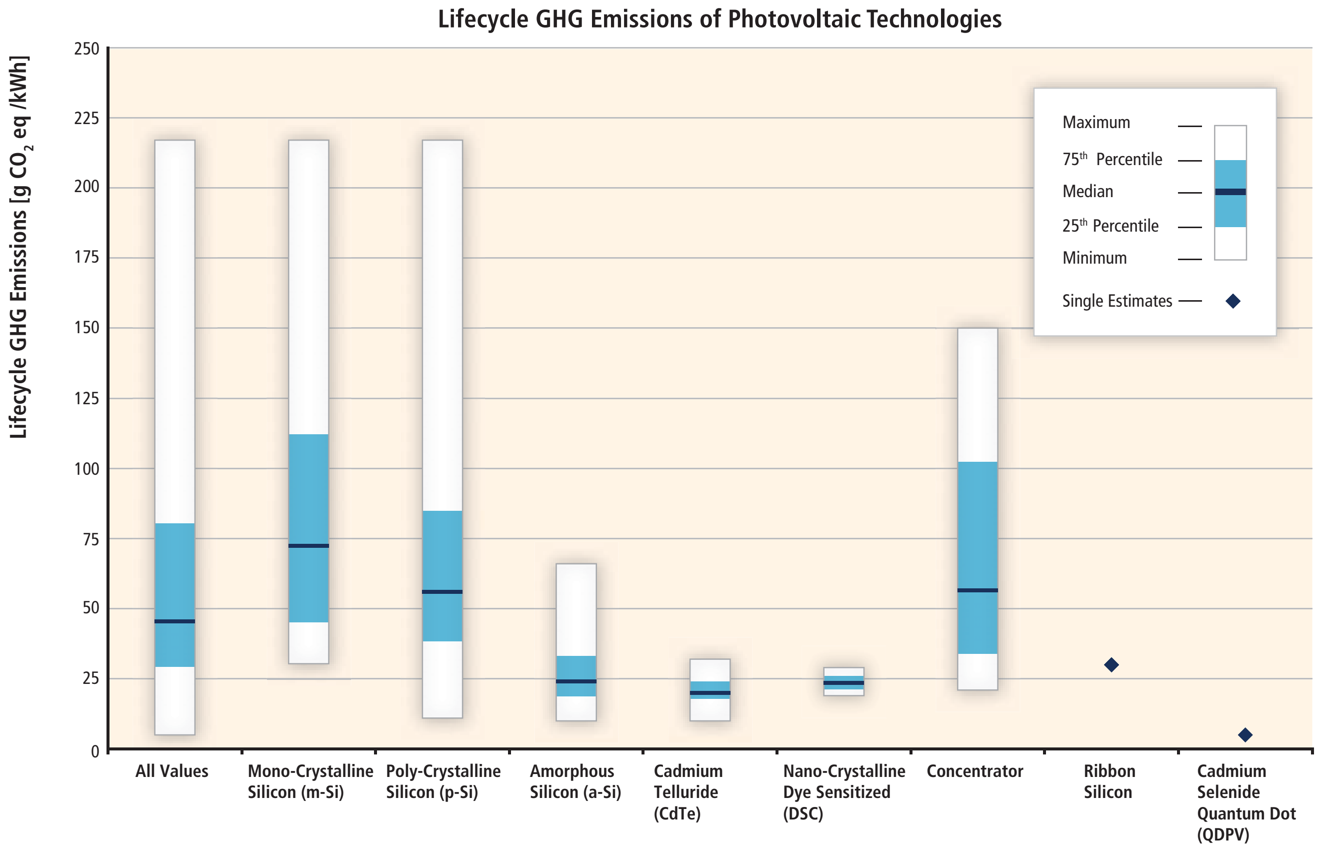
It is noted that, in certain locations, periodic cleaning of the PV panels may be necessary to maintain performance, resulting in non-negligible water requirements.

With respect to lifecycle GHG emissions, Figure 3.14 shows the result of a comprehensive literature review of PV-related lifecycle assessment (LCA) studies published since 1980 conducted by the National Renewable Energy Laboratory. The majority of lifecycle GHG emission estimates cluster between about 30 and 80 g CO_2eq/kWh, with potentially important outliers at greater values (Figure 3.14). Note that the distributions shown in Figure 3.14 do not represent an assessment of likelihood; the figure simply reports the distribution of currently published literature estimates passing screens for quality and relevance. Refer to Annex II for a description of literature search methods and complete reference list, and Section 9.3.4.1 for further details on interpretation of LCA data. Variability in estimates stems from differences in study context (e.g., solar resource, technological vintage), technological performance (e.g., efficiency, silicon thickness) and methods (e.g., LCA system boundaries). Efforts to harmonize the methods and assumptions of these studies are recommended such that more robust estimates of central tendency and variability can be realized, as well as a better understanding of the upper-quartile estimates. Further LCA studies are also needed to increase the number of estimates for some technologies (e.g., CdTe).

As for the energy payback of PV (see also Box 9.3), Perpinan et al. (2009) report paybacks of 2.0 and 2.5 years for microcrystalline silicon and monocrystalline silicon PV, respectively, taking into account use in locations with moderate solar irradiation levels of around 1,700 kWh/m^2/yr (6,120 MJ/m^2/yr). Fthenakis and Kim (2010) show payback times of grid-connected PV systems that range from 2 to 5 years for locations with global irradiation ranges from 1,900 to 1,400 kWh/m^2/yr (6,840 MJ/m^2/yr).

For CSP plants, the environmental consequences vary depending on the technology. In general, GHG emissions and other pollutants are reduced without incurring additional environmental risks. Each square metre of CSP concentrator surface is enough to avoid the annual production of 0.25 to 0.4 t of CO_2. The energy payback time of CSP systems can be as low as five months, which compares very favourably with their lifespan of about 25 to 30 years (see Box 9.3 for further discussion). Most CSP solar field materials can be recycled and reused in new plants (SolarPACES, 2008).

Land consumption and impacts on local flora and wildlife during the build-up of the heliostat field and other facilities are the main environmental issues for CSP systems (Pregger et al., 2009). Other impacts are associated with the construction of the steel-intensive infrastructure for solar energy collection due to mineral and fossil resource consumption,



Estimates:	124	30	56	12	13	4	6	2*	1
References:	26	9	15	3	3	1	2	2	1

*same value

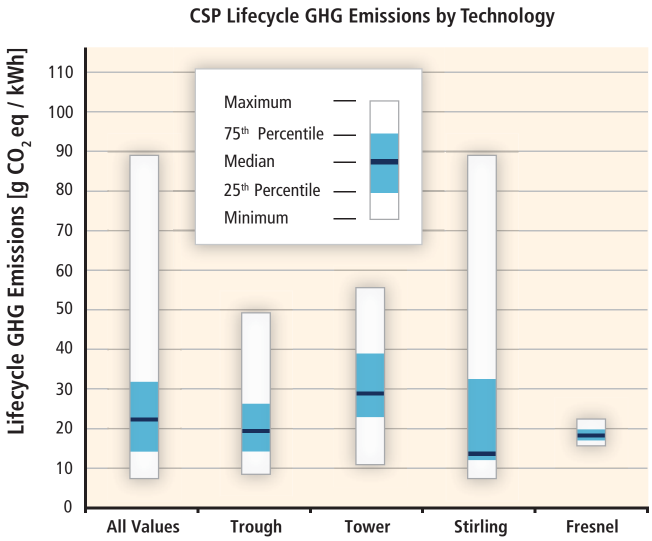
Figure 3.14 | Lifecycle GHG emissions of PV technologies (unmodified literature values, after quality screen). See Annex II for details of the literature search and citations of literature contributing to the estimates displayed.

as well as discharge of pollutants related to today's steel production technology (Felder and Meier, 2008).

The cost of land generally represents a very minor cost proportion of the whole plant. A 100-MW CSP plant with a solar multiple of one (see Section 3.3.4) would require 2 km^2 of land. However, the land does need to be relatively flat (particularly for linear trough and Fresnel systems), ideally near transmission lines and roads for construction traffic, and not on environmentally sensitive land. Although the mirror area itself is typically only about 25 to 35% of the land area occupied, the site of a solar plant will usually be arid. Thus, it is generally not suitable for other agricultural pursuits, but may still have protected or sensitive species. For this kind of system, sunny deserts close to electricity infrastructure are ideal. As CSP plant capacity is increased, however, the economics of longer electricity transmission distances improves. So, more distant siting might be expected with according increases in transmission infrastructure needs. Attractive sites exist in many regions of the world, including southern Europe, northern and southern African countries, the Middle East, Central Asian countries, China (Tibet, Xinjan), India (Rajasthan and Gujarat states), Australia, Chile, Peru, Mexico and south-western USA.

In the near term, water availability may be important to minimize the cost of Rankine cycle-based CSP systems. Water is also needed for steam-cycle make-up and mirror cleaning, although these two uses represent only a few percent of that needed if wet cooling is used. However, there will be otherwise highly favourable sites where water is not available for cooling. In these instances, water use can be substantially reduced if dry or hybrid cooling is used, although at an additional cost. The additional cost of electricity from a dry-cooled plant is 2 to 10% (US DOE, 2009), although it depends on many factors such as ambient conditions and technology, for example, tower plants operating at higher temperatures require less cooling per MWh than troughs. Tower and dish Brayton and Stirling systems are being developed for their ability to operate efficiently without cooling water.

In a manner similar to that for PV, NREL conducted an analogous search for CSP lifecycle assessments. Figure 3.15 displays distributions



	All Values	Trough	Tower	Stirling	Fresnel
Estimates:	42	20	14	4	4
References:	13	7	5	3	1

Figure 3.15 | Lifecycle GHG emissions of CSP technologies (unmodified literature values, after quality screen). See Annex II for details of literature search and citations of literature contributing to the estimates displayed.

of as-published estimates of lifecycle GHG emissions. The majority of estimates fall between 14 and 32 g CO_2eq/kWh for trough, tower, Stirling and Fresnel systems, and no great difference between technologies emerges from the available literature. Less literature is available to evaluate CSP systems than for some PV designs; however, the current state of knowledge of lifecycle GHG emissions for these technologies appears fairly consistent, although augmentation with additional LCAs is recommended.

In *solar fuel production*, solar thermal processes use concentrated solar irradiance as the main or sole source of high-temperature process heat. Such a plant consists of a central-receiver system comprising a heliostat field focusing direct solar irradiance on a receiver mounted on a tower. The receiver comprises a chemical reactor or a heat-exchanging device. Direct CO_2 emissions released by the thermochemical processes are negligible or significantly lower than from current processes (Pregger et al., 2009). All other possible effects are comparable to the conventional processes or can be prevented by safety measures and equipment that are common practice in the chemical industry.

3.6.2 Social impacts

Solar energy has the potential to meet rising energy demands and decrease GHG emissions, but solar technologies have faced resistance due to public concerns among some groups. The land area requirements for centralized CSP and PV plants raise concerns about visual impacts, which can be minimized during the siting phase by choosing locations in areas with low population density, although this will usually be the case for suitable solar sites anyway. Visual concerns also exist for distributed solar systems in built-up areas, which may find greater resistance for applications on historical or cultural buildings versus modern construction. By avoiding conservation areas and incorporating solar technologies into building design, these conflicts can be minimized. Noise impacts may be of concern in the construction phase, but impacts can be mitigated in the site-selection phase and by adopting good work practices (Tsoutsos et al., 2005). Community engagement throughout the planning process of renewable projects can also significantly increase public acceptance of projects (Zoellner et al., 2008).

Increased deployment of consumer-purchased systems still faces barriers with respect to costs, subsidy structures that may be confusing, and misunderstandings about reliability and maintenance requirements (Faiers and Neame, 2006). Effective marketing of solar technologies—including publicizing impacts relative to traditional power generation facilities, environmental benefits and contribution to a secure energy supply—have helped to accelerate social acceptance and increase willingness to pay (Batley et al., 2001). Government spending on solar technologies through fiscal incentives and R&D could garner increased public support through increased quantification and dissemination of the economic impacts associated with those programs. A recent study comparing job impacts across energy technologies showed that solar PV had the greatest job-generating potential at an average of 0.87 job-years per GWh, whereas CSP yielded an average of 0.23 job-years per GWh, both of which exceeded estimated job creation for fossil technologies (Wei et al., 2010). Section 9.3.1 discusses qualifications and limitations of assessing the job market impact of RE.

Solar technologies can also improve the health and livelihood opportunities for many of the world's poorest populations. Solar technologies have the potential to address some of the gap in availability of modern energy services for the roughly 1.4 billion people who do not have access to electricity and the more than 2.7 billion people who rely on traditional biomass for home cooking and heating needs (IEA, 2010d; see Section 9.3.2).

Solar home systems and PV-powered community grids can provide economically favourable electricity to many areas for which connection to a main grid is impractical, such as in remote, mountainous and delta regions. Electric lights are the most frequently owned and operated household appliance in electrified households, and access to electric lighting is widely accepted as the principal benefit of electrification programs (Barnes, 1988). Electric lighting may replace light supplied by kerosene lanterns, which are generally associated with poor-quality light and high household fuel expenditures, and which pose fire and poisoning risks. The improved quality of light allows for increased reading by household members, study by children, and home-based enterprise activities after dark, resulting in increased education and income opportunities for the household. Higher-quality light can also be provided through solar lanterns, which can afford the same benefits achieved through solar home system-generated lighting. Solar lantern models can be stand-alone or can require central-station charging, and programs of manufacture, distribution and maintenance can provide micro-enterprise opportunities. Use of solar lighting can represent a significant cost savings to households over the lifetime of the technology compared to kerosene, and it can reduce the 190 Mt of estimated annual CO_2 emissions attributed to fuel-based lighting (Mills, 2005). Solar-powered street lights and lights for community buildings can increase security and safety and provide night-time gathering locations for classes or community meetings. PV systems have been effectively deployed in disaster situations to provide safety, care and comfort to victims in the USA and Caribbean and could be similarly deployed worldwide for crisis relief (Young, 1996).

Solar home systems can also power televisions, radios and cellular telephones, resulting in increased access to news, information and distance education opportunities. A study of Bangladesh's Rural Electrification Program revealed that in electrified households all members are more knowledgeable about public health issues, women have greater knowledge of family planning and gender equality issues, the income and gender discrepancies in adult literacy rates are lower, and immunization guidelines for children are adhered to more regularly when compared with non-electrified households (Barkat et al., 2002). Electrified households may also buy appliances such as fans, irons, grinders, washing machines and refrigerators to increase comfort and reduce the drudgery associated with domestic tasks (ESMAP, 2004).

Indoor smoke from solid fuels is responsible for more than 1.6 million deaths annually and 3.6% of the global burden of disease. This mortality rate is similar in scale to the 1.7 million annual deaths associated with unsafe sanitation and more than twice the estimated 0.8 million yearly deaths from exposure to urban air pollution (Ezzati et al., 2002; see Sections 9.3.2 and 9.3.4.3). In areas where solar cookers can satisfactorily produce meals, these cookers can reduce unhealthy exposure to high levels of particulate matter from traditional use of solid fuels for cooking and heating and the associated morbidity and mortality from respiratory and other diseases. Decreased consumption of firewood will correspondingly reduce the time women spend collecting firewood. Studies in India and Africa have collected data showing that this time can total 2 to 15 hours per week, and this is increasing in areas of diminishing fuelwood supply (Brouwer et al., 1997; ESMAP, 2004). Risks to women collecting fuel include injury, snake bites, landmines and sexual violence (Manuel, 2003; Patrick, 2007); when children are enlisted to help with this activity, they may do so at the expense of educational opportunities (Nankhuni and Findeis, 2004). Well-being may be acutely at risk in refugee situations, as are strains on the natural resource systems where fuel is collected (Lynch, 2002). Solar cookers do not generally fulfil all household cooking needs due to technology requirements or their inability to cook some traditional foods; however, even partial use of solar cookers can realize fuelwood savings and reductions in exposure to indoor air pollution (Wentzel and Pouris, 2007).

Solar technologies also have the potential to combat other prevalent causes of morbidity and mortality in poor, rural areas. Solar desalination and water purification technologies can help combat the high prevalence of diarrhoeal disease brought about by lack of access to potable water supplies. PV systems for health clinics can provide refrigeration for vaccines and lights for performing medical procedures and seeing patients at all hours. Improved working conditions for rural health-care workers can also lead to decreased attrition of talented staff to urban centres.

Solar technologies can improve the economic opportunities and working conditions for poor rural populations. Solar dryers can be used to preserve foods and herbs for consumption year round and produce export-quality products for income generation. Solar water pumping can minimize the need for carrying water long distances to irrigate crops, which can be particularly important and impactful in the dry seasons and in drought years. Burdens and risks from water collection parallel those of fuel collection, and decreased time spent on this activity can also increase the health and well-being of women, who are largely responsible for these tasks.

3.7 Prospects for technology improvements and innovation[7]

This section considers technical innovations that are possible in the future for a range of solar technologies, under the following headings: passive solar and daylighting technologies; active solar heat and cooling; PV electricity generation; CSP electricity generation; solar fuel production; and other possible applications.

3.7.1 Passive solar and daylighting technologies

Passive solar technologies, particularly the direct-gain system, are intrinsically highly efficient because no energy is needed to move collected energy to storage and then to a load. The collection, storage and use are all integrated. Through technological advances such as low-emissivity coatings and the use of gases such as argon in glazings, near-equatorial-facing windows have reached a high level of performance at increasingly affordable cost. Nevertheless, in heating-dominated climates, further advances are possible, such as the following: 1) reduced thermal conductance by using dynamic exterior night insulation (night shutters); 2) use of evacuated glazing units; and 3) translucent glazing systems, which may include materials that change solar/visible transmittance with temperature (including a

7 Section 10.5 offers a complementary perspective on drivers and trends of technological progress across RE technologies.

possible phase change) while providing increased thermal resistance in the opaque state.

Increasingly larger window areas become possible and affordable with the drop in prices of highly efficient double-glazed and triple-glazed low-emissivity argon-filled windows (see Sections 3.4.1 and 3.4.2). These increased window areas make systematic solar gain control essential in mild and moderate climatic conditions, but also in continental areas that tend to be cold in winter and hot in summer. Solar gain control techniques may increasingly rely on active systems such as automatically controlled blinds/shades or electrochromic, thermochromic and gasochromic coatings to admit the solar gains when they are desirable or keep them out when overheating in the living space is detected or anticipated. Solar gain control, thermal storage design and heating/cooling system control are three strongly linked aspects of passive solar design and control.

Advances in thermal storage integrated in the interior of direct-gain zones are still possible, such as phase-change materials integrated in gypsum board, bricks, or tiles and concrete. The target is to maximize energy storage per unit volume/mass of material so that such materials can be integrated in lightweight wood-framed homes common in cold-climate areas. The challenge for such materials is to ensure that they continue to store and release heat effectively after 10,000 cycles or more while meeting other performance requirements such as fire resistance. Phase-change materials may also be used systematically in plasters to reduce high indoor temperatures in summer.

Considering cooling-load reduction in solar buildings, advances are possible in areas such as the following: 1) cool-roof technologies involving materials with high solar reflectivity and emissivity; 2) more systematic use of heat-dissipation techniques such as using the ground and water as a heat sink; 3) advanced pavements and outdoor structures to improve the microclimate around the buildings and decrease urban ambient temperatures; and 4) advanced solar control devices allowing penetration of daylight, but not thermal energy.

In any solar building, there are normally some direct-gain zones that receive high solar gains and other zones behind that are generally colder in winter. Therefore, it is beneficial to circulate air between the direct-gain zones and back zones in a solar home, even when heating is not required. With forced-air systems commonly used in North America, this is increasingly possible and the system fan may be run at a low flow rate when heating is not required, thus helping to redistribute absorbed direct solar gains to the whole house (Athienitis, 2008).

During the summer period, hybrid ventilation systems and techniques may be used to provide fresh air and reduce indoor temperatures (Heiselberg, 2002). Various types of hybrid ventilation systems have been designed, tested and applied in many types of buildings. Performance tests have found that although natural ventilation cannot maintain appropriate summer comfort conditions, the use of a hybrid system is the best choice—using at least 20% less energy than any purely mechanical system.

Finally, design tools are expected to be developed that will facilitate the simultaneous consideration of passive design, daylighting, active solar gain control, heating, ventilation and air-conditioning (HVAC) system control, and hybrid ventilation at different stages of the design of a solar building. Indeed, systematically adopting these technologies and their optimal integration is essential to move towards the goal of cost-effective solar buildings with net-zero annual energy consumption (IEA, 2009b). Optimal integration of passive with active technologies requires smart buildings with optimized energy generation and use (Candanedo and Athienitis, 2010). A smart solar house would rely on predictions of the weather to optimally control solar gains and their storage, ensure good thermal comfort, and optimize its interaction with the electricity grid, applying a mixture of inexpensive and effective communications systems and technologies (see Section 8.2.1).

3.7.2 Active solar heating and cooling

Improved designs for solar heating and cooling systems are expected to address longer lifetimes, lower installed costs and increased temperatures. The following are some design options: 1) the use of plastics in residential solar water-heating systems; 2) powering air-conditioning systems using solar energy systems, especially focusing on compound parabolic concentrating collectors; 3) the use of flat-plate collectors for residential and commercial hot water; and 4) concentrating and evacuated-tube collectors for industrial-grade hot water and thermally activated cooling (see Section 3.3.4).

Heat storage represents a key technological challenge, because the wide deployment of active solar buildings, covering 100% of their demand for heating (and cooling, if any) with solar energy, largely depends on developing cost-effective and practical solutions for seasonal heat storage (Hadorn, 2005; Dincer and Rosen, 2010). The European Solar Thermal Technology Platform vision assumes that by 2030, heat storage systems will be available that allow for seasonal heat storage with an energy density eight times higher than water (ESTTP, 2006).

In the future, active solar systems—such as thermal collectors, PV panels, and PV-thermal systems—will be the obvious components of roof and façades, and will be integrated into the construction process at the earliest stages of building planning. The walls will function as a component of the active heating and cooling systems, supporting thermal energy storage by applying advanced materials (e.g., phase-change materials). One central control system will lead to optimal regulation of the whole HVAC system, maximizing the use of solar energy within the comfort parameters set by users. Heat- and cold-storage systems will play an increasingly important role in reaching maximum solar thermal contributions to cover the thermal requirements in buildings.

Solar-assisted air-conditioning technology is still in an early stage of development (Henning, 2007). However, increased efforts in technological development will help to increase the competitiveness of this technology in the future. The major trends are as follows:

- Research in providing thermally driven cooling equipment in the low cooling power range (less than 20 kW);
- Developing single-effect cycles with increased COP values at low driving temperatures;
- Studying new approaches to enhance heat transfer in compartments containing sorption material to improve the power density and thermal performance of adsorption chillers;
- Developing new schemes and new working fluids for steam jet cycles and promising candidates for closed cycles to produce chilled water; and
- Research activities on cooled open sorption cycles for solid and liquid sorbents.

3.7.3 Photovoltaic electricity generation

This subsection discusses photovoltaic technology improvements and innovation within the areas of solar PV cells and the entire PV system. Photovoltaic modules are the basic building blocks of flat-plate PV systems. Further technological efforts will likely lead to reduced costs, enhanced performance and improved environmental profiles. It is useful to distinguish between technology categories that require specific R&D approaches.

Funding of PV R&D over the past four decades has supported innovation and gains in PV cell quality, efficiencies and price. In 2008, public budgets for R&D programs in the IEA Photovoltaic Power Systems Programme countries collectively reached about USD_{2005} 390 million (assumed 2008 base), a 30% increase compared to 2007, but stagnated in 2009 (IEA, 2009c, 2010e).

For wafer-based crystalline silicon, existing thin-film technologies, and emerging and novel technologies (including 'boosters' to the first two categories), the following paragraphs list R&D topics that have highest priority. Further details can be found in the various PV roadmaps, for example, the Strategic Research Agenda for Photovoltaic Solar Energy Technology (US Photovoltaic Industry Roadmap Steering Committee, 2001; European Commission, 2007; NEDO, 2009).

- **Efficiency, energy yield, stability and lifetime.** Research often aims at optimizing rather than maximizing these parameters, which means that additional costs and gains are critically compared. Because research is primarily aimed at reducing the cost of electricity generation, it is important not to focus only on initial costs (USD/W_p), but also on lifecycle gains, that is, actual energy yield (kWh/W_p or kJ/W_p over the economic or technical lifetime).
- **High-productivity manufacturing, including in-process monitoring and control.** Throughput and yield are important parameters in low-cost manufacturing and essential to achieve the cost targets. In-process monitoring and control are crucial tools to increase product quality and yield. Focused effort is needed to bring PV manufacturing to maturity.
- **Environmental sustainability.** The energy and materials requirements in manufacturing, as well as the possibilities for recycling, are important parameters in the overall environmental quality of the product. Further shortening of the energy payback time, design for recycling and, ideally, avoiding the use of materials that are not abundant on Earth are the most important issues to be addressed.
- **Applicability.** As discussed in more detail in the paragraphs on BOS and systems, standardization and harmonization are important to bring down the investment costs of PV. Some related aspects are addressed on a module level. In addition, improved ease of installation is partially related to module features. Finally, aesthetic quality of modules (and systems) is an important aspect for large-scale use in the built environment.

Advanced technologies include those that have passed some proof-of-concept phase or can be considered as 10- to 20-year development options for the PV approaches discussed in Section 3.3.3 (Green, 2001, 2003; Nelson, 2003). These emerging PV concepts are medium to high risk and are based on extremely low-cost materials and processes with high performance. Examples are four- to six-junction concentrators (Marti and Luque, 2004; Dimroth et al., 2005), multiple-junction polycrystalline thin films (Coutts et al., 2003), crystalline silicon in the sub-100-µm-thick regime (Brendel, 2003), multiple-junction organic PV (Yakimov and Forrest, 2002; Sun and Sariciftci, 2005) and hybrid solar cells (Günes and Sariciftci, 2008).

Even further out on the timeline are concepts that offer exceptional performance and/or very low cost but are yet to be demonstrated beyond some preliminary stages. These technologies are truly high risk, but have extraordinary technical potential involving new materials, new device architectures and even new conversion concepts (Green, 2001, 2003; Nelson, 2003). They go beyond the normal Shockley-Queisser limits (Shockley and Queisser, 1961) and may include biomimetic devices (Bar-Cohen, 2006), quantum dots (Conibeer et al., 2010), multiple-exciton generation (Schaller and Klimov, 2004; Ellingson et al., 2005) and plasmonic solar cells (Catchpole and Polman, 2008).

PV concentrator systems are considered a separate category, because the R&D issues are fundamentally different compared to flat-plate technologies. As mentioned in Section 3.3.3, CPV offers a variety of technical solutions that are provided at the system level. Research issues can be divided into the following activities: 1) concentrator solar cell manufacturing; 2) optical system; 3) module assembly and fabrication method of concentrator modules and systems; and 4) system aspects, such as tracking, inverter and installation issues.

However, it should be clearly stated once more: CPV is a system approach. The whole system is optimized only if all the interconnections between the components are considered. A corollary is that an optimized component is not necessarily the best choice for the optimal CPV system. Thus, strong interactions are required among the various research groups.

A photovoltaic system is composed of the PV module, as well as the *balance-of-system components and system*, which can include an inverter, storage, charge controller, system structure and the energy network. Users meet PV technology at the system level, and their interest is in a reliable, cost-effective and attractive solution to their energy supply needs. This research agenda concentrates on topics that will achieve one or more of the following: 1) reduce costs at the component and/or system level; 2) increase the overall performance of the system, including increased and harmonized component lifetimes, reduced performance losses and maintenance of performance levels throughout system life; and 3) improve the functionality of and services provided by the system, thus adding value to the electricity produced (US Photovoltaic Industry Roadmap Steering Committee, 2001; Navigant Consulting Inc., 2006; EU PV European Photovoltaic Technology Platform, 2007; Kroposki et al., 2008; NEDO, 2009).

At the component level, a major objective of BOS development is to extend the lifetime of BOS components for grid-connected applications to that of the modules, typically 20 to 30 years.

For off-grid systems, component lifetime should be increased to around 10 years, and components for these systems need to be designed so that they require little or no maintenance. Storage devices are necessary for off-grid PV systems and will require innovative approaches to the short-term storage of small amounts of electricity (1 to 10 kWh, or 3,600 to 36,000 kJ), and for providing a single streamlined product (such as integrating the storage component into the module) that is easy to use in off-grid and remote applications.

For on-grid systems, high penetration of distributed PV may raise concerns about potential impacts on the stability and operation of the grid, and these concerns may create barriers to future expansion (see also Section 8.2.1). An often-cited disadvantage is the greater sensitivity to grid interconnection issues such as overvoltage and unintended islanding in the low- or middle-voltage network (Kobayashi and Takasaki, 2006; Cobben et al., 2008; Ropp et al., 2008). Moreover, imbalance between demand and supply is often discussed with respect to the variation of PV system output (Braun et al., 2008; NEDO, 2009; Piwko et al., 2010). PV system designs and operation technologies can address these issues to a degree through technical solutions and through more accurate solar energy forecasting. Moreover, PV inverters can help to improve the quality of grid electricity by controlling reactive power or filtering harmonics with communication in a new energy network that applies a mixture of inexpensive and effective communications systems and technologies, including smart meters (see Section 8.2.1).

As new module technologies emerge in the future, some ideas relating to BOS, such as micro-converters, may need to be revised. Furthermore, the quality of the system needs to be assured and adequately maintained according to defined standards, guidelines and procedures. To assure system quality, assessing performance is important, including on-line analysis (e.g., early fault detection) and off-line analysis of PV systems. The gathered knowledge can help to validate software for predicting the energy yield of future module and system technology designs.

Furthermore, very-large-scale PV systems with capacities ranging from several MW to GW are beginning to be planned for deployment (Komoto et al., 2009). In the long term, these systems may play an important role in the worldwide energy network (DESERTEC Foundation, 2007), but may demand new transmission infrastructure and new technical and institutional solutions for electricity system interconnection and operational management.

Standards, quality assurance, and safety and environmental aspects are other important issues. National and especially local authorities and utilities require that PV systems meet agreed-upon standards (such as building standards, including fire and electrical safety requirements). In a number of cases, the development of the PV market is being hindered by either: 1) existing standards, 2) differences in local standards (e.g., inverter requirements/settings) or 3) the lack of standards (e.g., PV modules/PV elements not being certified as a building element because of the lack of an appropriate standard). Standards and/or guidelines are required for the whole value chain. In many cases, developing new and adapted standards and guidelines implies that dedicated R&D is required.

Quality assurance is an important tool that assures the effective functioning of individual components in a PV system, as well as the PV system as a whole. Standards and guidelines are an important basis for quality assurance. In-line production control procedures and guidelines must also be developed. At the system level, monitoring techniques must be developed for early fault detection.

Recycling is an important building block to ensure a sustainable PV industry. Through 2010, most attention has focused on recycling crystalline silicon and CdTe solar modules. Methods for recycling other thin-film modules and BOS components (where no recycling procedures exist) must be addressed in the future. LCA studies are an important tool for evaluating the environmental profile of the various RE sources. Reliable LCA data are required to assure the position of PV with respect to other sources. From these data, properties such as the CO_2 emission per kWh or kJ of electricity produced and the energy payback time can be calculated. In addition, the results of LCA analyses can be used in the design phase of new processes and equipment for cell and module production lines.

3.7.4 Concentrating solar power electricity generation

CSP is a proven technology at the utility scale. The longevity of components has been established over two decades, O&M aspects are understood, and there is enough operational experience to have enabled O&M cost-reduction studies not only to recommend, but also to test, those improvements. In addition, field experience has been fed back to industry and research institutes and has led to improved components and more advanced processes. Importantly, there is now substantial experience that allows researchers and developers to better understand the limits of performance, the likely potential for cost reduction, or both. Studies (Sargent and Lundy LLC Consulting Group, 2003) have concluded that cost reductions will come from technology improvement, economies of scale and mass production. Other innovations related to power cycles and collectors are discussed below.

CSP is a technology driven largely by thermodynamics. Thus, the *thermal energy conversion cycle* plays a critical role in determining overall performance and cost. In general, thermodynamic cycles with higher temperatures will perform more efficiently. Of course, the solar collectors that provide the higher-temperature thermal energy to the process must be able to perform efficiently at these higher temperatures, and today, considerable R&D attention is on increasing the operating temperature of CSP systems. Although CSP works with turbine cycles used by the fossil-fuel industry, there are opportunities to refine turbines such that they can better accommodate the duties associated with thermal cycling invoked by solar inputs.

Considerable development is taking place to optimize the linkage between solar collectors and higher-temperature thermodynamic cycles. The most commonly used power block to date is the steam turbine (Rankine cycle). The steam turbine is most efficient and most cost effective in large capacities. Present trough plants using oil as the heat transfer fluid limit steam turbine temperatures to 370°C and turbine cycle efficiencies to around 37%, leading to design-point solar-to-electric efficiencies of the order of 18% and annual average efficiency of 14%. To increase efficiency, alternatives to the use of oil as the heat transfer fluid—such as producing steam directly in the receiver or using molten salts—are being developed for troughs.

These fluids and others are already preferred for central receivers. Central receivers and dishes are capable of reaching the upper temperature limits of these fluids (around 600°C for present molten salts) for advanced steam turbine cycles, whether subcritical or supercritical, and they can also provide the temperatures needed for higher-efficiency cycles such as gas turbines (Brayton cycle) and Stirling engines. Such high-temperature cycles have the capacity to boost design-point solar-to-electricity efficiency to 35% and annual average efficiency to 25%. The penalty for dry cooling is also reduced, and at higher temperatures thermal storage is more efficient.

The *collector* is the single largest area for potential cost reduction in CSP plants. For CSP collectors, the objective is to lower their cost while achieving the higher optical efficiency necessary for powering higher-temperature cycles. Trough technology will benefit from continuing advances in solar-selective surfaces, and central receivers and dishes will benefit from improved receiver/absorber design that allows collection of very high solar fluxes. Linear Fresnel is attractive in part because the inverted-cavity design can reduce some of the issues associated with the heat collection elements of troughs, although with reduced annual optical performance.

Improved overall efficiency yields a corresponding decrease in the area of mirrors needed in the field, and thus, lower collector cost and lower O&M cost. Investment cost reduction is expected to come primarily from the benefits of mass production of key components that are specific to the solar industry, and from economies of scale as the fixed price associated with manufacturing tooling and installation is spread over larger and larger capacities. In addition, the benefits of 'learning by doing' cannot be overestimated. A more detailed assessment of future technology improvements that would benefit CSP can be found in ECOSTAR (2005), a European project report edited by the German Aerospace Center.

3.7.5 Solar fuel production

The ability to store solar energy in the form of a fuel may be desirable not only for the transportation industry, but also for high-efficiency electricity generation using today's combined cycles, improved combined cycles using advances in gas turbines, and fuel cells. In addition, solar fuels offer a form of storage for solar electricity generation.

Future solar fuel processes will benefit from the continuing development of high-temperature solar collectors, but also from other fields of science such as electrochemistry and biochemistry. Many researchers consider hydrogen to offer the most attraction for the future, although intermediate and transitional approaches are also being developed. Hydrogen is considered in this section, with other solar fuels having been covered in previous sections.

Future technology innovation for solar electrolysis is the photoelectrochemical (PEC) cell, which converts solar irradiance into chemical energy such as H_2. A PEC cell is fabricated using an electrode that absorbs the solar light, two catalytic films, and a membrane separating H_2 and oxygen (O_2). Semiconductor material can be used as a solar light-absorbing anode in PEC cells (Bolton, 1996; Park and Holt, 2010).

Promising *thermochemical* processes for future 'clean' hydrogen mass production encompass the hybrid-sulphur cycle and metal oxide-based cycles. The hybrid-sulphur cycle is a two-step water-splitting process using an electrochemical, instead of thermochemical, reaction for one of the two steps. In this process, sulphur dioxide depolarizes the anode of the electrolyzer, which results in a significant decrease in the reversible cell potential—and, therefore, the electric power requirement for the electrochemical reaction step. A number of solar reactors applicable to solar thermochemical metal oxide-based cycles have been developed, including a 100-kW$_{th}$ monolithic dual-chamber solar reactor for a mixed-iron-oxide cycle, demonstrated within the European R&D project *HYDROSOL-2* (Roeb et al., 2009); a rotary solar reactor for the ZnO/Zn process being scaled up to 100 kW$_{th}$ (Schunk et al., 2009); the Tokyo Tech rotary-type solar reactor (Kaneko et al., 2007); and the Counter-Rotating-Ring Receiver/Reactor/Recuperator, a device using recuperation of sensible heat to efficiently produce H_2 in a two-step thermochemical process (Miller et al., 2008).

High temperatures demanded by the thermodynamics of the thermochemical processes pose considerable material challenges and also increase re-radiation losses from the reactor, thereby lowering the absorption efficiency (Steinfeld and Meier, 2004). The overall energy conversion efficiency is improved by reducing thermal losses at high temperatures through improved mirror optics and cavity-receiver design, and by recovering part of the sensible heat from the thermochemical processes.

High-temperature thermochemical processes require thermally and chemically stable reactor-wall materials that can withstand the extreme operating conditions of the various solar fuel production processes. For many lower-temperature processes (e.g., sulphur-based thermochemical cycles), the major issue is corrosion. For very high-temperature metal-oxide cycles, the challenge is the thermal shock resistance of the ceramic wall materials. Near-term solutions include surface modification of thermally compatible refractory materials such as graphite and silicon carbide. Longer-term solutions include modifications of bulk materials. Novel reactor designs may prevent wall reactions.

A key aspect is integrating the chemical process into the solar concentrating system. The concentrating optics—consisting of heliostats and secondary concentrators (compound parabolic concentrator)—need to be further developed and specifically optimized to obtain high solar-flux intensities and high temperatures in solar chemical reactors for producing fuels.

Photochemical and photobiological processes are other strong candidates for solar fuel conversion. Innovative technologies are being developed for producing biofuels from modified photosynthetic microorganisms and photocatalytic cells for fuel production. Both approaches have the potential to provide fuels with solar energy conversion efficiencies far greater than those based on field crops (Turner et al., 2008). Solar-driven fuel production requires biomimetic nanotechnology, where scientists must develop a series of fundamental and technologically advanced multi-electron redox catalysts coupled to photochemical elements. Hydrogen production by these methods at scale has vast technical potential and promising avenues are being vigorously pursued.

A combination of all three forms is found in the *synthesis of biogas*, a mixture of methane and CO_2, with solar-derived hydrogen. Solar hydrogen is added by electrochemical water-splitting. Bio-CO_2 reacts with hydrogen in a thermochemical process to generate hydrocarbons such as synthetic natural gas or liquid solar fuels (Sterner, 2009). These approaches are still nascent, but could become viable in the future as energy market prices increase and solar power generation costs continue to decrease.

3.7.6 Other potential future applications

There are also methods for producing electricity from solar thermal energy without the need for an intermediate thermodynamic cycle. This direct solar thermal power generation includes such concepts as thermoelectric, thermionic, magnetohydrodynamic and alkali-metal methods. The thermoelectric concept is the most investigated to date, and all have the attraction that the absence of a heat engine should mean a quieter and theoretically more efficient method of producing electricity, with suitability for distributed generation. Specialized applications include military and space power.

Space-based solar power (SSP) is the concept of collecting vast quantities of solar power in space using large satellites in Earth orbit, then sending that power to receiving antennae (rectennae) on Earth via microwave power beaming. The concept was first introduced in 1968 by Peter Glaser. NASA and the US Department of Energy (US DOE) studied SSP extensively in the 1970s as a possible solution to the energy crisis of that time. Scientists studied system concepts for satellites large enough to send GW of power to Earth and concluded that the concept seemed technically feasible and environmentally safe, but the state of enabling technologies was insufficient to make SSP economically competitive. Since the 1970s, however, great advances have been made in these technologies, such as high-efficiency PV cells, highly efficient solid-state microwave power electronics, and lower-cost space launch vehicles (Mankins, 1997, 2002, 2009; Kaya et al., 2001; Hoffert et al., 2002). Still, significant breakthroughs will be required to achieve cost-competitive terrestrial base-load power (NAS, 2004).

3.8 Cost trends[8]

3.8.1 Passive solar and daylighting technologies

High-performance building envelopes entail greater upfront construction costs, but lower energy-related costs during the lifetime of the building (Harvey, 2006). The total investment cost of the building may or may not be higher, depending on the extent to which heating and cooling systems can be downsized, simplified or eliminated altogether as a result of the high-performance envelope. Any additional investment cost will be compensated for, to some extent, by reduced energy costs over the lifetime of the building.

8 Discussion of costs in this section is largely limited to the perspective of private investors. Chapters 1 and 8 to 11 offer complementary perspectives on cost issues covering, for example, costs of integration, external costs and benefits, economy-wide costs and costs of policies.

The reduction in the cost of furnaces or boilers due to substantially better thermal envelopes is normally only a small fraction of the additional cost of the better thermal envelope. However, potentially larger cost savings can occur through downsizing or eliminating other components of the heating system, such as ducts to deliver warm air or radiators (Harvey, 2006). High-performance windows eliminate the need for perimeter heating. A very high-performance envelope can reduce the heating load to that which can be met by ventilation airflow alone. High-performance envelopes also lead to a reduction in peak cooling requirements, and hence, in cooling equipment sizing costs, and they permit use of a variety of passive and low-energy cooling techniques.

If a fully integrated design takes advantage of all opportunities facilitated by a high-performance envelope, savings in the cost of mechanical systems may offset all or much of the additional cost of the high-performance envelope.

In considering daylighting, the economic benefit for most commercial buildings is enhanced when sunlight is plentiful because daylighting reduces electricity demand for artificial lighting. This is also when the daily peak in electricity demand tends to occur (Harvey, 2006). Several authors report measurements and simulations with annual electricity savings from 50 to 80%, depending on the hours and the location. Daylighting can lead to reduced cooling loads if solar heat gain is managed and an integrated thermal-daylighting design of the building is followed (Tzempelikos et al., 2010). This means that replacing artificial light with just the amount of natural light needed reduces internal heating. Savings in lighting plus cooling energy use of 22 to 86%, respectively, have been reported (Duffie and Beckman, 2006).

Daylighting and passive solar features in buildings can have significant financial benefits not easily addressed in standard lifecycle and payback analysis. They generally add value to the building, and in the case of office buildings, can contribute to enhanced productivity (Nicol et al., 2006).

3.8.2 Active solar heating and cooling

Solar drying of crops and timber is common worldwide, either by using natural processes or by concentrating the heat in specially designed storage buildings. However, market data are not available.

Advanced applications—such as solar cooling and air conditioning, industrial applications and desalination/water treatment—are in the early stages of development, with only a few hundred first-generation systems in operation. Considerable cost reductions are expected if R&D efforts are increased over the next few years.

Solar water heating is characterized by a higher first cost investment and low operation and maintenance (O&M) costs. Some solar heating applications require an auxiliary energy source, and then annual loads are met by a combination of different energy sources. Solar thermal hot water systems are generally more competitive in sunny regions but this picture changes for space heating due to its usually higher overall heating load. In colder regions, capital costs can be spread over a longer heating season and solar thermal can then become more competitive (IEA, 2007).

The investment costs for solar water heating depend on the complexity of the technology used as well as the market conditions in the country of operation (IEA, 2007; Chang et al., 2009; Han et al., 2010). The costs for an installed solar hot-water system vary from as low as USD_{2005} 83/m^2 to more than USD_{2005} 1,200/m^2, which is equivalent to the USD_{2005} 120 to 1,800/kW$_p$[9] used in Annex III and the resulting levelized cost of heat (LCOH) calculations presented here as well as in Chapters 1 and 10. For the costs of the delivered heat, there is an additional geographic variable related to the available solar irradiation and the number of heating degree days (Mills and Schleich, 2009).

Based on the data and assumptions provided in Annex III, and the methods specified in Annex II, the plot in Figure 3.16 shows the sensitivity of the LCOH with respect to investment cost as a function of capacity factor.
Research to decrease the cost of solar water-heating systems is mainly oriented towards developing the next generation of low-cost, polymer-based systems for mild climates. The focus includes testing the durability of materials. The work to date includes unpressurized polymer integral collector-storage systems that use a load-side immersed heat exchanger and direct thermosyphon systems.

Over the last decade, for each 50% increase in the installed capacity of solar water heaters, investment costs have fallen by around 20% in Europe (ESTTP, 2008). According to the IEA (2010a), cost reductions in OECD countries will come from the use of cheaper materials, improved manufacturing processes, mass production, and the direct integration into buildings of collectors as multi-functional building components and modular, easy to install systems. Delivered energy costs are anticipated by the IEA to eventually decline by around 70 to 75%. One measure suggested by the IEA to realize those cost reductions are more research, development and demonstration (RD&D) investments. Priority areas for attention include new flat-plate collectors that can be more easily integrated into building façades and roofs, especially as multi-functional building components.

Energy costs should fall with ongoing decreases in the costs of individual system components and with better optimization and design. For example, Furbo et al. (2005) show that better design of solar domestic hot-water storage tanks when combined with an auxiliary energy source can improve the utilization of solar energy by 5 to 35%, thereby permitting a smaller collector area for the same solar yield.

9 1 m^2 of collector area is converted into 0.7 kW$_{th}$ of installed capacity (see Section 3.4.1).

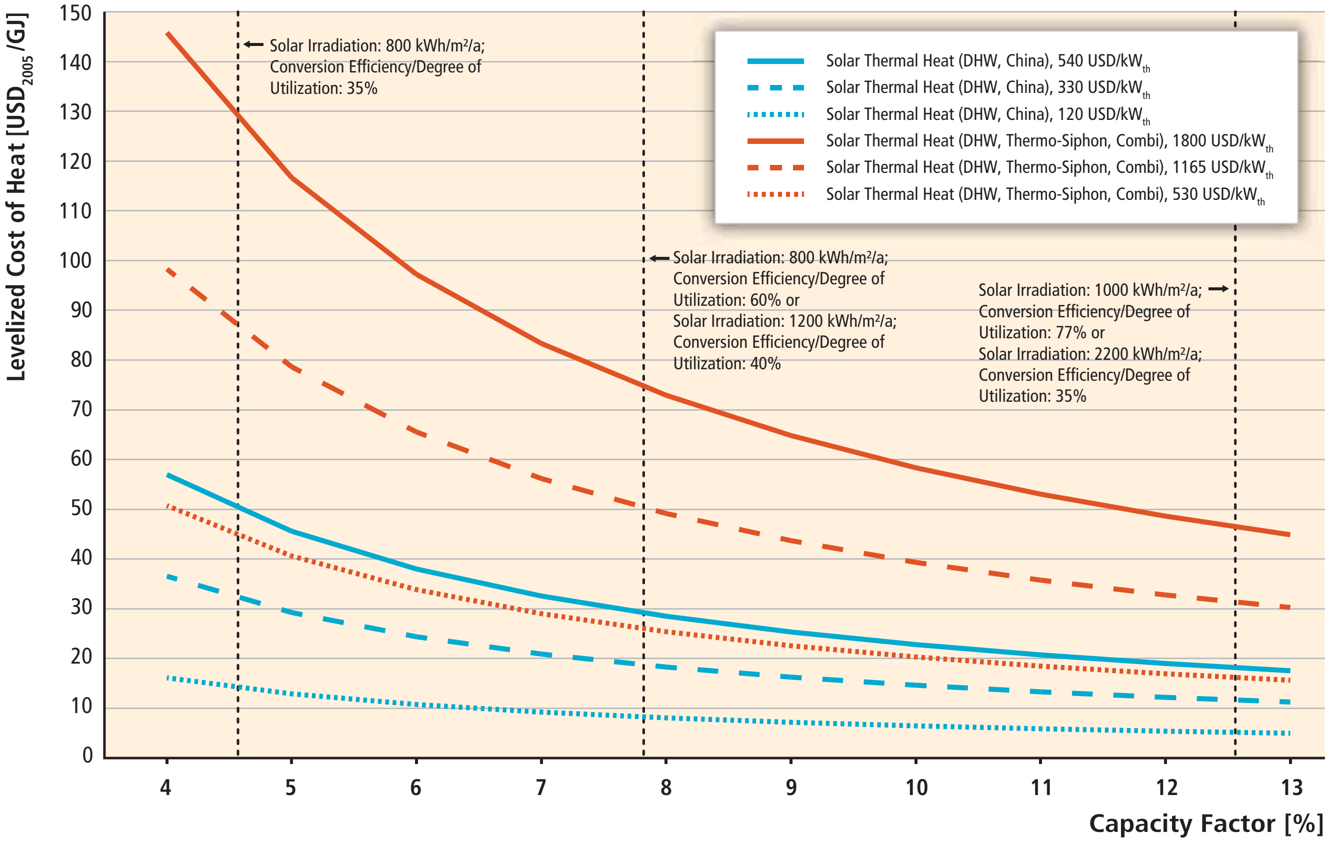


Figure 3.16 | Sensitivity of LCOH with respect to investment cost as a function of capacity factor (Source: Annex III).

3.8.3 Photovoltaic electricity generation

PV prices have decreased by more than a factor of 10 over the last 30 years; however, the current levelized cost of electricity (LCOE) from solar PV is generally still higher than wholesale market prices for electricity.[10] The competitiveness in other markets depends on a variety of local conditions.

The LCOE of PV systems is generally highly dependent on the cost of individual system components as well as on location and other factors affecting the overall system performance. The largest component of the investment cost of PV systems is the cost of the PV module. Other cost factors that affect the LCOE include—but are not limited to—BOS components, labour cost of installation and O&M costs. Due to the dynamic development of the cost of PV systems, this section focuses on cost trends rather than current cost. Nonetheless, recent costs are presented in the discussion of individual cost factors and resulting LCOE below.

Average global PV module factory prices dropped from about USD_{2005} 22/W in 1980 to less than USD_{2005} 1.5/W in 2010 (Bloomberg, 2010). Most studies about learning curve experience in photovoltaics focus on PV modules because they represent the single-largest cost item of a PV system (Yang, 2010). The PV module historical learning experience ranges between 11 and 26% (Maycock, 2002; Parente et al., 2002; Neij, 2008; IEA, 2010c) with a median progress ratio of 80%, and consequently, a median historical learning rate (price experience factor) of 20%, which means that the price was reduced by 20% for each doubling of cumulative sales (Hoffmann, 2009; Hoffmann et al., 2009). Figure 3.17 depicts the price developments for crystalline silicon modules over the last 35 years. The huge growth of demand after 2003 led to an increase in prices due to the supply-constrained market, which then changed into a demand-driven market leading to a significant price reduction due to module overcapacities in the market (Jäger-Waldau, 2010a).

The second-largest technical-related costs are the BOS components, and therein, the single largest item is the inverter. While the overall BOS experience curve was between 78 and 81%, or a 19 to 22% learning rate, quite similar to the module rates, learning rates for inverters were just in the range of 10% (Schaeffer et al., 2004). A similar trend was found in the USA for cost reduction for labour costs attributed to installed PV systems (Hoff et al., 2010).

The average investment cost of PV systems, that, the sum of the costs of the PV module, BOS components and labour cost of installation, has also

10 LCOE is not the sole determinant of its value or economic competitiveness (relative environmental and social impacts must be considered, as well as the contribution that the technology provides to meeting specific energy services, for example, peak electricity demands, or integration costs).

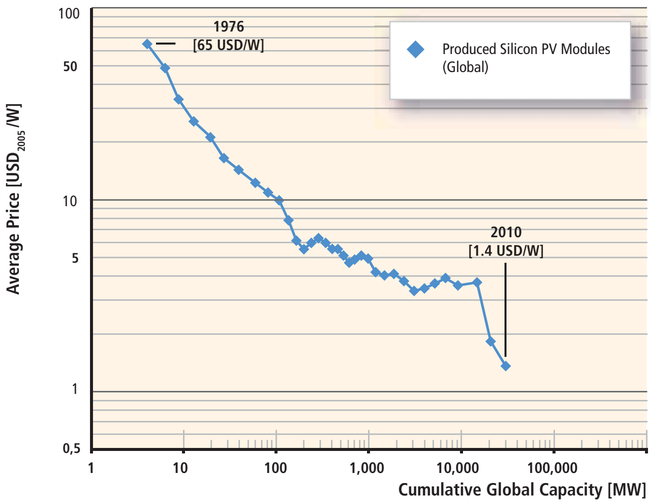


Figure 3.17 | Solar price experience or learning curve for silicon PV modules. Data displayed follow the supply and demand fluctuations. Data source: Maycock (1976-2003); Bloomberg (2010).

decreased significantly over the past couple of decades and is projected to continue decreasing rapidly as PV technology and markets mature. However, the system price decrease[11] varies significantly from region to region and depends strongly on the implemented support schemes and maturity of markets (Wiser et al., 2009). Figure 3.18 shows the system price developments in Europe, Japan, and the USA.

The capacity-weighted average investment costs of PV systems installed in the USA declined from USD$_{2005}$ 9.7/W in 1998 to USD$_{2005}$ 6.8/W in 2008. This decline was attributed primarily to a drop in non-module (BOS) costs. Figure 3.18 also shows that PV system prices continued to decrease considerably since the second half of 2008. This decrease is considered to be due to huge increases in production capacity and production overcapacities and, as a result, increased competition between PV companies (LBBW, 2009; Barbose et al., 2010; Mints, 2011). More generally, Figure 3.18 shows that the gap between PV system prices or investment cost between and within different world regions narrowed until 2005. In the period from 2006 to 2008, however, the cost spread widened at least temporarily. The first-quarter 2010 average PV system price in Germany dropped to € 2,864/kW$_p$ (USD$_{2005}$ 3,315/kW$_p$) for systems below 100 kW$_p$ (Bundesverband Solarwirtschaft e.V., 2010). In 2009, thin-film projects at utility scale were realized at costs as low as USD$_{2005}$ 2.72/W$_p$ (Bloomberg, 2010).

O&M costs of PV electricity generation systems are low and are found to be in a range between 0.5 and 1.5% annually of the initial investment costs (Breyer et al., 2009; IEA, 2010c).

11 System prices determine the investment cost for independent project developers. Since, prices can contain profit mark-ups, the investment cost may be higher for independent project developers than for vertically integrated companies that are engaged in the production of PV systems or components thereof.

The main parameter that influences the capacity factor of a PV system is the actual annual solar irradiation at a given location given in kWh/m^2/yr. Capacity factors for PV installations are found to be between 11 and 24% (Sharma, 2011), which is in line with earlier findings of the IEA Implementing Agreement PVPS (IEA, 2007), which found that most of the residential PV systems had capacity factors in the range of 11 to 19%. Utility-scale systems currently under construction or in the planning phase are projected to have 20 to 30% capacity factors (Sharma, 2011).

Based on recent data representative of the global range of investment cost around 2008 as discussed above, assumptions provided in Annex III of this report, and the methods specified in Annex II, the following two plots show the sensitivity of the LCOE of various types of PV systems with respect to investment cost (Figure 3.19a) and discount rates (Figure 3.19b) as a function of the capacity factor.

Note that 1-axis tracking for utility-scale PV systems range from 15-20% increase in investment cost over fixed utility-scale PV systems. Modeling studies for c-Si indicate 16% increase for 1-axis tracking over fixed utility-scale PV systems (Goodrich et al., 2011). In 2008 and 2009, commercial rooftop PV systems of 20 to 500 kW were reported to be roughly 5% lower in investment cost than residential rooftop PV systems of 4 to 10 kW (NREL, 2011).

These figures highlight that the LCOE of individual projects depends strongly on the particular combination of investment costs, discount rates and capacity factors as well as on the type of project (residential, commercial, utility-scale).

Several studies have published LCOEs for PV electricity generation based on different assumptions and methodologies. Based on investment cost for thin-film projects of USD$_{2005}$ 2.72/W$_p$ in 2009 and further assumptions, Bloomberg (2010) finds LCOEs in the range of 14.5 and 36.3 US cent$_{2005}$/kWh. Breyer et al. (2009) find LCOEs in the range of 19.2 to 22.6 US cent$_{2005}$/kWh in regions of high solar irradiance (>1,800 kWh/m^2/yr) in Europe and the USA in 2009. All of these ranges can be considered to be reasonably achievable according to the LCOE ranges shown in Figure 3.19 and included in Annex III.

Assuming the PV market will continue to grow at more than 35% per year, the cost is expected to drop more than 50% to about 7.3 US cent$_{2005}$/kWh by 2020 (Breyer et al., 2009). Table 3.5 shows the 2010 IEA PV roadmap projections, which are somewhat less ambitious, but still show significant reductions (IEA, 2010c). The underlying deployment scenario assumes 3,155 GW of cumulative installed PV capacity by 2050.

The goal of the US DOE Solar Program's Technology Plan is to make PV-generated electricity cost-competitive with market prices in the USA by 2015. Their ambitious energy cost targets for various market sectors are 8 to 10 US cents$_{2005}$/kWh for residential, 6 to 8 US cents$_{2005}$/kWh for commercial

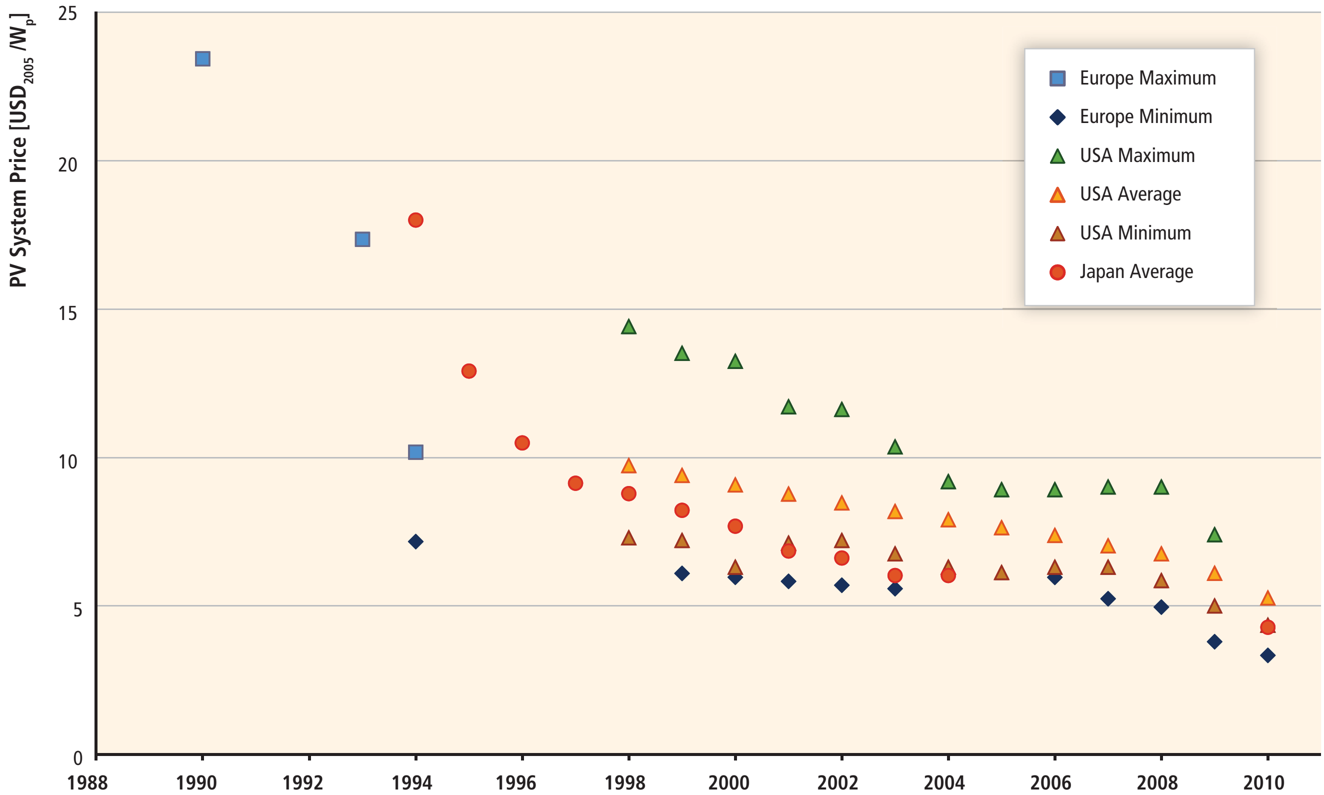


Figure 3.18 | Installed cost of PV systems smaller than 100 kW_p in Europe, Japan and the USA. Data sources: Urbschat et al. (2002); Jäger-Waldau (2005); Wiser et al. (2009); Bundesverband Solarwirtschaft e.V. (2010); SEIA (2010a,b).

and 5 to 7 US $cents_{2005}$/kWh for utilities (US DOE, 2008). All of these cost targets are just below what seems to be possible to achieve for projects of similar type realized around 2008 even under very optimistic conditions (see Figure 3.19 as well as Annex III). Given continued cost reductions in the near term, these cost targets appear to be well within reach for projects that can be realized under favourable conditions. Relatively more progress will be required, however, to allow achieving such costs on a broader scale.

3.8.4 Concentrating solar power electricity generation

Concentrating solar power electricity systems are a complex technology operating in a complex resource and financial environment, so many factors affect the LCOE (Gordon, 2001). A study for the World Bank (World Bank Global Environment Facility Program, 2006) suggested four phases of cost reduction for CSP technology and forecast that cost competitiveness with non-renewable fuel could be reached by 2025. Figure 3.20 shows that cost reductions for CSP technologies are expected to come from plant economies of scale, reducing costs of components through material improvements and mass production, and implementing higher-efficiency processes and technologies.

The total investment for the nine plants comprising the Solar Electric Generating Station (SEGS) in California was USD_{2005} 1.18 billion, and construction and associated costs for the Nevada Solar One plant amounted to 245 million (USD_{2005}, assumed 2007 base).

The publicized investment costs of CSP plants are often confused when compared with other renewable sources, because varying levels of integrated thermal storage increase the investment, but also improve the annual output and capacity factor of the plant.

The two main parameters that influence the solar capacity factor of a CSP plant are the solar irradiation and the amount of storage or the availability of a gas-fired boiler as an auxiliary heater, for example, the SEGS plants in California (Fernández-García et al., 2010). In case of solar-only CSP plants, the capacity factor is directly related to the available solar irradiation. With storage, the capacity factor could in theory be increased to 100%; however, this is not an economic option and trough plants are now designed for 6 to 7.5 hours of storage and a capacity factor of 36 to 41% (see Section 3.3.4). Tower plants, with their higher temperatures, can charge and store molten salt more efficiently, and projects designed for up to

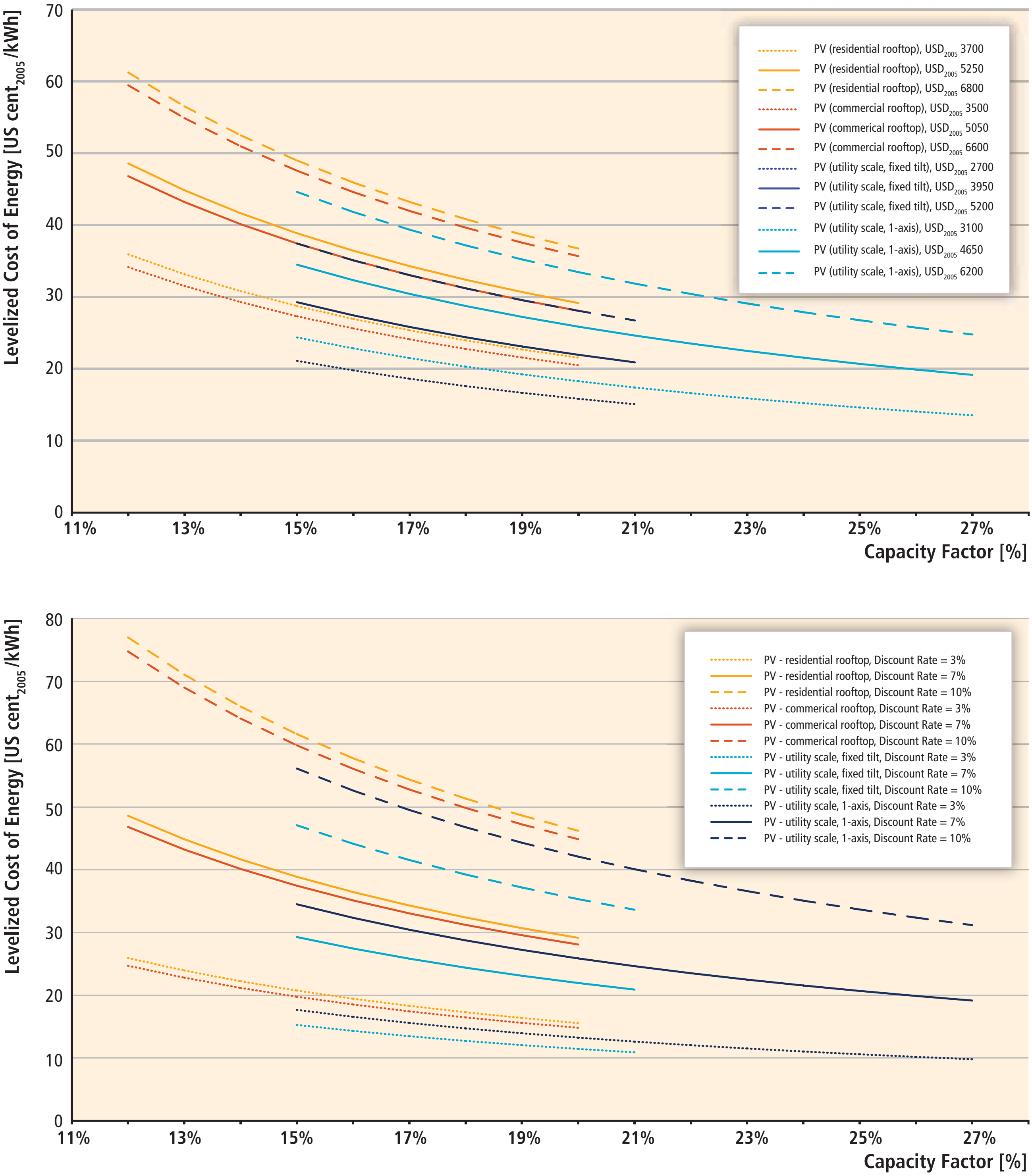


Figure 3.19 | Levelized cost of PV electricity generation, 2009. Upper panel: Cost of PV electricity generation as a function of capacity factor and investment cost[1,3]. Lower panel: Cost of PV electricity generation as a function of capacity factor and discount rate[2,3]. Source: (Annex III).

Notes: 1. Discount rate assumed to equal 7%. 2. Investment cost for residential rooftop systems assumed at USD_{2005} 5,250/kW, for commercial rooftop systems at USD_{2005} 5,050/kW, for utility-scale fixed tilt projects at USD_{2005} 3,950/kW and for utility-scale one-axis projects at USD_{2005} 4,650/kW. 3. Annual O&M cost assumed at USD_{2005} 41 to 64/kW, lifetime at 25 years.

Table 3.5 | IEA price forecasts for 2020 and 2050. The ranges are given for 2,000 kWh/kW_p and 1,000 kWh/kW_p (IEA, 2010c).

	2020 (US cents$_{2005}$)		2050 (US cents$_{2005}$)	
Energy yields (kWh/kW_p)	*2000*	*1000*	*2000*	*1000*
Equivalent Capacity Factor	*22.8%*	*11.4%*	*22.8%*	*11.4%*
Residential PV	14.5	28.6	5.9	12.2
Utility-scale PV	9.5	19.0	4.1	8.2

15 hours of storage, giving a 75% annual capacity factor, are under construction.

Because, other than the SEGS plants, new CSP plants only became operational from 2007 onwards, few actual performance data are available. For the SEGS plants, capacity factors of between 12.5 and 28% are reported (Sharma, 2011). The predicted yearly average capacity factor of a number of European CSP plants in operation or close to completion of construction is given as 22 to 29% without thermal storage and 27 to 75% with thermal storage (Arce et al., 2011). These numbers are well in line with the capacity figures given in the IEA CSP Roadmap (IEA, 2010b) and the US Solar Vision Study (US DOE, 2011). However, the limited available performance data for the thermal storage state should be noted.

For large, state-of-the-art trough plants, current investment costs are reported as USD$_{2005}$ 3.82/W (without storage) to USD$_{2005}$ 7.65/W (with storage) depending on labour and land costs, technologies, the amount and distribution of direct-normal irradiance and, above all, the amount of storage and the size of the solar field (IEA, 2010b). Storage increases the investment costs due to the storage itself, as well as the additional collector area needed to charge the storage. But it also improves the ability to dispatch electricity at times of peak tariffs in the market or when balancing power is needed. Thus, a strategic approach to storage can improve a project's internal rate of return.

The IEA (2010b) estimates LCOEs for large solar troughs in 2009 to range from USD$_{2005}$ 0.18 to 0.27/kWh for systems with different amounts of thermal storage and for different levels of solar irradiation. This is broadly in line with the range of LCOEs derived for a system with six hours of storage at a 10% discount rate (as applied by the IEA), although the full range of values derived for different discount rates is broader (see Annex III). Based on the data and assumptions provided in Annex III of this report, and the methods specified in Annex II, the following two

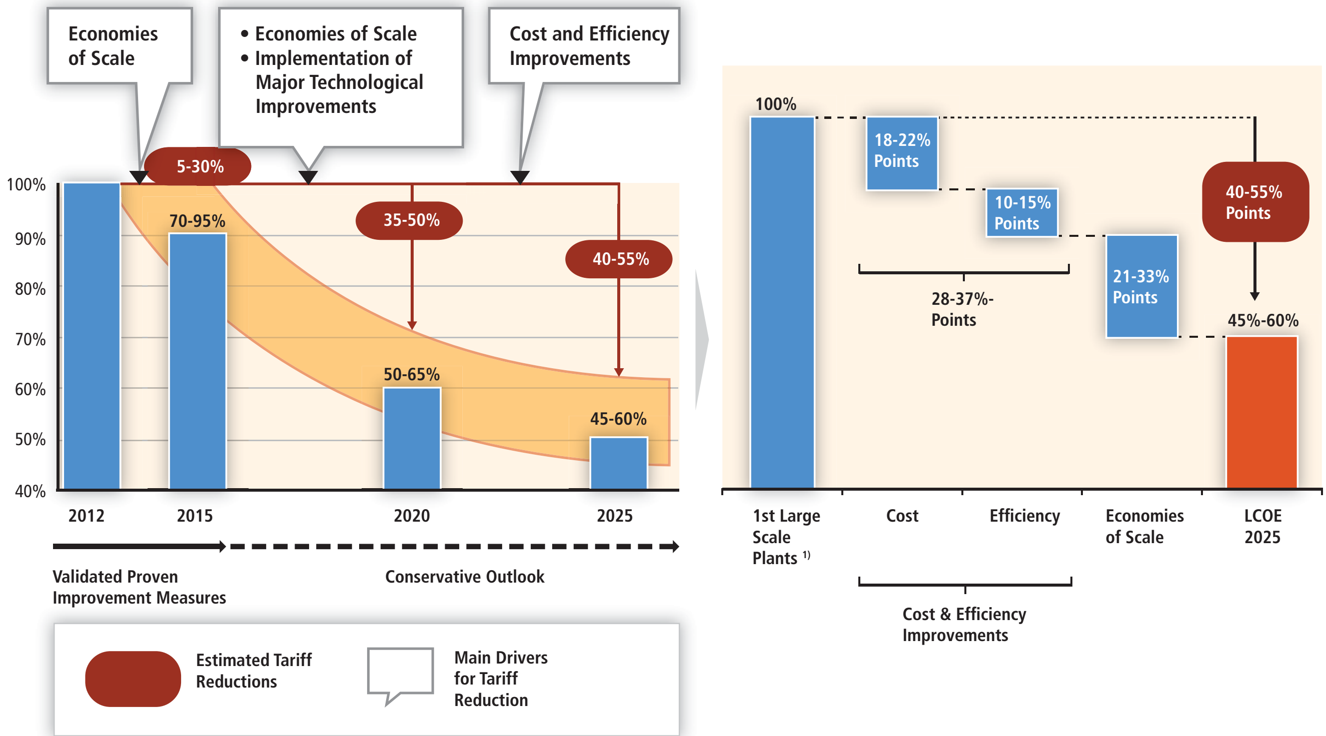


Figure 3.20 | Expected cost decline for CSP plants from 2012 to 2025. The cost number includes the cost of the plant plus financing (A.T. Kearney, 2010). As reduction ranges for cost, efficiency and economies of scale in the right panel overlap, their total contribution in 2025 amounts to less than their overall total.

Note: General. Tariffs equal the minimum required tariff, and are compared to 2012 tariffs. 1. Referring to 2010 to 2013 according to planned commercialization date of each technology (reference plant).

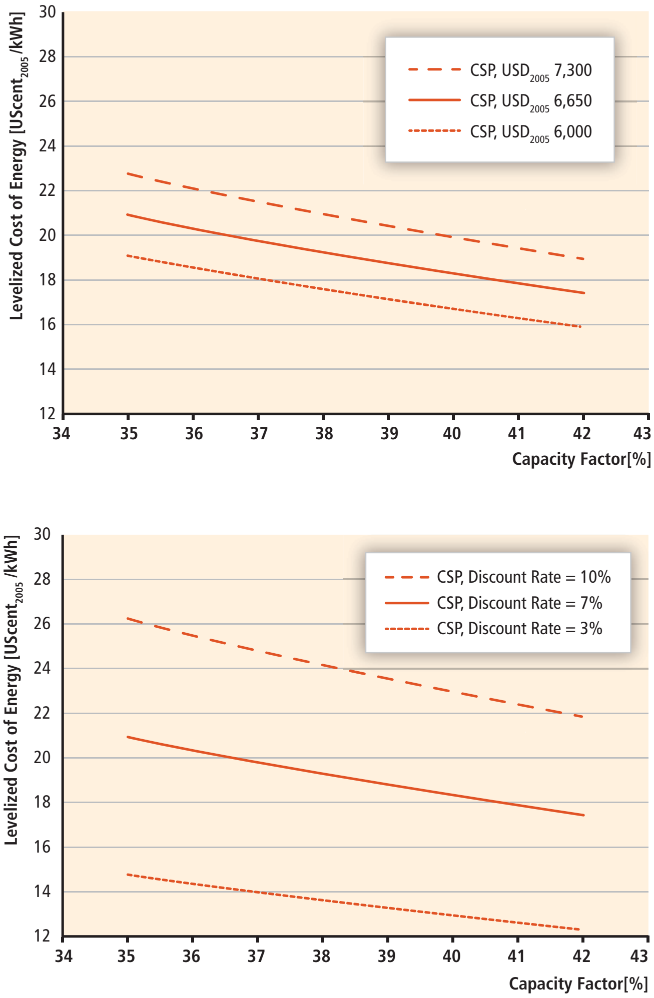


Figure 3.21 | Levelized cost of CSP electricity generation, 2009. Upper panel: Cost of CSP electricity generation as a function of capacity factor and investment cost[1,3]. Lower panel: Cost of CSP electricity generation as a function of capacity factor and discount rate[2,3]. Source: Annex III.

Notes: 1. Discount rate assumed to equal 7%. 2. Investment cost for CSP plant with six hours of thermal storage assumed at USD_{2005} 6,650/kW. 3. Annual O&M cost assumed at USD_{2005} 71/kW, lifetime at 25 years.

plots show the sensitivity of the LCOE of CSP plants with six hours of thermal storage with respect to investment cost (Figure 3.21, upper) and discount rates (Figure 3.21, lower) as a function of capacity factor.

The learning ratio for CSP, excluding the power block, is given as 10 ±5% by Neij (2008; IEA, 2010b). Other studies provide learning rates according to CSP components: Trieb et al. (2009b) give 10% for the solar field, 8% for storage, and 2% for the power block, whereas NEEDS (2009) and Viebahn et al. (2010) state 12% for the solar field, 12% for storage, and 5% for the power block.

Cost reductions for trough plants of the order of 30 to 40% within the next decade are considered achievable. Central-receiver technology is less commercially mature than troughs and thus presents slightly higher investment costs than troughs at the present time; however, cost reductions of 40 to 75% are predicted for central-receiver technology (IEA, 2010b).

The US DOE (2011) states its CSP goals for the USA in terms of USD/kWh, rather than USD/W, because the Solar Energy Technologies Program is designed to affect the LCOE and includes significant storage. The specific CSP goals are the following: 9 to 11 US $cents_{2005}$/kWh by 2010; 6 to 8 US $cents_{2005}$/kWh (with 6 hours of thermal storage) by 2015; and 5 to 6 US $cents_{2005}$/kWh (with 12 to 17 hours of thermal storage) by 2020 (USD_{2005}, assumed 2009 base). The EU is pursuing similar goals through a comprehensive RD&D program.

3.8.5 Solar fuel production

Direct conversion of solar energy to fuel is not yet widely demonstrated or commercialized. Thermochemical cycles along with electrolysis of water are the most promising processes for 'clean' hydrogen production in the future. In a comparison study, both the hybrid-sulphur cycle and a metal-oxide-based cycle were operated by solar tower technology for multi-stage water splitting (Graf et al., 2008). The electricity required for the alkaline electrolysis was produced by a parabolic trough power plant. For each process, the investment, operating and hydrogen production costs were calculated on a 50-MW_{th} scale. The study points out the market potential of sustainable hydrogen production using solar energy and thermochemical cycles compared to commercial electrolysis. A sensitivity analysis was done for three different cost scenarios: conservative, standard and optimistic (Table 3.6).

As a result, variation of the chosen parameters has the least impact on the hydrogen production costs of the hybrid-sulphur process, ranging from USD_{2005} 4.4 to 6.4/kg (Graf et al., 2008). The main cost factor for electrolysis is the electricity: just the variation of electricity costs leads to hydrogen costs of between USD_{2005} 2.4 to 7.7/kg. The highest range of hydrogen costs is obtained with the metal oxide-based process: USD_{2005} 4.0 to 14.5/kg. The redox system has the largest impact on the costs for the metal oxide-based cycle. The high electrical energy demand for nitrogen recycling influences the result significantly.

A substitute natural gas can be produced by the combination of solar hydrogen and CO_2 in a thermochemical synthesis at cost ranges from 12 to 14 US $cents_{2005}$/kWh_{th} with renewable power costs of 2 to 6 US $cents_{2005}$/kWh_e (Sterner, 2009). These costs depend highly on the operation mode of the plant and can be reduced by improving efficiency and reducing electricity costs.

The weakness of current economic assessments is primarily related to the uncertainties in the viable efficiencies and investment costs of the various solar components due to their early stage of development and their economy of scale as well as the limited amount of available literature data.

Table 3.6 | Overview of parameters for sensitivity (Graf et al., 2008).

	Cost scenario		
	Conservative	Standard	Optimistic
Heliostat costs (USD_{2005}/m^2)	159	136	114
Lifetime (years)	20	25	30
Redox system costs (USD_{2005}/kg)	1,700	170	17
Electricity costs (USD_{2005}/kWh_e)	0.14	0.11	0.05
Electrolyzer (decrease in %)	0	-10	-20
Chemical application (decrease in %)	0	-10	-20
Recycling of nitrogen (decrease in %)	0	-20	-40

3.9 Potential deployment[12]

Forecasts for the future deployment of direct solar energy may be underestimated, because direct solar energy covers a wide range of technologies and applications, not all of which are adequately captured in the energy scenarios literature. Nonetheless, this section presents near-term (2020) and long-term (2030 to 2050) forecasts for solar energy deployment. It then comments on the prospects and barriers to solar energy deployment in the longer-term scenarios, and the role of the deployment of solar energy in reaching different GHG concentration stabilization levels. This discussion is based on energy-market forecasts and carbon and energy scenarios published in recent literature.

3.9.1 Near-term forecasts

In 2010, the main market drivers are the various national support programs for solar-powered electricity systems or low-temperature solar heat installations. These programs either support the installation of the systems or the generated electricity. The market support for the different solar technologies varies significantly between the technologies, and also varies regionally for the same technology. This leads to very different thresholds and barriers for becoming competitive with existing technologies. Regardless, the future deployment of solar technologies depends strongly on public support to develop markets, which can then drive down costs due to learning. It is important to remember that learning-related cost reductions depend, in part at least, on actual production and deployment volumes, not just on the passage of time, though other factors such as R&D also act to drive costs down (see Section 10.5).

Table 3.7 presents the results of a selection of scenarios for the growth in solar deployment capacities in the near term, until 2020. It should be highlighted that passive solar gains are not included in these statistics, because this technology reduces demand and is therefore not part of the supply chain considered in energy statistics. The same PV technology can be applied for stand-alone, mini-grid, or hybrid systems in remote areas without grid connection, as well as for distributed and centralized grid-connected systems. The deployment of CSP technology is limited by regional availability of good-quality direct-normal irradiance of 2,000 kWh/m^2 (7,200 MJ/m^2) or more in the Earth's sunbelt. As shown in Table 3.7, solar capacity is expected to expand even in reference or baseline scenarios, but that growth is anticipated to accelerate dramatically in alternative scenarios that seek a more dramatic transformation of the global energy sector towards lower carbon emissions.

Photovoltaic market projections at the end of 2009 for the short term until 2013 indicate a steady increase, with annual growth rates ranging between 10 and more than 50% (UBS, 2009; EPIA, 2010; Fawer and Magyar, 2010). Several countries are discussing and proposing ambitious targets for the accelerated deployment of solar technologies. If fully implemented, the following policies could drive global markets in the period up to 2020:

- The National Development and Reform Commission (NDRC) expects non-fossil energy to supply 15% of China's total energy demand by 2020. Specifically for installed solar capacity, the NDRC's 2007 'Medium and Long-Term Development Plan for Renewable Energy in China' set a target of 1,800 MW by 2020. However, these goals have been discussed as being too low, and the possibility of reaching 20 GW or more seems more likely.

- The 2009 European Directive on the Promotion of Renewable Energy set a target of 20% RE in 2020 (The European Parliament and the Council of the European Union, 2010), and the Strategic Energy Technology plan is calling for electricity from PV in Europe of up to 12% in 2020 (European Commission, 2007).

- The 2009 Indian Solar Plan ('India Solar Mission') calls for a goal of 20 GW of solar power in 2022: 12 GW are to come specifically from ground-mounted PV and CSP plants; 3 GW from rooftop PV systems; another 3 GW from off-grid PV arrays in villages; and 2 GW from other PV projects, such as on telecommunications towers (Ministry of New and Renewable Energy, 2009).

- Relating to US cumulative installed capacity by 2030, the USDOE-sponsored Solar Vision Study (US DOE, 2011) is exploring the following two scenarios: a 10% solar target of 180 GW PV (120 GW central, 60 GW distributed); and a 20% solar target of 300 GW PV (200 GW central, 100 GW distributed).

3.9.2 Long-term deployment in the context of carbon mitigation

The IPCC Fourth Assessment Report estimated the available (technical) solar energy resource as 1,600 EJ/yr for PV and 50 EJ/yr for CSP; however, this estimate was given as very uncertain, with sources reporting values orders of magnitude higher (Sims et al., 2007). On the other hand, the projected deployment of direct solar in the IPCC Fourth Assessment Report gives an economic potential contribution of

12 Complementary perspectives on potential deployment based on a comprehensive assessment of numerous model-based scenarios of the energy system are presented in Sections 10.2 and 10.3.

Table 3.7 | Evolution of cumulative solar capacities based on different scenarios reported in EREC-Greenpeace (Teske et al., 2010) and IEA Roadmaps (IEA, 2010b,c).

Cumulative installed capacity	Low-Temperature Solar Heat (GW_{th})			Solar PV Electricity (GW)			CSP Electricity (GW)		
	2009	2015	2020	2009	2015	2020	2009	2015	2020
Current value	180			22			0.7		
EREC – Greenpeace (reference scenario)		180	230		44	80		5	12
EREC – Greenpeace ([r]evolution scenario)		715	1,875		98	335		25	105
EREC – Greenpeace (advanced scenario)		780	2,210		108	439		30	225
IEA Roadmaps		N/A			95[1]	210		N/A	148

Note: 1. Extrapolated from average 2010 to 2020 growth rate.

direct solar to the world electricity supply by 2030 of 633 TWh (2.3 EJ/yr) (Sims et al., 2007).

Chapter 10 provides a summary of the literature on the possible future contribution of RE supplies in meeting global energy needs under a range of GHG concentration stabilization scenarios. Focusing specifically on solar energy, Figure 3.22(a) presents modelling results for the global supply of solar energy. Figure 3.22(b) shows solar thermal heat generation, and Figures 3.22(c) and (d) present solar PV and CSP electricity generation respectively, all at the global scale. Depending on the quantity shown, between 44 and about 156 different long-term scenarios underlie these figures derived from a diversity of modelling teams and spanning a wide range of assumptions about—among other variables—energy demand growth, cost and availability of competing low-carbon technologies, and cost and availability of RE technologies (including solar energy). Chapter 10 discusses how changes in some of these variables impact RE deployment outcomes, with Section 10.2.2 describing the literature from which the scenarios have been taken. Figures 3.22(a) to 3.22(d) present the solar energy deployment results under these scenarios for 2020, 2030 and 2050 for three GHG concentration stabilization ranges, based on the IPCC's Fourth Assessment Report: >600 ppm CO_2 (Baselines), 440 to 600 ppm (Categories III and IV) and <440 ppm (Categories I and II), all by 2100. Results are presented for the median scenario, the 25th to 75th percentile range among the scenarios, and the minimum and maximum scenario results.[13]

In the baseline scenarios, that is, without any climate policies assumed, the median deployment levels for solar energy remain very low, in the range of today's solar primary energy supply of below 1 EJ/yr, until 2050. It is worthwhile noting that the much smaller set of scenarios that reports solar thermal heat generation (44 compared to the full set of 156 that report solar primary energy) shows substantially higher median deployment levels of solar thermal heat of up to about 12 EJ/yr by 2050 even in the baseline cases. In contrast, electricity generation from solar PV and CSP is projected to stay at very low levels.

The picture changes with increasingly low GHG concentration stabilization levels that exhibit significantly higher median contributions from solar energy than the baseline scenarios. By 2030 and 2050, the median deployment levels of solar energy reach 1.6 and 12.2 EJ/yr, respectively, in the intermediate stabilization categories III and IV that result in atmospheric CO_2 concentrations of 440-600 ppm by 2100. In the most ambitious stabilization scenario category, where CO_2 concentrations remain below 440 ppm by 2100, the median contribution of solar energy to primary energy supply reaches 5.9 and 39 EJ/yr by 2030 and 2050, respectively.

The scenario results suggest a strong dependence of the deployment of solar energy on the climate stabilization level, with significant growth expected in the median cases until 2030 and in particular until 2050 in the most ambitious climate stabilization scenarios. Breaking down the development by individual technology, it appears that solar PV deployment is most dependent on climate policies to reach significant deployment levels while CSP and even more so solar thermal heat deployment show a lower dependence on climate policies. However, this interpretation should be applied with care, because CSP electricity and solar thermal heat generation were reported by significantly fewer scenarios than solar PV electricity generation.

The ranges of solar energy deployment at the global level are extremely large, also compared to other RE sources (see Section 10.2.2.5), indicating

13 In scenario ensemble analyses such as the review underlying the figures, there is a constant tension between the fact that the scenarios are not truly a random sample and the sense that the variation in the scenarios does still provide real and often clear insights into collective knowledge or lack of knowledge about the future (see Section 10.2.1.2 for a more detailed discussion).

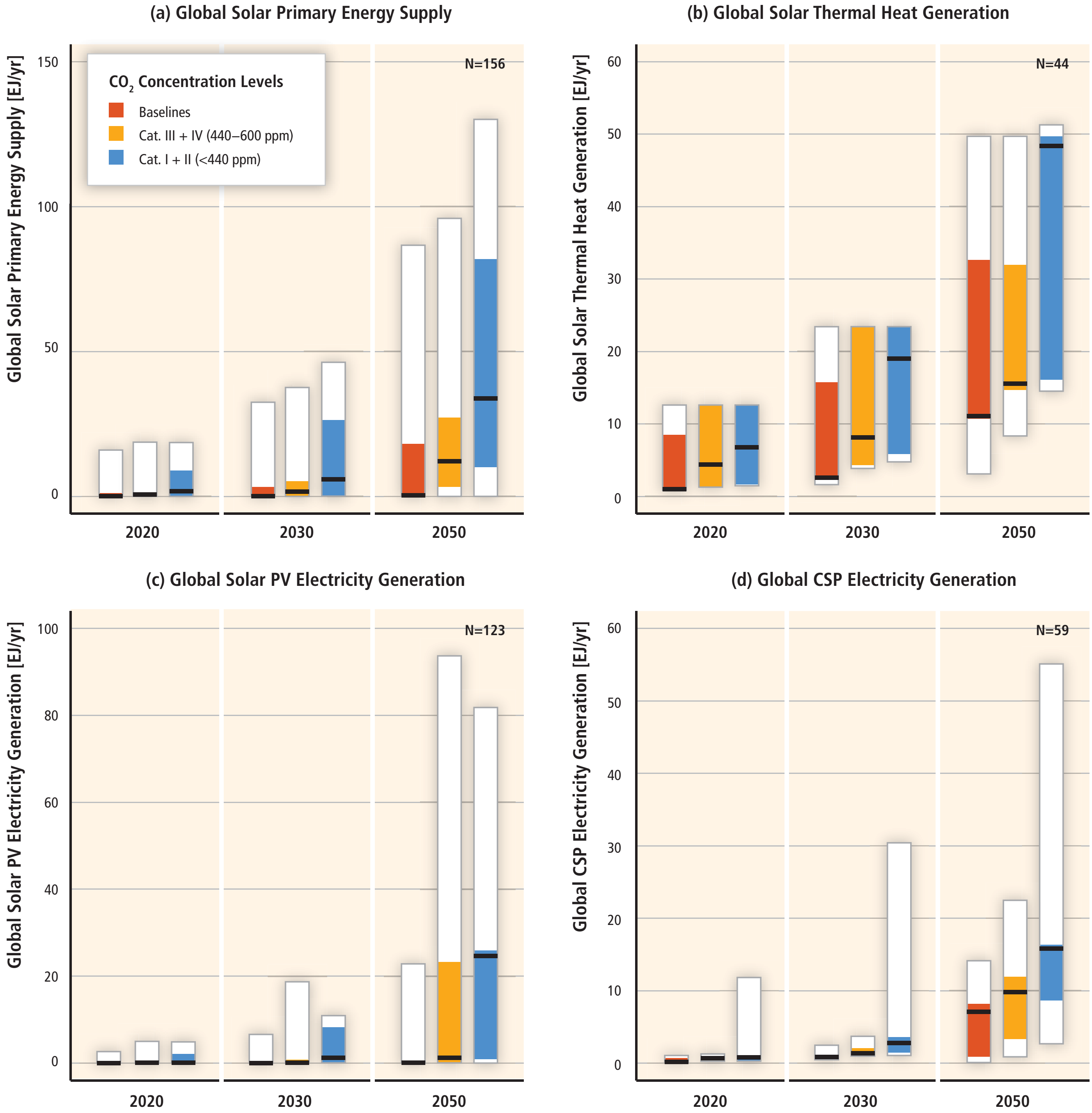


Figure 3.22 | Global solar energy supply and generation in long-term scenarios (median, 25th to 75th percentile range, and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration level in 2100; the specific number of scenarios underlying the figure is indicated in the right upper corner): (a) Global solar primary energy supply; (b) global solar thermal heat generation; (c) global PV electricity generation; and (d) Global CSP electricity generation (adapted from Krey and Clarke, 2011; see also Chapter 10).

a very wide range of assumptions about the future development of solar technologies in the reviewed scenarios. In the majority of baseline scenarios the solar deployment remains low until 2030, with the 75th percentile reaching some 3 EJ/yr and only very few scenarios showing significantly higher levels. By 2050, this relatively narrow deployment range in the baselines disappears; the 75th percentile shows roughly a 30-fold increase compared to the median baseline case, reaching about 15 EJ/yr and even much higher levels in the uppermost quartile. A combination of increasing relative prices of fossil fuels with more optimistic assumptions about cost declines for solar technologies is likely to be responsible for the higher baseline deployment levels.

In the most ambitious climate stabilization scenarios, the 75th percentiles of the solar primary energy supply by 2030 reach up to 26 EJ/yr, a five-fold increase compared to the median of the same category and the highest estimates even reach up to 50 EJ/yr. For 2050 the equivalent numbers are 82 EJ/yr (75th percentile) and 130 EJ/yr (maximum level), which can be attributed to a large extent to solar PV electricity generation, which reaches deployment levels of more than 80 EJ/yr by 2050, but CSP electricity and solar thermal heat also contribute significantly under these very high solar deployment levels. The share of solar PV in global electricity generation in the most extreme scenarios reaches up to about 12% by 2030 and up to one-third by 2050, but in the vast majority of scenarios remains in the single digit percentage range.

To achieve the higher levels of deployment envisioned by some of these scenarios, policies to reduce GHG emissions and/or increase RE supplies are likely to be necessary, and those policies would need to be of adequate economic attractiveness *and* predictability to motivate substantial private investment (see Chapter 11). A variety of other possible challenges to rapid solar energy growth also deserve discussion, as do factors that can contribute to it.

Resource potential. The solar resource is virtually inexhaustible, and it is available and able to be used in most countries and regions of the world. The worldwide technical potential of solar energy is considerably larger than the current primary energy consumption (IEA, 2008), and will not serve as a primary barrier to even the most ambitious deployment paths included in the scenarios literature summarized above.

Regional deployment. Industry-driven scenarios with regional visions for up to 100% of RE supply by 2050 have been developed in various parts of the world, often with substantial levels of solar energy deployment.

The Semiconductor Equipment and Materials International Association developed PV roadmaps for China and India that go far beyond the targets of the national governments (SEMI, 2009b,c). These targets are about 20 GW by 2020 and 100 GW by 2050 for electricity generation in China and 20 GW and 200 GW in India (both PV and CSP) (Ministry of New and Renewable Energy, 2009; Zhang et al., 2010).

In Europe, the European Renewable Energy Council developed a 100% Renewable Energy vision based on the inputs of the various European industrial associations (Zervos et al., 2010). Assumptions for 2020 about final electricity, heating and cooling, as well as transport demand are based on the European Commission's New Energy Policy (NEP) scenario with both a moderate and high price environment as outlined in the Second Strategic Energy Review (European Commission, 2008). The scenarios for 2030 and 2050 assume a massive improvement in energy efficiency to realize the 100% RE goals. For Europe, this scenario assumes that solar can contribute about 557 TWh (2,005 PJ) and 1415 TWh (5,094 PJ) heating and cooling in 2030 and 2050, respectively. For electricity generation, about 556 TWh (2,002 PJ) from PV and 141 TWh (508 PJ) from CSP are anticipated for 2030 and 1,347 TWh (4,849 PJ) and 385 TWh (1,386 PJ) for 2050, respectively.

In Japan, the New Energy Development Organisation, the Ministry for Economy, Trade and Industry, the Photovoltaic Power Generation Technology Research Association and the Japan Photovoltaic Energy Association drafted the 'PV Roadmap Towards 2030' in 2004 (Kurokawa and Aratani, 2004). In 2009, the roadmap was revised: the target year was extended from 2030 to 2050, and a goal was set to cover between 5 and 10% of domestic primary energy demand with PV power generation in 2050. The targets for electricity from PV systems range between 35 TWh (126 PJ) for the reference scenario and 89 TWh (320 PJ) for the advanced scenario in 2050 (Komiyama et al., 2009).

In the USA, the industry associations—the Solar Electric Power Association and the Solar Energy Industry Association—are working together with the USDOE and other stakeholders to develop scenarios for electricity from solar resources (PV and CSP) of 10 and 20% in 2030. The results of the Solar Vision Study (USDOE, 2011) are expected in 2011.

Achieving the higher *global* scenario results for solar energy would clearly require substantial solar deployment in every region of the world. The *regional* scenarios presented here suggest that regional deployment paths may exist to support such a global result. Nonetheless, enabling this growth in regions new to solar energy may present cost and institutional challenges that would require active management; institutional and technical knowledge transfer from those regions that are already witnessing substantial solar energy activity may be required.

Supply chain issues. Passive solar energy markets and industries have largely developed locally to this point because the building market itself is local. Enabling high-penetration solar energy futures may require a globalization of at least knowledge on passive solar technologies to enable broader market penetration. Low-temperature solar thermal is implemented all over the world within local markets, with local suppliers, but a global market is starting to be developed. The PV industry is already global in scope, with a global supply chain, while CSP is starting to develop a global supply chain—in 2010, the CSP market was driven by Spain and the USA, but other countries such as Germany and India are also helping to expand the market. In general, supply chain and materials constraints may impact the speed and scope of solar energy deployment in certain regions and at certain times, but such factors are unlikely to restrict the ability of solar energy technologies to meet the higher penetrations envisioned by the more aggressive scenarios presented earlier. In fact, the modular nature of many of the solar technologies, both in manufacturing and use, as well as the diverse applications for solar energy suggest that supply chain issues are unlikely to constrain growth.

Technology and economics. The technical maturity and economic competitiveness of solar technologies vary. Passive solar consists of well-established technologies, though with room for improvement;

however, the awareness of the building sector is not always available. The economics are understood, but they depend on local solar resources and local support and building regulations. Low-temperature solar thermal is also a well-established technology, with economics that depend on the solar resource, the applications, and the cost of competing technologies—some regions may need support programs to create markets and enable growth, whereas in other regions solar thermal is already competitive.

PV is already an established technology, but substantial further technological advances are possible with the prospect for continued cost reduction. To this point, however, the deployment of PV technology has strongly depended on local support programs in most markets. Similarly, CSP technology has substantial room for additional improvement, but CSP costs have to this point exceeded market energy prices.

Continued cost reductions are therefore likely to be needed if solar energy is to meet the higher global scenario results presented earlier. Support programs to encourage solar deployment and R&D may both play an important role in seeking to achieve the necessary reductions.

Integration and transmission. Integration and transmission are not a central concern for passive solar applications. Integration issues in low-temperature solar, on the other hand, are especially important for larger systems where integration into local district heating systems is needed, and where the temporal variability of solar output needs to be matched with other supply sources to meet customer demands (see Chapter 8). Due to the availability of the resource only during the day and the short-time-period variability associated with passing clouds, proactive technical and institutional solutions to operational integration concerns will need to be implemented to enable large-scale PV penetration; CSP, if implemented with thermal storage, would not impose similar requirements. Moreover, high-penetration PV and CSP scenarios that involve larger-scale developments are likely to require additional transmission infrastructure in order to access the highest-quality solar sites. Section 8.2.1 identifies a variety of the technical and institutional challenges associated with increased deployment of variable generation sources, and also highlights the variety of solutions for managing those challenges. Though Chapter 8 finds no insurmountable technical barriers to increased variable renewable energy supply, as solar deployment increases, transmission expansion and operational integration costs are also expected to rise, potentially constraining growth on economic terms. Proactively managing these challenges is likely to be central to achieving the high-penetration solar energy scenarios described earlier.

Social and environmental concerns. Direct solar energy appears to have relatively few social and environmental concerns. Rather, the main benefit of passive solar is in reducing the energy demand of buildings. Similarly, low-temperature solar thermal applications are comparatively benign from an environmental perspective. One concern for some PV technologies is that the PV industry uses some toxic materials and corrosive liquids in its production lines. The presence and amount of those materials depend strongly on the cell type, however, and rigorous control methods are used to minimize the risk of accidental releases. Recycling of PV materials may also become more common as deployment continues. Water availability and consumption is the main environmental concern for CSP, though dry cooling technology can substantially reduce water usage. Finally, especially for central-station PV and CSP installations, the ecological, social and visual impacts associated with plant infrastructure may be of concern. Efforts to better understand the nature and magnitude of these impacts, together with efforts to minimize and mitigate them, may need to be pursued in concert with increasing solar energy deployment.

3.9.3 Conclusions regarding deployment

Potential deployment scenarios range widely—from a marginal role of direct solar energy in 2050 to one of the major sources of energy supply. Although direct solar energy provides only a very small fraction of global energy supply in 2011, it has the largest technical potential of all energy sources and, in concert with technical improvements and resulting cost reductions, could see dramatically expanded use in the decades to come.

Achieving continued cost reductions is the central challenge that will influence the future deployment of solar energy. Reducing cost, meanwhile, can only be achieved if the solar technologies decrease their costs along their learning curves, which depends in part on the level of solar energy deployment. In addition, continuous R&D efforts are required to ensure that the slopes of the learning curves do not flatten before solar is widely cost competitive with other energy sources.

The true costs of and potential for deploying solar energy are still unknown because the main deployment scenarios that exist today often consider only a single solar technology: PV. In addition, scenarios often do not account for the co-benefits of a renewable/sustainable energy supply (but see Section 9.4 for some research in this area). At the same time, as with some other forms of RE, issues of variable production profiles and energy market integration as well as the possible need for new transmission infrastructure will influence the magnitude, type and cost of solar energy deployment.

Finally, the regulatory and legal framework in place can also foster or hinder the uptake of direct solar energy applications. For example, minimum building standards with respect to building orientation and insulation can reduce the energy demand of buildings significantly, increasing the share of RE supply without increasing the overall demand, while building and technical standards can also support or hinder the installation of rooftop solar systems. Transparent, streamlined administrative procedures to site, permit, install and connect solar power sources can further support the deployment of direct solar energy.

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4

Geothermal Energy

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Executive Summary

Geothermal energy has the potential to provide long-term, secure base-load energy and greenhouse gas (GHG) emissions reductions. Accessible geothermal energy from the Earth's interior supplies heat for direct use and to generate electric energy. Climate change is not expected to have any major impacts on the effectiveness of geothermal energy utilization, but the widespread deployment of geothermal energy could play a meaningful role in mitigating climate change. In electricity applications, the commercialization and use of engineered (or enhanced) geothermal systems (EGS) may play a central role in establishing the size of the contribution of geothermal energy to long-term GHG emissions reductions.

The natural replenishment of heat from earth processes and modern reservoir management techniques enable the sustainable use of geothermal energy as a low-emission, renewable resource. With appropriate resource management, the tapped heat from an active reservoir is continuously restored by natural heat production, conduction and convection from surrounding hotter regions, and the extracted geothermal fluids are replenished by natural recharge and by injection of the depleted (cooled) fluids.

Global geothermal technical potential is comparable to global primary energy supply in 2008. For electricity generation, the technical potential of geothermal energy is estimated to be between 118 EJ/yr (to 3 km depth) and 1,109 EJ/yr (to 10 km depth). For direct thermal uses, the technical potential is estimated to range from 10 to 312 EJ/yr. The heat extracted to achieve these technical potentials can be fully or partially replenished over the long term by the continental terrestrial heat flow of 315 EJ/yr at an average flux of 65 mW/m^2. Thus, technical potential is not likely to be a barrier to geothermal deployment (electricity and direct uses) on a global basis. Whether or not the geothermal technical potential will be a limiting factor on a regional basis depends on the availability of EGS technology.

There are different geothermal technologies with distinct levels of maturity. Geothermal energy is currently extracted using wells or other means that produce hot fluids from: a) hydrothermal reservoirs with naturally high permeability; and b) EGS-type reservoirs with artificial fluid pathways. The technology for electricity generation from hydrothermal reservoirs is mature and reliable, and has been operating for more than 100 years. Technologies for direct heating using geothermal heat pumps (GHP) for district heating and for other applications are also mature. Technologies for EGS are in the demonstration stage. Direct use provides heating and cooling for buildings including district heating, fish ponds, greenhouses, bathing, wellness and swimming pools, water purification/desalination and industrial and process heat for agricultural products and mineral drying.

Geothermal resources have been commercially used for more than a century. Geothermal energy is currently used for base load electric generation in 24 countries, with an estimated 67.2 TWh/yr (0.24 EJ/yr) of supply provided in 2008 at a global average capacity factor of 74.5%; newer geothermal installations often achieve capacity factors above 90%. Geothermal energy serves more than 10% of the electricity demand in 6 countries and is used directly for heating and cooling in 78 countries, generating 121.7 TWh/yr (0.44 EJ/yr) of thermal energy in 2008, with GHP applications having the widest market penetration. Another source estimates global geothermal energy supply at 0.41 EJ/yr in 2008.

Environmental and social impacts from geothermal use are site and technology specific and largely manageable. Overall, geothermal technologies are environmentally advantageous because there is no combustion process emitting carbon dioxide (CO_2), with the only direct emissions coming from the underground fluids in the reservoir. Historically, direct CO_2 emissions have been high in some instances with the full range spanning from close to 0 to 740 g CO_2/kWh$_e$ depending on technology design and composition of the geothermal fluid in the underground reservoir. Direct CO_2 emissions for direct use applications are negligible and EGS power plants are likely to be designed with zero direct emissions. Life cycle assessment (LCA) studies estimate that full lifecycle CO_2-equivalent emissions for geothermal energy technologies are less than 50 g CO_2eq/kWh$_e$ for flash steam geothermal power plants, less than 80 g CO_2eq/kWh$_e$ for projected EGS power plants, and between 14 and 202 g CO_2eq/kWh$_{th}$ for district heating systems and GHP. Local hazards arising from natural phenomena, such as micro-earthquakes, may be influenced by the operation of geothermal fields. Induced seismic events have not been large enough to lead to human injury or relevant property

damage, but proper management of this issue will be an important step to facilitating significant expansion of future EGS projects.

Several prospects exist for technology improvement and innovation in geothermal systems. Technical advancements can reduce the cost of producing geothermal energy and lead to higher energy recovery, longer field and plant lifetimes, and better reliability. In exploration, research and development (R&D) is required for hidden geothermal systems (i.e., with no surface manifestations such as hot springs and fumaroles) and for EGS prospects. Special research in drilling and well construction technology is needed to reduce the cost and increase the useful life of geothermal production facilities. EGS require innovative methods to attain sustained, commercial production rates while reducing the risk of seismic hazard. Integration of new power plants into existing power systems does not present a major challenge, but in some cases can require extending the transmission network.

Geothermal-electric projects have relatively high upfront investment costs but often have relatively low levelized costs of electricity (LCOE). Investment costs typically vary between USD_{2005} 1,800 and 5,200 per kW, but geothermal plants have low recurring 'fuel costs'. The LCOE of power plants using hydrothermal resources are often competitive in today's electricity markets, with a typical range from US $cents_{2005}$ 4.9 to 9.2 per kWh considering only the range in investment costs provided above and medium values for other input parameters; the range in LCOE across a broader array of input parameters is US $cents_{2005}$ 3.1 to 17 per kWh. These costs are expected to decrease by about 7% by 2020. There are no actual LCOE data for EGS power plants, as EGS plants remain in the demonstration phase, but estimates of EGS costs are higher than those for hydrothermal reservoirs. The cost of geothermal energy from EGS plants is also expected to decrease by 2020 and beyond, assuming improvements in drilling technologies and success in developing well-stimulation technology.

Current levelized costs of heat (LCOH) from direct uses of geothermal heat are generally competitive with market energy prices. Investment costs range from USD_{2005} 50 per kW_{th} (for uncovered pond heating) to USD_{2005} 3,940 per kW_{th} (for building heating). Low LCOHs for these technologies are possible because the inherent losses in heat-to-electricity conversion are avoided when geothermal energy is used for thermal applications.

Future geothermal deployment could meet more than 3% of global electricity demand and about 5% of the global demand for heat by 2050. Evidence suggests that geothermal supply could meet the upper range of projections derived from a review of about 120 energy and GHG reduction scenarios summarized in Chapter 10. With its natural thermal storage capacity, geothermal energy is especially suitable for supplying base-load power. By 2015, geothermal deployment is roughly estimated to generate 122 TWh_e/yr (0.44 EJ/yr) for electricity and 224 TWh_{th}/yr (0.8 EJ/yr) for heat applications. In the long term (by 2050), deployment projections based on extrapolations of long-term historical growth trends suggest that geothermal could produce 1,180 TWh_e/yr (~4.3 EJ/yr) for electricity and 2,100 TWh_{th}/yr (7.6 EJ/yr) for heat, with a few countries obtaining most of their primary energy needs (heating, cooling and electricity) from geothermal energy. Scenario analysis suggests that carbon policy is likely to be one of the main driving factors for future geothermal development, and under the most favourable climate policy scenario (<440 ppm atmospheric CO_2 concentration level in 2100) considered in the energy and GHG scenarios reviewed for this report, geothermal deployment could be even higher in the near and long term.

High-grade geothermal resources have restricted geographic distribution—both cost and technology barriers exist for the use of low-grade geothermal resources and EGS. High-grade geothermal resources are already economically competitive with market energy prices in many locations. However, public and private support for research along with favourable deployment policies (drilling subsidies, targeted grants for pre-competitive research and demonstration to reduce exploration risk and the cost of EGS development) may be needed to support the development of lower-grade hydrothermal resources as well as the demonstration and further commercialization of EGS and other geothermal resources. The effectiveness of these efforts may play a central role in establishing the magnitude of geothermal energy's contributions to long-term GHG emissions reductions.

4.1 Introduction

Geothermal resources consist of thermal energy from the Earth's interior stored in both rock and trapped steam or liquid water. As presented in this chapter, climate change has no major impacts on the effectiveness of geothermal energy utilization, but its widespread deployment could play a significant role in mitigating climate change by reducing greenhouse gas (GHG) emissions as an alternative for capacity addition and/or replacement of existing base load fossil fuel-fired power and heating plants.

Geothermal systems as they are currently exploited occur in a number of geological environments where the temperatures and depths of the reservoirs vary accordingly. Many high-temperature (>180°C) hydrothermal systems are associated with recent volcanic activity and are found near plate tectonic boundaries (subduction, rifting, spreading or transform faulting), or at crustal and mantle hot spot anomalies. Intermediate- (100 to 180°C) and low-temperature (<100°C) systems are also found in continental settings, where above-normal heat production through radioactive isotope decay increases terrestrial heat flow or where aquifers are charged by water heated through circulation along deeply penetrating fault zones. Under appropriate conditions, high-, intermediate- and low-temperature geothermal fields can be utilized for both power generation and the direct use of heat (Tester et al., 2005).

Geothermal resources can be classified as convective (hydrothermal) systems, conductive systems and deep aquifers. Hydrothermal systems include liquid- and vapour-dominated types. Conductive systems include hot rock and magma over a wide range of temperatures (Mock et al., 1997) (Figure 4.1). Deep aquifers contain circulating fluids in porous media or fracture zones at depths typically greater than 3 km, but lack a localized magmatic heat source. They are further subdivided into systems at hydrostatic pressure and systems at pressure higher than hydrostatic (geo-pressured). Enhanced or engineered geothermal system (EGS) technologies enable the utilization of low permeability and low porosity conductive (hot dry rock) and low productivity convective and aquifer systems by creating fluid connectivity through hydraulic stimulation and advanced well configurations. In general, the main types of geothermal systems are hydrothermal and EGS.

Resource utilization technologies for geothermal energy can be grouped under types for electrical power generation, for direct use of the heat, or for combined heat and power in cogeneration applications. Geothermal heat pump (GHP) technologies are a subset of direct use. Currently, the only commercially exploited geothermal systems for power generation and direct use are hydrothermal (of continental subtype). Table 4.1 summarizes the resources and utilization technologies.

Hydrothermal, convective systems are typically found in areas of magmatic intrusions, where temperatures above 1,000°C can occur at less than 10 km depth. Magma typically emits mineralized liquids and gases, which then mix with deeply circulating groundwater. Such systems can last hundreds of thousands of years, and the gradually cooling magmatic heat sources can be replenished periodically with fresh intrusions from a deeper magma chamber. Heat energy is also transferred by conduction, but convection is the most important process in magmatic systems.

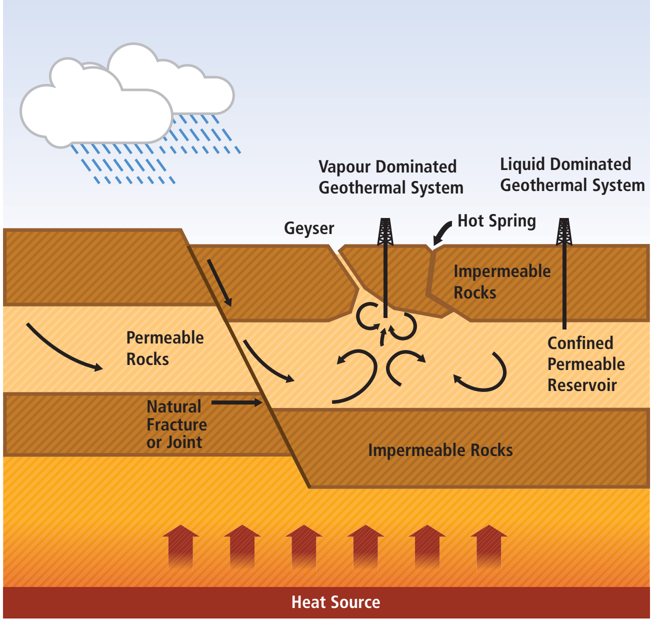


Figure 4.1a | Scheme showing convective (hydrothermal) resources. Adapted from Mock et al. (1997) and from US DOE publications.

Subsurface temperatures increase with depth and if hot rocks within drillable depth can be stimulated to improve permeability, using hydraulic fracturing, chemical or thermal stimulation methods, they form a potential EGS resource that can be used for power generation and direct heat applications. EGS resources include hot dry rock (HDR), hot fractured rock (HFR) and hot wet rock (HWR), among other terms. They occur in all geothermal environments, but are likely to be economic in geological settings where the thermal gradient is high enough to permit exploitation at depths of less than 5 km. In the future, given average geothermal gradients of 25 to 30°C/km, EGS resources at relatively high temperature (≥180°C) may be exploitable in broad areas at depths as shallow as 7 km, which is well within the range of existing drilling technology (~10 km depth). Geothermal resources of different types may occur at different depths below the same surface location. For example, fractured and water-saturated hot-rock EGS resources lie below deep-aquifer resources in the Australian Cooper Basin (Goldstein et al., 2009).

Direct use of geothermal energy has been practised at least since the Middle Palaeolithic when hot springs were used for ritual or routine bathing (Cataldi, 1999), and industrial utilization began in Italy by exploiting boric acid from the geothermal zone of Larderello, where in 1904 the first kilowatts of geothermal electric energy were generated and in 1913 the first 250-kW_e commercial geothermal power unit was installed (Burgassi, 1999). Larderello is still active today.

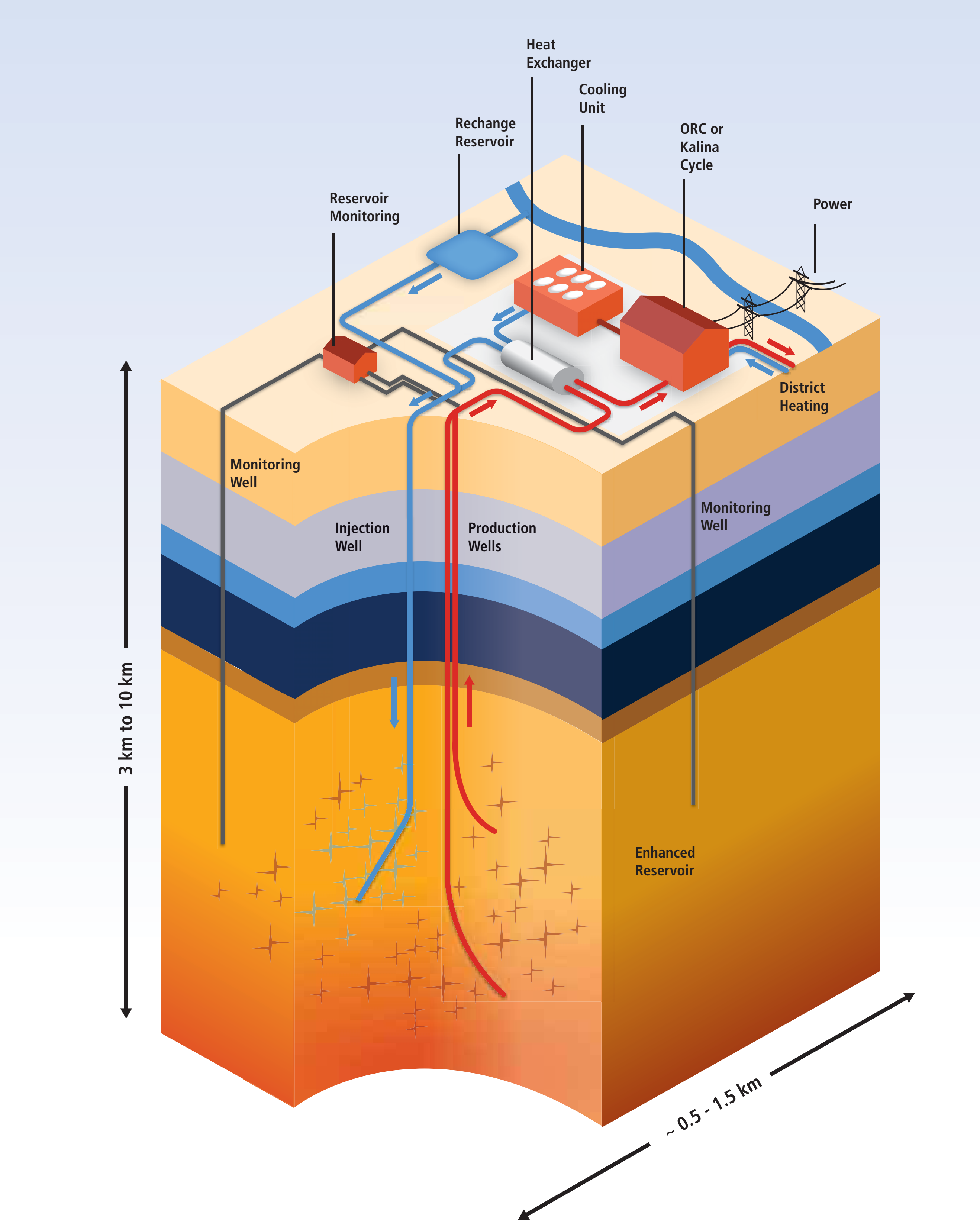


Figure 4.1b | Scheme showing conductive (EGS) resources. Adapted from Mock et al. (1997) and from US DOE publications.

Table 4.1 | Types of geothermal resources, temperatures and uses.

Type	In-situ fluids	Subtype	Temperature Range	Utilization	
				Current	Future
Convective systems (hydrothermal)	Yes	Continental	H, I & L	Power, direct use	
		Submarine	H	None	Power
Conductive systems	No	Shallow (<400 m)	L	Direct use (GHP)	
		Hot rock (EGS)	H, I	Prototypes	Power, direct use
		Magma bodies	H	None	Power, direct use
Deep aquifer systems	Yes	Hydrostatic aquifers	H, I & L	Direct use	Power, direct use
		Geo-pressured		Direct use	Power, direct use

Note: Temperature range: H: High (>180°C), I: Intermediate (100-180°C), L: Low (ambient to 100°C). EGS: Enhanced (or engineered) geothermal systems. GHP: Geothermal heat pumps.

Geothermal energy is classified as a renewable resource (see Chapter 1) because the tapped heat from an active reservoir is continuously restored by natural heat production, conduction and convection from surrounding hotter regions, and the extracted geothermal fluids are replenished by natural recharge and by injection of the depleted (cooled) fluids. Geothermal fields are typically operated at production rates that cause local declines in pressure and/or in temperature within the reservoir over the economic lifetime of the installed facilities. These cooler and lower-pressure zones are subsequently recharged from surrounding regions when extraction ceases.

There are many examples where for economical reasons high extraction rates from hydrothermal reservoirs have resulted in local fluid depletion that exceeded the rate of its recharge, but detailed modelling studies (Pritchett, 1998; Mégel and Rybach, 2000; O'Sullivan and Mannington, 2005) have shown that resource exploitation can be economically feasible in practical situations, and still be renewable on a time scale of the order of 100 years or less, when non-productive recovery periods are considered. Models predict that replenishment will occur in hydrothermal systems on time scales of the same order as the lifetime of the geothermal production cycle where the extraction rate is designed to be sustainable over a 20 to 30 year period (Axelsson et al., 2005, 2010).

This chapter includes a brief discussion of the theoretical potential of geothermal resources, the global and regional technical potential, and the possible impacts of climate change on the resource (Section 4.2), the current technology and applications (Section 4.3) and the expected technological developments (Section 4.6), the present market status (Section 4.4) and its probable future evolution (Section 4.8), environmental and social impacts (Section 4.5) and cost trends (Section 4.7) in using geothermal energy to contribute to reduced GHG emissions.

4.2 Resource Potential

The total thermal energy contained in the Earth is of the order of 12.6 x 10^{12} EJ and that of the crust of the order of 5.4 x 10^{9} EJ to depths of up to 50 km (Dickson and Fanelli, 2003). The main sources of this energy are due to the heat flow from the Earth's core and mantle, and that generated by the continuous decay of radioactive isotopes in the crust itself. Heat is transferred from the interior towards the surface, mostly by conduction, at an average of 65 mW/m^2 on continents and 101 mW/m^2 through the ocean floor. The result is a global terrestrial heat flow rate of around 1,400 EJ/yr. Continents cover ~30% of the Earth's surface and their terrestrial heat flow has been estimated at 315 EJ/yr (Stefansson, 2005).

Stored thermal energy down to 3 km depth on continents was estimated to be 42.67 x 10^{6} EJ by EPRI (1978), consisting of 34.14 x 10^{6} EJ (80%) from hot dry rocks (or EGS resources) and 8.53 x 10^{6} EJ (20%) from hydrothermal resources. Within 10 km depth, Rowley (1982) estimated the continental stored heat to be 403 x 10^{6} EJ with no distinction between hot dry rock and hydrothermal resources, and Tester et al. (2005) estimated it to be 110.4 x 10^{6} EJ from hot dry rocks and only 0.14 x 10^{6} EJ from hydrothermal resources. A linear interpolation between the EPRI (1978) values for 3 km depth and the values from Rowley (1982) results in 139.5 x 10^{6} EJ down to 5 km depth, while linear interpolation between the EPRI (1978) values and those from Tester et al. (2005) only for EGS resources results in 55.9 x 10^{6} EJ down to 5 km depth (see second column of Table 4.2). Based on these estimates, the theoretical potential is clearly not a limiting factor for global geothermal deployment.

In practice geothermal plants can only utilize a portion of the stored thermal energy due to limitations in drilling technology and rock permeability. Commercial utilization to date has concentrated on areas in which geological conditions create convective hydrothermal reservoirs where drilling to depths up to 4 km can access fluids at temperatures of 180°C to more than 350°C.

4.2.1 Global technical potential

Regarding geothermal technical potentials,[1] one recent and comprehensive estimate for conventional hydrothermal resources in the world was presented by Stefansson (2005). For electric generation, he calculated the global geothermal technical potential for identified hydrothermal

1 Definition of technical potential is included in the Glossary (Annex I).

Table 4.2 | Global continental stored heat and EGS technical potentials for electricity.

Depth range (km)	Technically accessible stored heat from EGS		Estimated technical potential (electric) for EGS (EJ/yr)
	(10^6 EJ)	Source	
0–10	403	Rowley, 1982	1051.8
0–10	110.4	Tester et al., 2005	288.1
0–5	139.5	Interpolation between values from Rowley (1982) and EPRI (1978)	364.2
0–5	55.9	Interpolation between values from Tester et al. (2005) and EPRI (1978)	145.9
0–3	34.1	EPRI, 1978	89.1

resources as 200 GW_e (equivalent to 5.7 EJ/yr with a capacity factor (CF)[2] of 90%), with a lower limit of 50 GW_e (1.4 EJ/yr). He assumed that unidentified, hidden resources are 5 to 10 times more abundant than the identified ones and then estimated the upper limit for the worldwide geothermal technical potential as between 1,000 and 2,000 GW_e (28.4 and 56.8 EJ/yr at 90% CF), with a mean value of 1,500 GW_e (~42.6 EJ/yr). Mainly based on those numbers, Krewitt et al. (2009) estimated geothermal technical potential for 2050 at 45 EJ/yr, largely considering only hydrothermal resources.

No similar recent calculation of global technical potential for conductive (EGS) geothermal resources has been published, although the study by EPRI (1978) included some estimates as did others (Armstead and Tester, 1987). Estimating the technical potential of EGS is complicated due to the lack of commercial experience to date. EGS field demonstrations must achieve sufficient reservoir productivity and lifetime to prove both the viability of stimulation methods and the scalability of the technology. Once these features have been demonstrated at several locations, it will be possible to develop better assessments of technical potential, and it is possible that EGS will become a leading geothermal option for electricity and direct use globally because of its widespread availability and lower exploration risk relative to hydrothermal systems.

More recently, Tester et al. (2006; see their Table 1.1) estimated the accessible conductive resources in the USA (excluding Alaska, Hawaii and Yellowstone National Park) and calculated that the stored heat at depths less than 10 km is 13.4 x 10^6 EJ (in conduction-dominated EGS of crystalline basement and sedimentary rock formations). Assuming that 2% of the heat is recoverable and that average temperatures drop 10°C below initial conditions during exploitation, and taking into account all losses in the conversion of recoverable heat into electricity over a lifespan of 30 years, electrical generating capacity from EGS in the USA was estimated at 1,249 GW_e, corresponding to 35.4 EJ/yr of electricity at a CF of 90% (Tester et al., 2006; see their Table 3.3). Based on the same assumptions for the USA,[3] estimates for the global technical potential of EGS-based energy supply can be derived from estimates of the heat stored in the Earth's crust that is both accessible and recoverable (see Table 4.2, fourth column).

Therefore, the global technical potential of geothermal resources for electricity generation can be estimated as the sum of the upper (56.8 EJ/yr) and lower (28.4 EJ/yr) of Stefansson's estimate for hydrothermal resources (identified and hidden) and the EGS technical potentials of Table 4.2 (fourth column), obtaining a lower value of 117.5 EJ/yr (down to 3 km depth) to a maximum of 1,108.6 EJ/yr down to 10 km depth (Figure 4.2). It is important to note that the heat extracted to achieve these technical potentials can be fully or partially replenished over the long term by the continental terrestrial heat flow of 315 EJ/yr (Stefansson, 2005) at an average flux of 65 mW/m^2. Although hydrothermal resources are only a negligible fraction of total theoretical potential given in Tester et al. (2005), their contribution to technical potential might be considerably higher than implied by the conversion from theoretical potential data to technical potential data. This is the rationale for considering the Rowley (1982) estimate for EGS technical potential only and adding the estimate for hydrothermal technical potential from Stefansson (2005).

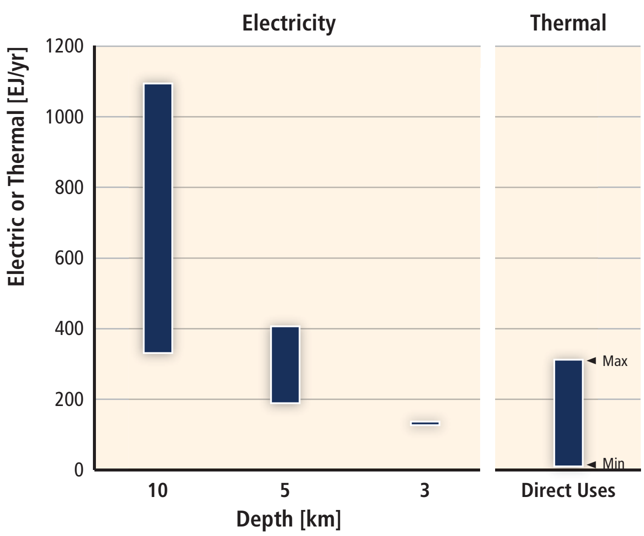


Figure 4.2 | Geothermal technical potentials for electricity and direct uses (heat). Direct uses do not require development to depths greater than approximately 3 km (Prepared with data from Tables 4.2 and 4.3).

2 Capacity factor (CF) definition is included in the Glossary (Annex I).

3 1 x 10^6 EJ stored heat equals approximately 2.61 EJ/yr of technical potential for electricity at a 90% CF for 30 years.

For hydrothermal submarine vents, an estimate of >100 GW_e (>2.8 EJ/yr) offshore technical potential has been made (Hiriart et al., 2010). This is based on the 3,900 km of ocean ridges confirmed as having hydrothermal vents,[4] with the assumption that only 1% could be developed for electricity production using a recovery factor of 4%. This assumption is based on capturing part of the heat from the flowing submarine vent without any drilling, but considering offshore drilling, a technical potential of 1,000 GW_e (28.4 EJ/yr) from hydrothermal vents may be possible. However, the technical potential of these resources is still highly uncertain, and is therefore not included in Figure 4.2.

For geothermal direct uses, Stefansson (2005) estimated 4,400 GW_{th} from hydrothermal systems as the world geothermal technical potential from resources <130°C, with a minimum of 1,000 GW_{th} and a maximum, considering hidden resources, of 22,000 to 44,000 GW_{th}. Taking a worldwide average CF for direct uses of 30%, the geothermal technical potential for heat can be estimated to be 41.6 EJ/yr with a lower value of 9.5 EJ/yr and an upper value of 312.2 EJ/yr (equivalent to 33,000 GW_{th} of installed capacity) (Figure 4.2). Krewitt et al. (2009) used the same values estimated by Stefansson (2005) in GW_{th}, but a CF of 100% was assumed when converted into EJ/r, leading to an average upper limit of 33,000 GW_{th}, or 1,040 EJ/yr.

In comparison, the IPCC Fourth Assessment Report (AR4) estimated an available energy resource for geothermal (including potential reserves) of 5,000 EJ/yr (Sims et al., 2007; see their Table 4.2). This amount cannot be properly considered as technical potential and looks overestimated compared with the geothermal technical potentials presented in Figure 4.2. It is important to note, however, that technical potentials tend to increase as technology progresses and overcomes some of the technical constraints of accessing theoretically available resources.

4.2.2 Regional technical potential

The assessed geothermal technical potentials included in Table 4.2 and Figure 4.2 are presented on a regional basis in Table 4.3. The regional breakdown in Table 4.3 is based on the methodology applied by EPRI (1978) to estimate theoretical geothermal potentials for each country, and then countries were grouped into the IEA regions. Thus, the present disaggregation of the global technical potentials is based on factors accounting for regional variations in the average geothermal gradient and the presence of either a diffuse geothermal anomaly or a high-temperature region, associated with volcanism or plate boundaries as estimated by EPRI (1978). Applying these factors to the global technical potentials listed in Table 4.2 gives the values stated in Table 4.3. The separation into electric and thermal (direct uses) technical potentials is somewhat arbitrary in that most higher-temperature resources could be used for either or both in combined heat and power applications depending on local market conditions and the distance between geothermal facilities and the consuming centres. Technical potentials for direct uses include only identified and hidden hydrothermal systems as estimated by Stefansson (2005), and are presented independently from depth since direct uses of geothermal energy usually do not require developments over 3 km in depth.

4.2.3 Possible impact of climate change on resource potential

Geothermal resources are not dependent on climate conditions and climate change is not expected to have a significant impact on the geothermal resource potential. The operation of geothermal heat pumps will not be affected significantly by a gradual change in ambient temperature associated with climate change, but in some power plants it may affect the ability to reject heat efficiently and perhaps adversely impact power generation (Hiriart, 2007). On a local basis, the effect of climate change on rainfall distribution may have a long-term effect on the recharge to specific groundwater aquifers, which in turn may affect discharges from some hot springs, and could have an effect on water levels in shallow geothermally heated aquifers. Also, the availability of cooling water from surface water supplies could be affected by changes in rainfall patterns, and this may require air-cooled power plant condensers (Saadat et al., 2010). However, each of these effects, if they occur, can be remedied by adjustments to the technology, generally for an incremental cost. Regarding future EGS projects, water management may impact the development of EGS particularly in water-deficient regions, where availability is an issue.

4.3 Technology and applications

For the last 100 years, geothermal energy has provided safe, reliable, environmentally benign energy used in a sustainable manner to generate electric power and provide direct heating services from hydrothermal-type resources, using mature technologies. Geothermal typically provides base-load generation, but it has also been used for meeting peak demand. Today's technologies for using hydrothermal resources have demonstrated high average CFs (up to 90% in newer plants, see DiPippo (2008)) in electric generation with low GHG emissions. However, technologies for EGS-type geothermal resources are still in demonstration (see Section 4.3.4).

Geothermal energy is currently extracted using wells or other means that produce hot fluids from: (a) hydrothermal reservoirs with naturally high permeability; or (b) EGS-type reservoirs with artificial fluid pathways. Production wells discharge hot water and/or steam. In high-temperature hydrothermal reservoirs, as pressure drops a fraction of the liquid water component 'flashes' to steam. Separated steam is piped to a turbine to generate electricity and the remaining hot water may be flashed again at lower pressures (and temperatures) to obtain more steam. The

4 Some discharge thermal energy of up to 60 MW_{th} (Lupton, 1995) but there are other submarine vents, such as the one known as 'Rainbow', with an estimated output of 1 to 5 GW_{th} (German et al., 1996).

Table 4.3 | Geothermal technical potentials on continents for the International Energy Agency (IEA) regions (prepared with data from EPRI (1978) and global technical potentials described in section 4.2.1).

REGION*	Electric technical potential in EJ/yr at depths to:						Technical potentials (EJ/yr) for direct uses	
	3 km		5 km		10 km			
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
OECD North America	25.6	31.8	38.0	91.9	69.3	241.9	2.1	68.1
Latin America	15.5	19.3	23.0	55.7	42.0	146.5	1.3	41.3
OECD Europe	6.0	7.5	8.9	21.6	16.3	56.8	0.5	16.0
Africa	16.8	20.8	24.8	60.0	45.3	158.0	1.4	44.5
Transition Economies	19.5	24.3	29.0	70.0	52.8	184.4	1.6	51.9
Middle East	3.7	4.6	5.5	13.4	10.1	35.2	0.3	9.9
Developing Asia	22.9	28.5	34.2	82.4	62.1	216.9	1.8	61.0
OECD Pacific	7.3	9.1	10.8	26.2	19.7	68.9	0.6	19.4
Total	**117.5**	**145.9**	**174.3**	**421.0**	**317.5**	**1108.6**	**9.5**	**312.2**

Note: *For regional definitions and country groupings see Annex II.

remaining brine is sent back to the reservoir through injection wells or first cascaded to a direct-use system before injecting. A few reservoirs, such as The Geysers in the USA, Larderello in Italy, Matsukawa in Japan, and some Indonesian fields, produce vapour as 'dry' steam (i.e., pure steam, with no liquid water) that can be sent directly to the turbine. In these cases, control of steam flow to meet power demand fluctuations is easier than in the case of two-phase production, where continuous up-flow in the well bore is required to avoid gravity collapse of the liquid phase. Hot water produced from intermediate-temperature hydrothermal or EGS reservoirs is commonly utilized by extracting heat through a heat exchanger for generating power in a binary cycle, or in direct use applications. Recovered fluids are also injected back into the reservoir (Armstead and Tester, 1987; Dickson and Fanelli, 2003; DiPippo, 2008).

Key technologies for exploration and drilling, reservoir management and stimulation, and energy recovery and conversion are described below.

4.3.1 Exploration and drilling

Since geothermal resources are underground, exploration methods (including geological, geochemical and geophysical surveys) have been developed to locate and assess them. The objectives of geothermal exploration are to identify and rank prospective geothermal reservoirs prior to drilling, and to provide methods of characterizing reservoirs (including the properties of the fluids) that enable estimates of geothermal reservoir performance and lifetime. Exploration of a prospective geothermal reservoir involves estimating its location, lateral extent and depth with geophysical methods and then drilling exploration wells to test its properties, minimizing the risk. All these exploration methods can be improved (see Section 4.6.1).

Today, geothermal wells are drilled over a range of depths down to 5 km using methods similar to those used for oil and gas. Advances in drilling technology have enabled high-temperature operation and provide directional drilling capability. Typically, wells are deviated from vertical to about 30 to 50° inclination from a 'kick-off point' at depths between 200 and 2,000 m. Several wells can be drilled from the same pad, heading in different directions to access larger resource volumes, targeting permeable structures and minimizing the surface impact. Current geothermal drilling methods are presented in more detail in Chapter 6 of Tester et al. (2006). For other geothermal applications such as GHP and direct uses, smaller and more flexible rigs have been developed to overcome accessibility limitations.

4.3.2 Reservoir engineering

Reservoir engineering efforts are focused on two main goals: (a) to determine the volume of geothermal resource and the optimal plant size based on a number of conditions such as sustainable use of the available resource; and (b) to ensure safe and efficient operation during the lifetime of the project. The modern method of estimating reserves and sizing power plants is to apply reservoir simulation technology. First a conceptual model is built, using available data, and is then translated into a numerical representation, and calibrated to the unexploited, initial thermodynamic state of the reservoir (Grant et al., 1982). Future behaviour is forecast under selected load conditions using a heat and mass transfer algorithm (e.g., TOUGH2)[5], and the optimum plant size is selected.

Injection management is an important aspect of geothermal development, where the use of isotopic and chemical tracers is common. Cooling of production zones by injected water that has had insufficient contact with hot reservoir rock can result in production declines. In some circumstances, placement of wells could also aim to enhance deep hot recharge through production pressure drawdown, while suppressing shallow inflows of peripheral cool water through injection pressure increases.

5 More information is available on the TOUGH2 website: esd.lbl.gov/TOUGH2/.

Given sufficient, accurate calibration with field data, geothermal reservoir evolution can be adequately modelled and proactively managed. Field operators monitor the chemical and thermodynamic properties of geothermal fluids, and map their flow and movement in the reservoir. This information, combined with other geophysical data, is fed back to recalibrate models for better predictions of future production (Grant et al., 1982).

4.3.3 Power plants

The basic types of geothermal power plants in use today are steam condensing turbines and binary cycle units. Steam condensing turbines[6] can be used in flash or dry-steam plants operating at sites with intermediate- and high-temperature resources (≥150°C). The power plant generally consists of pipelines, water-steam separators, vaporizers, de-misters, heat exchangers, turbine generators, cooling systems, and a step-up transformer for transmission into the electrical grid (see Figure 4.3, top). The power unit size usually ranges from 20 to 110 MW_e (DiPippo, 2008), and may utilize a multiple flash system, flashing the fluid in a series of vessels at successively lower pressures, to maximize the extraction of energy from the geothermal fluid. The only difference between a flash plant and a dry-steam plant is that the latter does not require brine separation, resulting in a simpler and cheaper design.

Binary-cycle plants, typically organic Rankine cycle (ORC) units, are commonly installed to extract heat from low- and intermediate-temperature geothermal fluids (generally from 70 to 170°C), from hydrothermal- and EGS-type reservoirs. Binary plants (Figure 4.3, bottom) are more complex than condensing ones since the geothermal fluid (water, steam or both) passes through a heat exchanger heating another working fluid. This working fluid, such as isopentane or isobutene with a low boiling point, vaporizes, drives a turbine, and then is air cooled or condensed with water. Binary plants are often constructed as linked modular units of a few MW_e in capacity.

There are also combined or hybrid plants, which comprise two or more of the above basic types, such as using a binary plant as a bottoming cycle with a flash steam plant, to improve versatility, increase overall thermal efficiency, improve load-following capability, and efficiently cover a wide resource temperature range.

Cogeneration plants, or combined or cascaded heat and power plants (CHP), produce both electricity and hot water for direct use. Relatively small industries and communities of a few thousand people provide sufficient markets for CHP applications. Iceland has three geothermal cogeneration plants with a combined capacity of 580 MW_{th} in operation (Hjartarson and Einarsson, 2010). At the Oregon Institute of Technology, a CHP plant provides most of the electricity needs and all the heat demand (Lund and Boyd, 2009).

4.3.4 Enhanced Geothermal Systems (EGS)

EGS require stimulation of subsurface regions where temperatures are high enough for effective utilization. A reservoir consisting of a fracture network is created or enhanced to provide well-connected fluid pathways between injection and production wells (see Figure 4.1). Heat is extracted by circulating water through the reservoir in a closed loop and can be used for power generation with binary-cycle plants and for industrial or residential heating (Armstead and Tester, 1987; Tester et al., 2006).

Knowledge of temperature at drillable depth is a prerequisite for site selection for any EGS development. The thermo-mechanical signature of the lithosphere and crust are equally important as they provide critical constraints affecting the crustal stress field, heat flow and temperature gradients. Recently developed analogue and numerical models provide insights useful for geothermal exploration and production, including improved understanding of fundamental mechanisms for predicting crustal stress and basin and basement heat flow (Cloetingh et al., 2010).

EGS projects are currently at a demonstration and experimental stage in a number of countries. The key challenge for EGS is to stimulate and maintain multiple reservoirs with sufficient volumes to sustain long-term production at acceptable rates, and flow impedances, while managing water losses and risk from induced seismicity (Tester et al., 2006).

4.3.5 Direct use

Direct use provides heating and cooling for buildings[7] including district heating, fish ponds, greenhouses, bathing, wellness and swimming pools, water purification/desalination, and industrial and process heat for agricultural products and mineral extraction and drying.

For space heating, two basic types of systems are used: open or closed loop. Open loop (single pipe) systems utilize directly the geothermal water extracted from a well to circulate through radiators (Figure 4.4, top). Closed loop (double pipe) systems use heat exchangers to transfer heat from the geothermal water to a closed loop that circulates heated freshwater through the radiators (Figure 4.4, bottom). This system is commonly used because of the chemical composition of the geothermal water. In both cases the spent geothermal water is disposed of into injection wells and a conventional backup boiler may be provided to meet peak demand.

6 A condensing turbine will expand steam to below atmospheric pressure to maximize power production. Vacuum conditions are usually maintained by a direct contact condenser. Back-pressure turbines, much less common and less efficient than condensing turbines, let steam down to atmospheric pressure and avoid the need for condensers and cooling towers.

7 Space and water heating are significant parts of the energy budget in large parts of the world. In Europe, 30% of energy use is for space and water heating alone, representing 75% of total building energy use (Lund et al., 2010a).

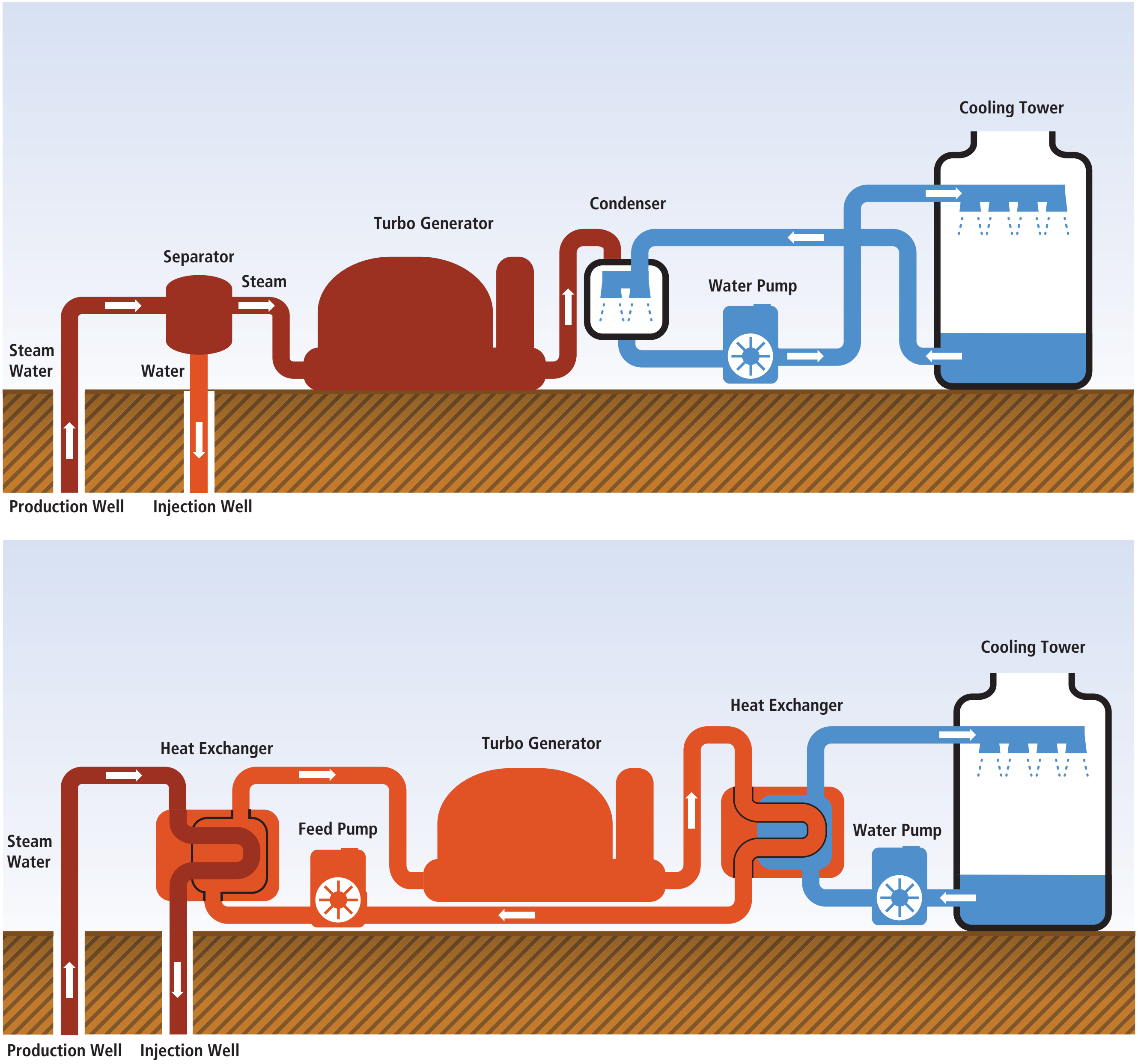


Figure 4.3 | Schematic diagram of a geothermal condensing steam power plant (top) and a binary-cycle power plant (bottom) (adapted from Dickson and Fanelli (2003)).

Transmission pipelines consist mostly of steel insulated by rock wool (surface pipes) or polyurethane (subsurface). However, several small villages and farming communities have successfully used plastic pipes (polybutylene) with polyurethane insulation, as transmission pipes. The temperature drop is insignificant in large-diameter pipes with a high flow rate, as observed in Iceland where geothermal water is transported up to 63 km from the geothermal fields to towns.

Although it is debatable whether geothermal heat pumps, also called ground source heat pumps (GHP), are a 'true' application of geothermal energy or whether they are partially using stored solar energy, in this chapter they are treated as a form of direct geothermal use. GHP technology is based on the relatively constant ground or groundwater temperature ranging from 4°C to 30°C to provide space heating, cooling and domestic hot water for all types of buildings. Extracting energy during heating periods cools the ground locally. This effect can be minimized by dimensioning the number and depth of probes in order to avoid harmful impacts on the ground. These impacts are also reduced by storing heat underground during cooling periods in the summer months.

There are two main types of GHP systems: closed loop and open loop. In ground-coupled systems a closed loop of plastic pipe is placed into

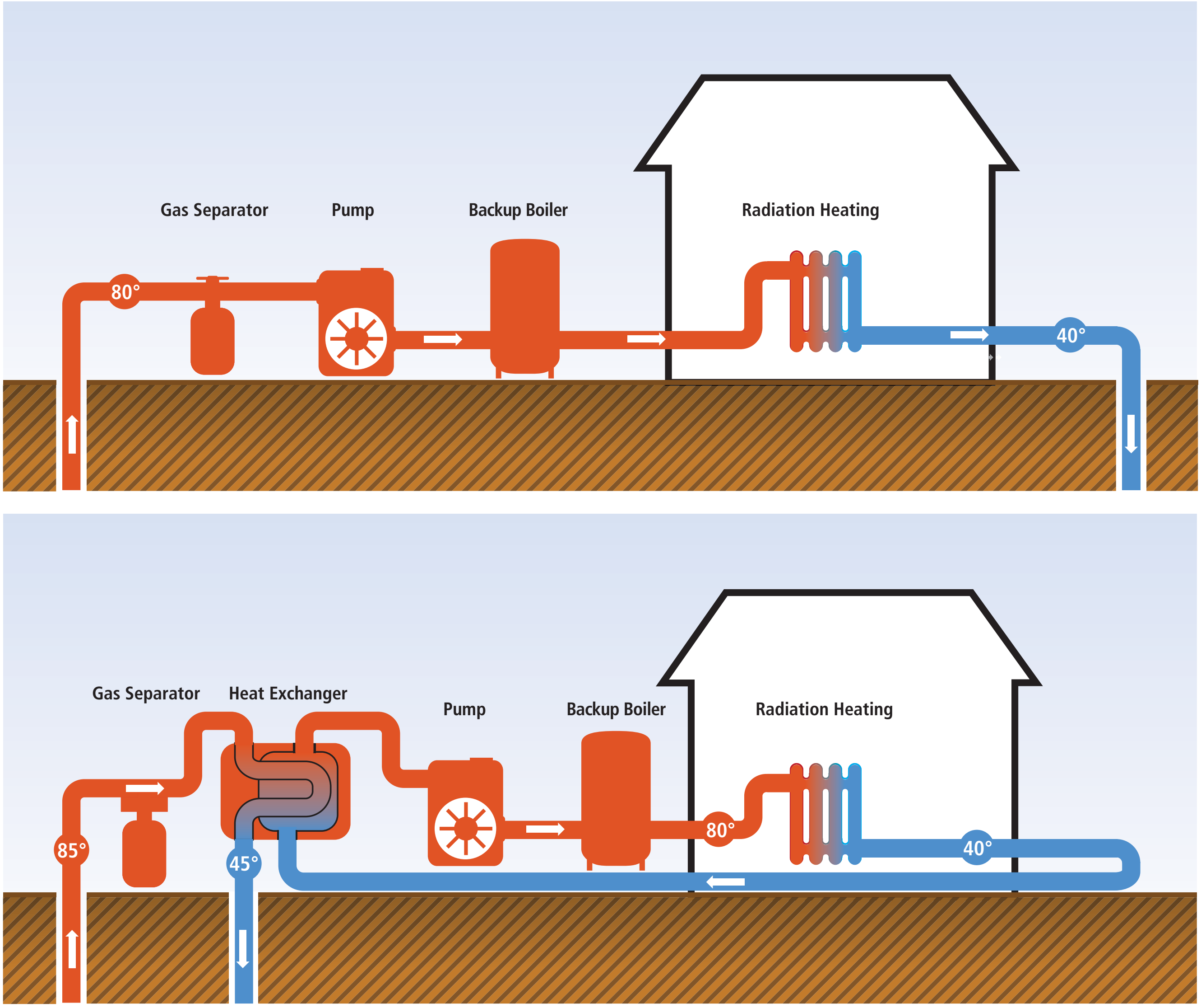


Figure 4.4 | Two main types of district heating systems: top, open loop (single pipe system), bottom, closed loop (double pipe system) (adapted from Dickson and Fanelli, (2003)).

the ground, either horizontally at 1 to 2 m depth or vertically in a borehole down to 50 to 250 m depth. A water-antifreeze solution is circulated through the pipe. Heat is collected from the ground in the winter and rejected to the ground in the summer. An open loop system uses groundwater or lake water directly as a heat source in a heat exchanger and then discharges it into another well or into the same water reservoir (Lund et al., 2003).

Heat pumps operate similarly to vapour compression refrigeration units with heat rejected in the condenser used for heating or extracted in the evaporator used for cooling. GHP efficiency is described by a coefficient of performance (COP) that scales the heating or cooling output to the electrical energy input, and typically lies between 3 and 4 (Lund et al., 2003; Rybach, 2005). The seasonal performance factor (SPF) provides a metric of the overall annual efficiency. It is the ratio of useful heat to the consumed driving energy (both in kWh/yr), and it is slightly lower than the COP.

4.4 Global and regional status of market and industry development

Electricity has been generated commercially by geothermal steam since 1913. Currently, the geothermal industry has a wide range of participants, including major energy companies, private and public utilities, equipment manufacturers and suppliers, field developers and drilling companies. The geothermal-electric market appears to be accelerating compared to previous years, as indicated by the increase in installed and planned capacity (Bertani, 2010; Holm et al., 2010).

4.4.1 Status of geothermal electricity from conventional geothermal resources

In 2009, electricity was being produced from conventional (hydrothermal) geothermal resources in 24 countries with an installed capacity of 10.7 GW_e (Figure 4.5), with an annual increase of 405 MW (3.9%) over the previous year (Bertani, 2010, see his Table X). The worldwide use of geothermal energy for power generation was 67.2 TWh/yr (0.24 EJ/yr)[8] in 2008 (Bertani, 2010) with a worldwide CF of 74.5% (see also Table 4.7). Many developing countries are among the top 15 in geothermal electricity production.

Conventional geothermal resources currently used to produce electricity are either high-temperature systems (>180°C), using steam power cycles (either flash or dry steam driving condensing turbines), or low to intermediate temperature (<180°C) using binary-cycle power plants. Around 11% of the installed capacity in the world in 2009 was composed of binary plants (Bertani, 2010).

In 2009, the world's top geothermal producer was the USA with almost 29% of the global installed capacity (3,094 MW_e; Figure 4.5). The US geothermal industry is currently expanding due to state Renewable Portfolio Standards (RPS) and various federal subsidies and tax incentives (Holm et al., 2010). US geothermal activity is concentrated in a few western states, and only a fraction of the geothermal technical potential has been developed so far.

Outside of the USA, about 29% of the global installed geothermal capacity in 2009 was located in the Philippines and Indonesia. Mexico, Italy, Japan, Iceland and New Zealand together account for one-third of the global installed geothermal capacity. Although some of these markets have seen relatively limited growth over the past few years, others

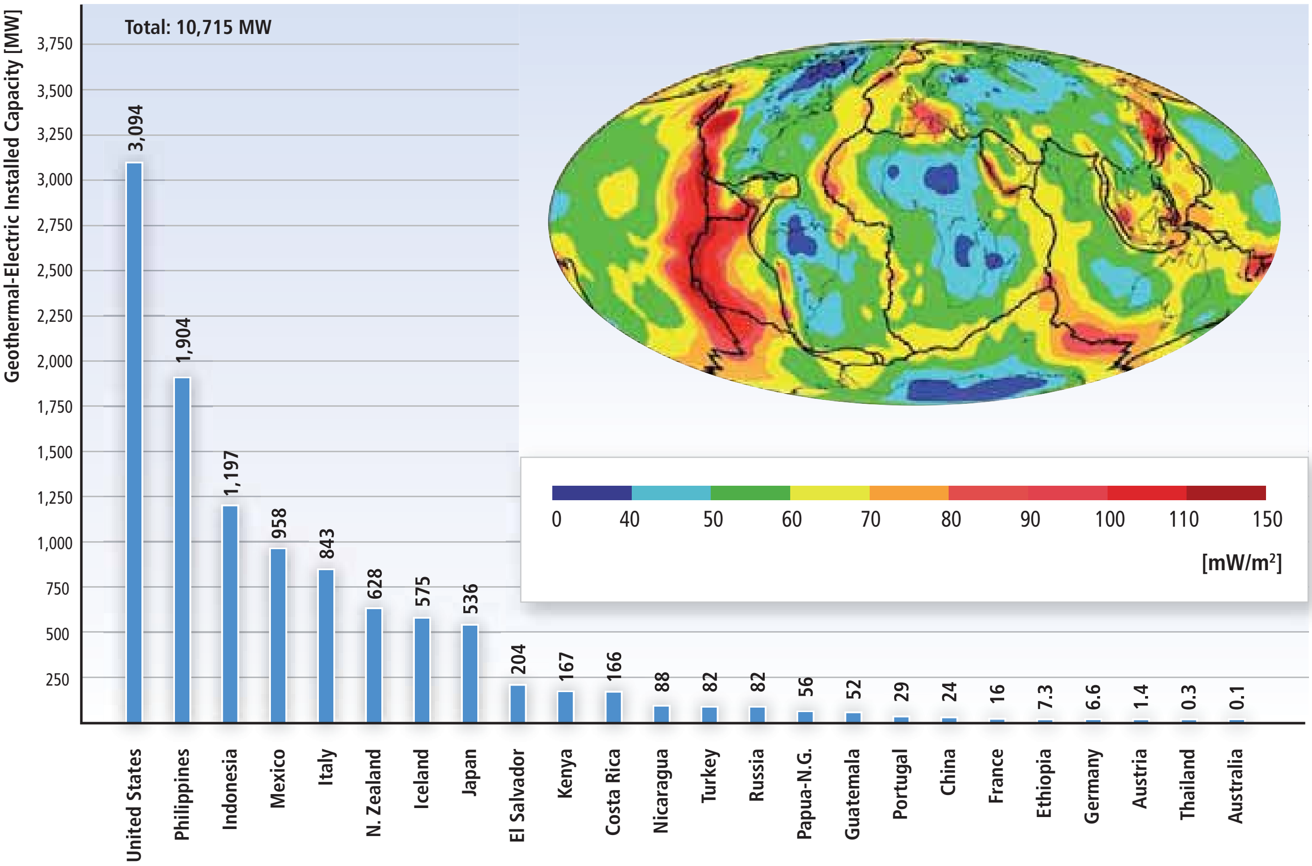


Figure 4.5 | Geothermal-electric installed capacity by country in 2009. Inset figure shows worldwide average heat flow in mW/m² and tectonic plates boundaries (figure from Hamza et al. (2008), used with kind permission from Springer Science+Business Media B.V.; data from Bertani (2010)).

8 Based on IEA data presented in Chapter 1, electricity production from geothermal energy in 2008 equaled 65 TWh/yr.

such as Iceland and New Zealand doubled the installed capacity from 2005 to 2009 (IEA-GIA, 2009). Moreover, attention is turning to new markets such as Chile, Germany and Australia.

The majority of existing geothermal assets are operated by state-owned utilities or independent power producers. Currently, more than 30 companies globally have an ownership stake in at least one geothermal field. Altogether, the top 20 owners of geothermal capacity control approximately 90% of the installed global market (Bertani, 2010).

At the end of 2008, geothermal electricity contributed only about 0.3% of the total worldwide electric generation. However, 6 of the 24 countries shown in Figure 4.5 (El Salvador, Kenya, Philippines, Iceland, Costa Rica and New Zealand) obtained more than 10% of their national electricity production from high-temperature geothermal resources (Bromley et al., 2010).

Worldwide evolution of geothermal power and geothermal direct uses during the last 40 years is presented in Table 4.4, including the annual average rate of growth over each period. The average annual growth of geothermal-electric installed capacity over the last 40 years is 7%, and for geothermal direct uses (heat applications) is 11% over the last 35 years.

Table 4.4 | Average annual growth rate in geothermal power capacity and direct uses (including GHP) in the last 40 years (prepared with data from Lund et al., 2005, 2010a; Fridleifsson and Ragnarsson, 2007; Gawell and Greenberg, 2007; Bertani, 2010).

Year	Electric capacity		Direct uses capacity	
	MW_e	%	MW_{th}	%
1970	720	—	N/A	—
1975	1,180	10.4	1,300	—
1980	2,110	12.3	1,950	8.5
1985	4,764	17.7	7,072	29.4
1990	5,834	4.1	8,064	2.7
1995	6,833	3.2	8,664	1.4
2000	7,972	3.1	15,200	11.9
2005	8,933	2.3	27,825	12.9
2010*	10,715	3.7	50,583	12.7
Total annual average:		**7.0**		**11.0**

Notes:

%: Average annual growth in percent over the period.
N/A: Reliable data not available.
*End of 2009.

4.4.2 Status of EGS

While there are no commercial-scale operating EGS plants, a number of demonstrations are active in Europe, the USA and Australia. In the latter, by 2009, 50 companies held about 400 geothermal exploration licences to develop EGS (AL-AGEA, 2009) with investments of USD_{2005} 260 million and government grants of USD_{2005} 146 million (Goldstein et al., 2009). In France, the EU project 'EGS Pilot Plant' at Soultz-sous-Forêts started in 1987 and has recently commissioned the first power plant (1.5 MW_e) to utilize the enhanced fracture permeability at 200°C. In Landau, Germany, a 2.5 to 2.9 MW_e EGS plant went into operation in late 2007 (Hettkamp et al., 2010). Deep sedimentary aquifers are being tapped at the geothermal test site in Groß Schönebeck, Germany, using two research wells (Huenges et al., 2009). These demonstration prototypes have provided data on the performance of the EGS concepts subject to real field conditions. Nonetheless, sustained multiyear commitments to field-scale demonstrations in different geologic settings are still needed to reduce technical and economic risks.

The USA has recently increased support for EGS research, development and demonstration as part of a revived national geothermal program. Currently the main short-term goals for the US program are to demonstrate commercial viability of EGS and upscale to several tens of megawatts (Holm et al., 2010). A US commitment to multiyear EGS demonstrations covering a range of resource grades is less certain.

The availability of water, other lower-cost renewable resources, transmission and distribution infrastructure, and most importantly project financing, will play major roles in regional growth trends of EGS projects (Tester et al., 2006).

4.4.3 Status of direct uses of geothermal resources

The world installed capacity of direct-use geothermal energy in 2009 was estimated at 50.6 GW_{th} (Table 4.4), with a total thermal energy usage of about 121.7 TWh_{th}/yr (0.44 EJ/yr) in 2008, distributed in 78 countries, with an annual average CF of 27.5% (Lund et al., 2010a). Another source (REN21, 2010) estimates geothermal direct use at 60 GW_{th} as of the end of 2009.

Direct heat supply temperatures are typically close to actual process temperatures in district heating systems that range from approximately 60°C to 120°C. In 2009 the main types (and relative percentages) of direct applications in annual energy use were: space heating of buildings[9] (63%), bathing and balneology (25%), horticulture (greenhouses and soil heating) (5%), industrial process heat and agricultural drying (3%), aquaculture (fish farming) (3%) and snow melting (1%) (Lund et al., 2010a).

When the resource temperature is too low for other direct uses, it is possible to use GHP. GHP contributed 70% (35.2 GW_{th}) of the worldwide installed geothermal heating capacity in 2009, and has been the fastest growing form of all geothermal direct use since 1995 (Rybach, 2005; Lund et al., 2010a).

9 China is the world's largest user of geothermal heat for space heating (Lund et al., 2010a).

Bathing, swimming and balneology are globally widespread. In addition to the thermal energy, the chemicals dissolved in the geothermal fluid are used for treating various skin and health diseases. Greenhouses heated by geothermal energy and heating soil in outdoor agricultural fields have been developed in several countries. A variety of industrial processes utilize heat applications, including drying of forest products, food and minerals industries as in the USA, Iceland and New Zealand. Other applications are process heating, evaporation, distillation, sterilization, washing, and CO_2 and salt extraction. Aquaculture using geothermal heat allows better control of pond temperatures, with tilapia, salmon and trout the most common fish raised. Low-temperature geothermal water is used in some colder climate countries for snow melting or de-icing. City streets, sidewalks and parking lots are equipped with buried piping systems carrying hot geothermal water (Lund et al., 2005, 2010a).

Geothermal direct uses have experienced a significant global increase in the last 15 years (Table 4.4) after a period of stagnation (1985 to 1995), mainly due to the increasing costs of fossil fuels for heating and cooling and the need to replace them with renewable sources. The technical potential of direct-use applications for heating and cooling buildings is still largely unrealized (Lund et al., 2010a).

4.4.4 Impact of policies[10]

For geothermal to reach its full capacity in climate change mitigation it is necessary to address the following technical and non technical barriers (Wonstolen, 1980; Mock et al., 1997; Imolauer et al., 2010).

Technical barriers. Distributions of potential geothermal resources vary from being almost site-independent (for GHP technologies and EGS) to being much more site-specific (for hydrothermal sources). The distance between electricity markets or centres of heat demand and geothermal resources, as well as the availability of transmission capacity, can be a significant factor in the economics of power generation and direct use.

Non-technical barriers.

- Information and awareness barriers. Lack of clarity in understanding geothermal energy is often a barrier, which could be overcome by dissemination of information on reliable and efficient geothermal technologies to enhance governmental and public knowledge. On the other hand, for deep geothermal drilling and reservoir management, skilled companies and well-trained personnel are currently concentrated in a few countries. For GHP installation and district heating, there is also a correlation between local availability and awareness of service companies and technology uptake. This constraint could be overcome by an improved global infrastructure of services and education programs (geothermal engineering programs) for an expanding workforce to replace retiring staff.

- Market failures and economic barriers, due to un-priced or underpriced environmental impacts of energy use, and poor availability of capital risk insurance.

- Institutional barriers due in many countries to the lack of specific laws governing geothermal resources, which are commonly considered as mining or water resources.

Policies set to drive uptake of geothermal energy work better if local demand and risk factors are taken into account (Rybach, 2010). For example, small domestic heat customers can be satisfied using GHP technologies, which require relatively small budgets. For other countries, district heating systems and industrial heat applications are more efficient and provide greater mitigation of CO_2 emissions, but these markets typically require larger-scale investments and a different policy framework.

Policies that support improved applied research and development would benefit all geothermal technologies, but especially emerging technologies such as EGS. Specific incentives for geothermal development can include fiscal incentives, public finance and regulation policies such as targeted grants for pre-competitive research and demonstration, subsidies, guarantees, tax write-offs to cover the commercial upfront exploration costs, including the higher-risk initial drilling costs, feed-in tariffs and additional measures like portfolio standards (Rybach, 2010). Feed-in tariffs (FITs, see Section 11.5.4.3) with defined geothermal pricing have been very successful in attracting commercial investment in some European countries such as Germany, Switzerland, Belgium, Austria, Spain and Greece, among others (Rybach, 2010). Direct subsidies for new building heating, refurbishment of existing buildings with GHP, and for district heating systems may be also applicable.

Experience has shown that the relative success of geothermal development in particular countries is closely linked to their government's policies, regulations, incentives and initiatives. Successful policies have taken into account the benefits of geothermal energy, such as its independence from weather conditions and its suitability for base-load power. Another important policy consideration is the opportunity to support the price of geothermal kWh (both power and direct heating and cooling) through the United Nations' Clean Development Mechanism (CDM) program. A recent example is the Darajat III geothermal power plant, developed by a private company in Indonesia in 2007, and registered with the CDM. The plant currently generates about 650,000 carbon credits (or certified emission reductions, CER) per year, thus reducing the lifecycle cost of geothermal energy by about 2 to 4% (Newell and Mingst, 2009).

10 Non-technology-specific policy issues are covered in Chapter 11 of this report.

4.5 Environmental and social impacts[11]

In general, negative environmental impacts associated with geothermal energy utilization are minor. Hot fluid production can emit varying quantities of GHGs, which are usually small. These originate from naturally sourced CO_2 fluxes that would eventually be released into the atmosphere through natural surface venting. The exploitation of geothermal energy does not ultimately create any additional CO_2 from the subsurface, since there is no combustion process, though the rate of natural emissions can be altered by geothermal production depending on the plant configuration.

Water is not a limiting factor for geothermal power generation, since geothermal fluids are usually brines (i.e., not competing with other uses). Flash power plants do not consume potable water for cooling and yield condensed water that can, with proper treatment, be used for agricultural and industrial purposes. Binary power plants can minimize their water use with air cooling.

Potential adverse effects from disposal of geothermal fluids and gases, induced seismicity and ground subsidence can be minimized by sound practices. Good practice can also optimize water and land use, improve long-term sustainability of production and protect natural thermal features that are valued by the community. The following sections address these issues in more detail.

4.5.1 Direct greenhouse gas emissions

The main GHG emitted by geothermal operations is CO_2. Geothermal fluids contain minerals leached from the reservoir rock and variable quantities of gas, mainly CO_2 and a smaller amount of hydrogen sulphide. The gas composition and quantity depend on the geological conditions encountered in the different fields. Depending on technology, most of the mineral content of the fluid and some of the gases are re-injected back into the reservoir. The gases are often extracted from a steam turbine condenser or two-phase heat exchanger and released through a cooling tower. CO_2, on average, constitutes 90% of these non-condensable gases (Bertani and Thain, 2002). A field survey of geothermal power plants operating in 2001 found a wide spread in the direct CO_2 emission rates. The average weighted by generation was 122 g CO_2/kWh, with values ranging from 4 to 740 g CO_2/kWh (Bertani and Thain, 2002). In closed-loop binary-cycle power plants, where the extracted geothermal fluid is passed through a heat exchanger and then completely injected, the operational CO_2 emission is near zero.

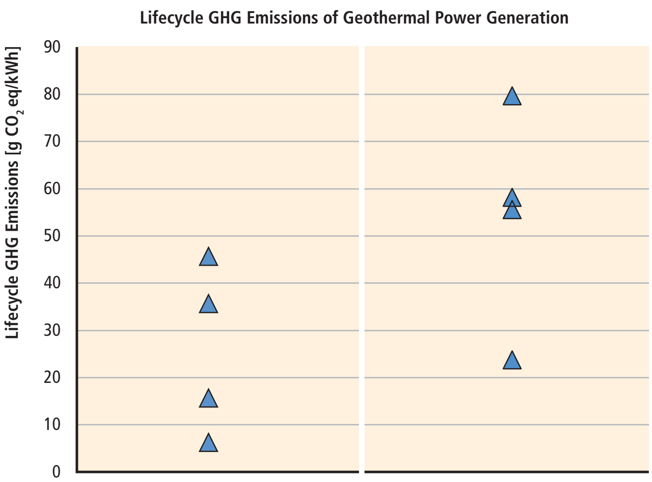
In direct heating applications, emissions of CO_2 are also typically negligible (Fridleifsson et al., 2008). For instance, in Reykjavik, Iceland, the CO_2 content of thermal groundwater used for district heating (0.05 mg CO_2/kWh$_{th}$) is lower than that of the cold groundwater. In China (Beijing, Tianjin and Xianyang) it is less than 1 g CO_2/kWh$_{th}$. In places such as Iceland, co-produced CO_2, when sufficiently pure, may also be used in greenhouses to improve plant growth, or extracted for use in carbonated beverages. In the case of Iceland, the replacement of fossil fuel with geothermal heating has avoided the emission of approximately 2 Mt of CO_2 annually and significantly reduced air pollution (Fridleifsson et al., 2008). Other examples of the environmental benefits of geothermal direct use are at Galanta in Slovakia (Fridleifsson et al., 2008), the Pannonian Basin in Hungary (Arpasi, 2005), and the Paris Basin (Laplaige et al., 2005).

EGS power plants are likely to be designed as liquid-phase closed-loop circulation systems, with zero direct emissions, although, if gas separation occurs within the circulation loop, some gas extraction and emission is likely. If the current trend towards more use of lower-temperature resources and binary plants continues, there will be a reduction in average emissions.

4.5.2 Lifecycle assessment

Life-cycle assessment (LCA) analyzes the whole lifecycle of a product 'from cradle to grave'. For geothermal power plants, all GHG emissions directly and indirectly related to the construction, operation and decommissioning of the plant are considered in LCA.

Figure 4.6 shows the result of a comprehensive literature review of geothermal electricity generation LCA studies published since 1980, which were screened for quality and completeness (see Annex II for details on methodology). All estimates of lifecycle GHG emissions are less than 50



	Flashed Steam	EGS
Estimates:	4	4
References:	3	3

Figure 4.6 | Estimates of lifecycle GHG emissions from geothermal power generation (flashed steam and EGS technologies). Unmodified literature values, after quality screen. (See Annex II and Section 9.3.4.1 for details of literature search and citations.)

11 A comprehensive assessment of social and environmental impacts of all RE sources covered in this report can be found in Chapter 9.

g CO_2eq/kWh for flash steam plants and less than 80 g CO_2eq/kWh for projected EGS plants.

The Bertani and Thain (2002) estimates are higher than these for several reasons. First, Bertani and Thain collected information from a very large fraction of global geothermal facilities (85% of world geothermal capacity in 2001), whereas qualifying LCA studies were few. Some open-loop facilities with high dissolved CO_2 concentrations can emit CO_2 at very high rates, though this is relevant for a minority of installed capacity only. For closed-loop geothermal systems with more common dissolved CO_2 concentrations, most lifecycle GHG emissions are embodied in plant materials and emitted during construction. These were the cases examined in the qualifying LCA literature displayed in Figure 4.6. Despite few available studies, it is tentatively observed that systems using flashed or dry geothermal steam appear to have lower GHG emissions than do systems combining EGS reservoir development with binary power conversion systems, though this difference is small relative to, for instance, coal-fired electricity generation GHG emissions (see Section 9.3.4.1). A key factor contributing to higher reported emissions for EGS/binary systems versus steam-driven geothermal systems is higher energy and materials requirements for EGS' well-field development. Additional LCA studies to increase the number of estimates for all geothermal energy technologies are needed.

Frick et al. (2010) compared LCA environmental indicators to those of European and German reference power mixes, the latter being composed of lignite coal (26%), nuclear power (26%), hard coal (24%), natural gas (12%), hydropower (4%), wind power (4%), crude oil (1%) and other fuels (3%), and observed that geothermal GHG emissions fall in a range between 8 and 12% of these reference mixes. At sites with above-average geological conditions, low-end GHG emissions from closed loop geothermal power systems can be less than 1% of corresponding emissions for coal technologies.

For lifecycle GHG emissions of geothermal energy, Kaltschmitt (2000) published figures of 14.3 to 57.6 g CO_2eq/kWh_{th} for low-temperature district heating systems, and 180 to 202 g CO_2eq/kWh_{th} for GHP, although the latter values depend significantly on the mix of electricity sources that power them.

The LCA of intermediate- to low-temperature geothermal developments is dominated by larger initial material and energy inputs during the construction of the wells, power plant and pipelines. For hybrid electricity/ district heating applications, greater direct use of the heat generally provides greater environmental benefits.

In conclusion, the LCA assessments show that geothermal is similar to other RE and nuclear energy in total lifecycle GHG emissions (see 9.3.4.1), and it has significant environmental advantages relative to a reference electricity mix dominated by fossil fuel sources.

4.5.3 Local environmental impacts

Environmental impact assessments for geothermal developments involve consideration of a range of local land and water use impacts during both construction and operation phases that are common to most energy projects (e.g., noise, vibration, dust, visual impacts, surface and ground water impacts, ecosystems, biodiversity) as well as specific geothermal impacts (e.g., effects on outstanding natural features such as springs, geysers and fumaroles).

4.5.3.1 Other gas and liquid emissions during operation

Geothermal systems involve natural phenomena, and typically discharge gases mixed with steam from surface features, and minerals dissolved in water from hot springs. Apart from CO_2, geothermal fluids can, depending on the site, contain a variety of other minor gases, such as hydrogen sulphide (H_2S), hydrogen (H_2), methane (CH_4), ammonia (NH_3) and nitrogen (N_2). Mercury, arsenic, radon and boron may be present. The amounts depend on the geological, hydrological and thermodynamic conditions of the geothermal field, and the type of fluid collection/ injection system and power plant utilized.

Of the minor gases, H_2S is toxic, but rarely of sufficient concentration to be harmful after venting to the atmosphere and dispersal. Removal of H_2S released from geothermal power plants is practised in parts of the USA and Italy. Elsewhere, H_2S monitoring is a standard practice to provide assurance that concentrations after venting and atmospheric dispersal are not harmful. CH_4, which has warming potential, is present in small concentrations (typically a few percent of the CO_2 concentration).

Most hazardous chemicals in geothermal fluids are in aqueous phase. If present, boron and arsenic are likely to be harmful to ecosystems if released at the surface. In the past, surface disposal of separated water has occurred at a few fields. Today, this happens only in exceptional circumstances, and geothermal brine is usually injected back into the reservoir to support reservoir pressures, as well as avoid adverse environmental effects. Surface disposal, if significantly in excess of natural hot spring flow rates, and if not strongly diluted, can have adverse effects on the ecology of rivers, lakes or marine environments. Shallow groundwater aquifers of potable quality are protected from contamination by injected fluids by using cemented casings, and impermeable linings provide protection from temporary fluid disposal ponds.

Such practices are typically mandated by environmental regulations. Geochemical monitoring is commonly undertaken by the field operators to investigate, and if necessary mitigate, such adverse effects (Bromley et al., 2006).

4.5.3.2 Potential hazards of seismicity and other phenomena

Local hazards arising from natural phenomena, such as micro-earthquakes, hydrothermal steam eruptions and ground subsidence may be influenced by the operation of a geothermal field (see also Section 9.3.4.7). As with other (non-geothermal) deep drilling projects, pressure or temperature changes induced by stimulation, production or injection of fluids can lead to geo-mechanical stress changes and these can affect the subsequent rate of occurrence of these phenomena (Majer et al., 2008). A geological risk assessment may help to avoid or mitigate these hazards.

Routine seismic monitoring is used as a diagnostic tool and management and protocols have been prepared to measure, monitor and manage systems proactively, as well as to inform the public of any hazards (Majer et al., 2008). In the future, discrete-element models would be able to predict the spatial location of energy releases due to injection and withdrawal of underground fluids. During 100 years of development, although turbines have been tripped offline for short periods, no buildings or structures within a geothermal operation or local community have been significantly damaged by shallow earthquakes originating from geothermal production or injection activities.

With respect to induced seismicity, ground vibrations or noise have been a social issue associated with some EGS demonstration projects, particularly in populated areas of Europe. The process of high-pressure injection of cold water into hot rock generates small seismic events. Induced seismic events have not been large enough to lead to human injury or significant property damage, but proper management of this issue will be an important step to facilitating significant expansion of future EGS projects. Collaborative research initiated by the IEA-GIA (Bromley and Mongillo, 2008), the USA and Australia (International Partnership for Geothermal Technology: IPGT)[12] and in Europe (GEISER)[13], is aimed at better understanding and mitigating induced seismicity hazards, and providing risk management protocols.

Hydrothermal steam eruptions have been triggered at a few locations by shallow geothermal pressure changes (both increases and decreases). These risks can be mitigated by prudent field design and operation.

Land subsidence has been an issue at a few high-temperature geothermal fields where pressure decline has affected some highly compressible formations causing them to compact anomalously and form local subsidence 'bowls'. Management by targeted injection to maintain pressures at crucial depths and locations can minimize subsidence effects. Some minor subsidence may also be related to thermal contraction and minor tumescence (inflation) can overlie areas of injection and rising pressure.

4.5.3.3 Land use

Good examples exist of unobtrusive, scenically landscaped developments (e.g., Matsukawa, Japan), and integrated tourism/energy developments (e.g., Wairakei, New Zealand and Blue Lagoon, Iceland). Nonetheless, land use issues still seriously constrain new development options in some countries (e.g., Indonesia, Japan, the USA and New Zealand) where new projects are often located within or adjacent to national parks or tourist areas. Spa resort owners are very sensitive to the possibility of depleted hot water resources. Potential pressure and temperature interference between adjacent geothermal developers or users can be another issue that affects all types of heat and fluid extraction, including heat pumps and EGS power projects (Bromley et al., 2006). Good planning should take this into account by applying predictive simulation models when allocating permits for energy extraction.

Table 4.5 presents the typical operational footprint for conventional geothermal power plants, taking into account surface installations (drilling pads, roads, pipelines, fluid separators and power-stations). Due to directional drilling techniques, and appropriate design of pipeline corridors, the land area above geothermal resources that is not covered by surface installations can still be used for other purposes such as farming, horticulture and forestry, as occurs, for example, at Mokai and Rotokawa in New Zealand (Koorey and Fernando, 2010), and a national park at Olkaria, Kenya.

Table 4.5 | Land requirements for typical geothermal power generation options expressed in terms of square meter per generation capacity and per annual energy output.

Type of power plant	Land Use	
	m^2/MW_e	$m^2/GWh/yr$
110-MW_e geothermal flash plants (excluding wells)	1,260	160
56-MW_e geothermal flash plant (including wells, pipes, etc.)	7,460	900
49-MW_e geothermal FC-RC plant (excluding wells)	2,290	290
20-MW_e geothermal binary plant (excluding wells)	1,415	170

Notes: FC: Flash cycle. RC: Rankine cycle (data from Tester et al. (2006) taken from DiPippo (1991); the CFs originally used to calculate land use vary between 90 and 95% depending on the plant type).

4.5.4 Local social impacts

The successful realization of geothermal projects often depends on the level of acceptance by local people. Prevention or minimization of detrimental impacts on the environment, and on land occupiers, as well as

12 A description of the project IPGT is available at: internationalgeothermal.org/IPGT.html.

13 A description of the GEISER project is available at: www.gfz-potsdam.de.

the creation of benefits for local communities, is indispensable to obtain social acceptance. Public education and awareness of the probability and severity of detrimental impacts are also important. The necessary prerequisites to secure agreement of local people are: (a) prevention of adverse effects on people's health; (b) minimization of environmental impacts; and (c) creation of direct and ongoing benefits for the resident communities (Rybach, 2010). Geothermal development creates local job opportunities during the exploration, drilling and construction period (typically four years minimum for a greenfield project). It also creates permanent and full-time jobs when the power plant starts to operate (Kagel, 2006) since the geothermal field from which the fluids are extracted must be operated locally. This can alleviate rural poverty in developing countries, particularly in Asia, Central and South America, and Africa, where geothermal resources are often located in remote mountainous areas. Some geothermal companies and government agencies have approached social issues by improving local security, building roads, schools, medical facilities and other community assets, which may be funded by contributions from profits obtained from operating the power plant (De Jesus, 2005).

Multiple land use arrangements that promote employment by integrating subsurface geothermal energy extraction with labour-intensive agricultural activities are also useful. In many developing countries, geothermal energy is also an appropriate energy source for small-scale distributed generation, helping accelerate development through access to energy in remote areas. This has occurred, for example, in Maguarichi, Mexico (Sánchez-Velasco et al., 2003).

4.6 Prospects for technology improvement, innovation and integration[14]

Geothermal resources can be integrated into all types of electrical power supply systems, from large, interconnected continental transmission grids to onsite use in small, isolated villages or autonomous buildings. They can be utilized in a variety of sustainable power generating modes, including continuous low power rates, long-term (decades long) cycles of high power rates separated by recovery periods and long-term, uninterrupted high power rates sustained with effective fluid reinjection (Bromley et al., 2006). Since geothermal typically provides base-load electric generation, integration of new power plants into existing power systems does not present a major challenge. Indeed, in some configurations, geothermal energy can provide valuable flexibility, such as the ability to increase or decrease production or start up/shut down as required. In some cases, however, the location dependence of geothermal resources requires new transmission infrastructure investments in order to deliver geothermal electricity to load centres.

14 Chapter 10.5 offers a complementary perspective on drivers of and trends in technological progress across RE technologies. Chapter 8 deals with other integration issues more widely.

For geothermal direct uses, no integration problems have been observed. For heating and cooling, geothermal (including GHP) is already widespread at the domestic, community and district scales. District heating networks usually offer flexibility with regard to the primary energy source and can therefore use low-temperature geothermal resources or cascaded geothermal heat (Lund et al., 2010b).

For technology improvement and innovation, several prospects can reduce the cost of producing geothermal energy and lead to higher energy recovery, longer field lifetimes, and better reliability. With time, better technical solutions are expected to improve power plant performance and reduce maintenance down time. The main technological challenges and prospects are described below.

4.6.1 Improvements in exploration, drilling and assessment technologies

In exploration, R&D is required to locate hidden geothermal systems (i.e., with no surface manifestations such as hot springs and fumaroles) and for EGS prospects. Refinement and wider usage of rapid reconnaissance geothermal tools such as satellite-based hyper-spectral, thermal infrared, high-resolution panchromatic and radar sensors could make exploration efforts more effective. Once a regional focus area has been selected, availability of improved cost-effective reconnaissance survey tools to detect as many geothermal indicators as possible is critical in providing rapid coverage of the geological environment being explored at an appropriate resolution.

Special research is needed to improve the rate of penetration when drilling hard rock and to develop advanced slim-hole technologies, and also in large-diameter drilling through ductile, creeping or swelling formations. Drilling must minimize formation damage that occurs as a result of a complex interaction of the drilling fluid (chemical, filtrate and particulate) with the reservoir fluid and formation. The objectives of new-generation geothermal drilling and well construction technologies are to reduce the cost and increase the useful life of geothermal production facilities through an integrated effort (see Table 4.6).

Improvements and innovations in deep drilling are expected as a result of the international Iceland Deep Drilling Project. The aim of this project is to penetrate into supercritical geothermal fluids, which can be a potential source of high-grade geothermal energy. The concept behind it is to flow supercritical fluid to the surface in such a way that it changes directly to superheated (>450°C) hot steam at sub-critical pressures. This would provide up to ten-fold energy output of approximately 50 MW_e as compared to average high enthalpy geothermal wells (Fridleifsson et al., 2010).

All tasks related to the engineering of the reservoir require a more sophisticated modelling of the reservoir processes and interactions to be

Table 4.6 | Priorities for advanced geothermal research (HTHF: high temperature and high flow rate).

Complementary research & share knowledge	Education / training
Standard geothermal resource & reserve definitions	Improved HTHF hard rock drill equipment
Predictive reservoir performance modelling	Improved HTHF multiple zone isolation
Predictive stress field characterization	Reliable HTHF slim-hole submersible pumps
Mitigate induced seismicity / subsidence	Improve resilience of casings to HTHF corrosion
Condensers for high ambient surface temperatures	Optimum HTHF fracture stimulation methods
Use of CO_2 as a circulating fluid for heat exchangers	HTHF logging tools and monitoring sensors
Improve power plant design	HTHF flow survey tools
Technologies & methods to minimize water use	HTHF fluid flow tracers
Predict heat flow and reservoirs ahead of the bit	Mitigation of formation damage, scale and corrosion

able to predict reservoir behaviour with time, to recommend management strategies for prolonged field operation and to minimize potential environmental impacts.

4.6.2 Efficient production of geothermal power, heat and/or cooling

Equipment needed to provide heating/cooling and/or electricity from geothermal wells is already available on the market. However, the efficiency of the different system components can still be improved, and it is even more important to develop conversion systems that more efficiently utilize energy in the produced geothermal fluid at competitive costs. It is basically inevitable that more efficient plants (and components) will have higher investment costs, but the objective would be to ensure that the increased performance justifies these costs. Combined heat and power (CHP) or cogeneration applications provide a means for significantly improving utilization efficiency and economics of geothermal projects, but one of the largest technical barriers is the inability in some cases to fully utilize the thermal energy produced (Bloomquist et al., 2001).

New and cost-effective materials for pipes, casing liners, pumps, heat exchangers and other components for geothermal plants is considered a prerequisite for reaching higher efficiencies.

Another possibility for an efficient type of geothermal energy production is the use of suitable oil fields. There are three types of oil and gas wells potentially capable of supplying geothermal energy for power generation: medium- to high-temperature (>120°C or so) producing wells with a sufficient water cut; abandoned wells due to a high water cut; and geo-pressured brine with dissolved gas. All of these types have been assessed and could be developed depending on the energy market evolution (Sanyal and Butler, 2010). The primary benefit from such a possibility is that the drilling is already in place and can greatly reduce the first costs associated with geothermal project development. However, these savings may be somewhat offset by the need to handle (separate and clean up) multi-phase co-produced fluids, consisting of water, hydrocarbons and other gases.

The potential development of valuable by-products may improve the economics of geothermal development, such as recovery of the condensate for industrial applications after an appropriate treatment, and in some cases recovery of valuable minerals from geothermal brines (such as lithium, zinc, high grade silica and in some cases, gold).

4.6.3 Technological and process challenges in enhanced geothermal systems

EGS require innovative methods, some of which are also applicable to power plants and direct-use projects based on hydrothermal resources. Among these are (Tester et al., 2006):

- Improvement and innovation in well drilling, casing, completion and production technologies for the exploration, appraisal and development of deep geothermal reservoirs (as generalized in Table 4.6).
- Improvement of methods to hydraulically stimulate reservoir connectivity between injection and production wells to attain sustained, commercial production rates. Reservoir stimulation procedures need to be refined to significantly enhance the productivity, while reducing the risk of seismic hazard. Imaging fluid pathways induced by hydraulic stimulation treatments through innovative technology would facilitate this. Technology development to create functional EGS reservoirs independent of local subsurface conditions will be essential.
- Development/adaptation of data management systems for interdisciplinary exploration, development and production of geothermal

reservoirs, and associated teaching tools to foster competence and capacity amongst the people who will work in the geothermal sector.

- Improvement of numerical simulators for production history matching and predicting coupled thermal-hydraulic-mechanical-chemical processes during development and exploitation of reservoirs. In order to accurately simulate EGS reservoirs, computer codes must fully couple flow, chemistry, poro-elasticity and temperature. Development of suitable fully coupled reservoir simulators, including nonlinear deformability of fractures, is a necessity. Modern laboratory facilities capable of testing rock specimens under simulated down-hole conditions of pressure and temperature are also needed.

- Improvement in assessment methods to enable reliable predictions of chemical interactions between geo-fluids and geothermal reservoir rocks, geothermal plants and equipment, enabling optimized, well, plant and field lifetimes.

- Performance improvement of thermodynamic conversion cycles for a more efficient utilization of the thermal heat sources in district heating and power generation applications.

Conforming research priorities for EGS and magmatic resources as determined in Australia (DRET, 2008), the USA, the EU ((ENGINE, 2008), the Joint Programme on Geothermal Energy of the European Energy Research Alliance)[15] and the already-mentioned IPGT (see footnote in Section 4.5.3.2) are summarized in Table 4.6. Successful deployment of the associated services and equipment is also relevant to many conventional geothermal projects.

The required technology development would clearly reflect assessment of environmental impacts including land use and induced micro-seismicity hazards or subsidence risks (see Section 4.5).

The possibility of using CO_2 as a working fluid in geothermal reservoirs, particularly in EGS, has been under investigation. Recent modelling studies show that CO_2 would achieve heat extraction at higher rates than aqueous fluids, and that in fractured reservoirs CO_2 arrival at production wells would occur a few weeks after starting CO_2 injection. A two-phase water-CO_2 mixture could be produced for a few years followed by production of a single phase of supercritical CO_2 (Pruess and Spycher, 2010). In addition, it could provide a means for enhancing the effect of geothermal energy deployment for lowering CO_2 emissions beyond just generating electricity with a carbon-free renewable resource: a 5 to 10% loss rate of CO_2 from the system ('sequestered'), which is equivalent to the water loss rate observed at the Fenton Hill test in the USA, leads to 'sequestration' of 3 MW of coal burning per 1 MW of EGS electricity (Pruess, 2006). As of 2010, much remains to be done before such an approach is technically proven.

15 The Joint Programme on Geothermal Energy (JPGE) is described at: www.eera-set.eu/index.php?index=36.

4.6.4 Technology of submarine geothermal generation

Currently no technologies are in use to tap submarine geothermal resources. However, in theory, electric energy could be produced directly from a hydrothermal vent using an encapsulated plant, like a submarine, containing an organic Rankine cycle (ORC) binary plant, as described by Hiriart and Espíndola (2005). The operation would be similar to other binary-cycle power plants using evaporator and condenser heat exchangers, with internal efficiency of the order of 80%. The overall efficiency for a submarine vent at 250°C of 4% (electrical power generated/thermal power) is a reasonable estimate for such an installation (Hiriart et al., 2010). Critical challenges for these resources include the distance from shore, water depth, grid connection costs, the current cable technology that limits ocean depths, and the potential impact on unique marine life around hydrothermal vents.

4.7 Cost trends[16]

Geothermal projects typically have high upfront investment costs due to the need to drill wells and construct power plants and relatively low operational costs. Operational costs vary depending on plant capacity, make-up and/or injection well requirements, and the chemical composition of the geothermal fluids. Without fuel costs, operating costs for geothermal plants are predictable in comparison to combustion-based power plants that are subject to market fluctuations in fuel prices. This section describes the fundamental factors affecting the levelized cost of electricity (LCOE) from geothermal power plants: upfront investment costs; financing costs (debt interest and equity rates); taxes; operation and maintenance (O&M) costs; decommissioning costs; capacity factor and the economic lifetime of the investment. This section also includes some historic and probable future trends, and presents investment and levelized costs of heat (LCOH) for direct uses of geothermal energy in addition to electric production.

Cost estimates for geothermal installations may vary widely (up to 20 to 25% not including subsidies and incentives) between countries (e.g., between Indonesia, the USA and Japan). EGS projects are expected to be more capital intensive than high-grade hydrothermal projects. Because there are no commercial EGS plants in operation, estimated costs are subject to higher uncertainties.

16 Discussion of costs in this section is largely limited to the perspective of private investors. Chapters 1 and 8 to 11 offer complementary perspectives on cost issues covering, for example, costs of integration, external costs and benefits, economy-wide costs and costs of policies. All values are expressed in USD_{2005}.

4.7.1 Investment costs of geothermal-electric projects and factors that affect them

Investment costs of a geothermal-electric project are composed of the following components: (a) exploration and resource confirmation; (b) drilling of production and injection wells; (c) surface facilities and infrastructure; and (d) the power plant. Component costs and factors influencing them are usually independent from each other, and each component is described in the text that follows, including its impact on total investment costs.

The first component (a) includes lease acquisition, permitting, prospecting (geology and geophysics) and drilling of exploration and test wells. Drilling of exploration wells in greenfield areas is reported to have a success rate of typically about 50 to 60%, and the first exploration well of 25% (Hance, 2005), although other sources (GTP, 2008) reduce the percentage success to 20 to 25%. Confirmation costs are affected by well parameters (mainly depth and diameter), rock properties, well productivity, rig availability, time delays in permitting or leasing land, and interest rates. This first component represents between 10 and 15% of the total investment cost (Bromley et al., 2010) but for expansion projects may be as low as 1 to 3%.

Drilling of production and injection wells (component b) has a success rate of 60 to 90% (Hance, 2005; GTP, 2008). Factors influencing the cost include well productivity (permeability and temperature), well depths, rig availability, vertical or directional design, special circulation fluids, special drilling bits, number of wells and financial conditions in a drilling contract (Hance, 2005; Tester et al., 2006). This component (b) represents 20 to 35% of the total investment (Bromley et al., 2010).

The surface facilities and infrastructure component (c) includes facilities for gathering steam and processing brine: separators, pumps, pipelines and roads. Vapour-dominated fields have lower facility costs since brine handling is not required. Factors affecting this component are reservoir fluid chemistry, commodity prices (steel, cement), topography, accessibility, slope stability, average well productivity and distribution (pipeline diameter and length), and fluid parameters (pressure, temperature, chemistry) (Hance, 2005). Surface facilities and infrastructure costs represent 10 to 20% of the investment (Bromley et al., 2010) although in some cases these costs could be <10%, depending upon plant size and location.

Power plant components (d) include the turbines, generator, condenser, electric substation, grid hook-up, steam scrubbers and pollution abatement systems. Power plant design and construction costs depend upon type (flash, dry steam, binary, or hybrid), location, size (a larger unit and plant size is cheaper per unit of production (Dickson and Fanelli, 2003; Entingh and Mines, 2006), fluid enthalpy (resource temperature) and chemistry, type of cooling cycle used (water or air cooling) and cooling water availability if using water. This component varies between 40 and 81% of the investment (Hance, 2005; Bromley et al., 2010).

Some historic and current investment costs for typical geothermal-electric projects are shown in Figure 4.7. For condensing flash power plants, the current (2009) worldwide range is estimated to be USD_{2005} 1,780 to 3,560/kW_e, and for binary cycle plants USD_{2005} 2,130 to 5,200/kW_e (Bromley et al., 2010).

One additional factor affecting the investment cost of a geothermal-electric project is the type of project: field expansion projects may cost 10 to 15% less than a greenfield project, since investments have already been made in infrastructure and exploration and valuable resource information has been learned from drilling and producing start-up wells (Stefansson, 2002; Hance, 2005).

Most geothermal projects are financed with two different kinds of capital with different rates of return: equity and debt interest. Equity rates can be up to 20% while debt interest rates are lower (6 to 8%). The capital structure of geothermal-electric projects is commonly composed of 55 to 70% debt and 30 to 45% equity, but in the USA, debt lenders usually require 25% of the resource capacity to be proven before lending money. Thus, the early phases of the project often have to be financed by equity due to the higher risk of failure in these phases (Hance, 2005). Real and perceived risks play major roles in setting equity rates and in determining the availability of debt interest financing.

From the 1980s until about 2003-2004, investment costs remained flat or even decreased (Kagel, 2006; Mansure and Blankenship, 2008). Since then project costs have increased (Figure 4.7) due to increases in the cost of engineering, commodities such as steel and cement, and particularly drilling rig rates. This cost trend was not unique to geothermal and was mirrored across most other power sectors.

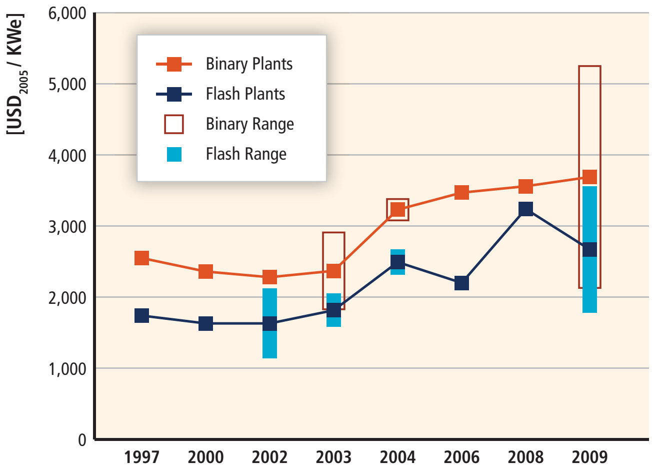


Figure 4.7 | Historic and current investment costs for typical turnkey (installed) geothermal-electric projects (rounded values taken from Kutscher, 2000; Owens, 2002; Stefansson, 2002; Hance, 2005; GTP, 2008; Cross and Freeman, 2009; Bromley et al., 2010; Hjartarson and Einarsson, 2010).

4.7.2 Geothermal-electric operation and maintenance costs

O&M costs consist of fixed and variable costs directly related to the electricity production phase. O&M per annum costs include field operation (labour and equipment), well operation and work-over and facility maintenance. For geothermal plants, an additional factor is the cost of make-up wells, that is, new wells to replace failed wells and restore lost production or injection capacity. Costs of these wells are typically lower than those for the original wells, and their success rate is higher.

Each geothermal power plant has specific O&M costs that depend on the quality and design of the plant, the characteristics of the resource, environmental regulations and the efficiency of the operator. The major factor affecting these costs is the extent of work-over and make-up well requirements, which can vary widely from field to field and typically increase with time (Hance, 2005). For the USA, O&M costs including make-up wells have been calculated to be between US cents$_{2005}$ 1.9 and 2.3/kWh (Lovekin, 2000; Owens, 2002), and Hance (2005) proposed an average cost of US cents$_{2005}$ 2.5/kWh. In terms of installed capacity, current O&M costs range between USD$_{2005}$ 152 and 187/kW per year, depending of the size of the power plant. In New Zealand, O&M costs range from US cents$_{2005}$ 1.0 to 1.4/kWh for 20 to 50 MW$_e$ plant capacity (Barnett and Quinlivan, 2009), which are equivalent to USD$_{2005}$ 83 to 117/kW per year.

4.7.3 Geothermal-electric performance parameters

One important performance parameter is the economic lifetime of the power plant. Twenty-five to thirty years is the common planned lifetime of geothermal power plants worldwide, although some of them have been in operation for more than 30 years, such as Units 1 and 2 in Cerro Prieto, Mexico (since 1973; Gutiérrez-Negrín et al., 2010), Eagle Rock and Cobb Creek in The Geysers, USA (since 1975 and 1979, respectively), and Mak-Ban A and Tiwi A, the Philippines (since 1979) (Bertani, 2010). This payback period allows for refurbishment or replacement of aging surface plants at the end of the plant lifetime, but is not equivalent to the economic lifetime of the geothermal reservoir, which is typically longer, for example, Larderello, The Geysers, Wairakei, Olkaria and Cerro Prieto, among others. In some reservoirs, however, the possibility of resource degradation over time is one of several factors that affect the economics of continuing plant operation.

Another performance parameter is the capacity factor (CF). The evolution of the worldwide average CF of geothermal power plants since 1995 is provided in Table 4.7, calculated from the installed capacity and the average annual generation as reported in different country updates gathered by Bertani (2010). For 2008, the installed capacity worldwide was 10,310 MW$_e$ (10,715 MW$_e$ as of the end of 2009, reduced by the 405 MW$_e$ added in 2009, according to Table X in Bertani (2010)), with an average CF of 74.5%. This worldwide average varies significantly by country and field. For instance, the annual average gross CF in 2008 for Mexico was 84% (data from Gutiérrez-Negrín et al., 2010), while for the USA it was 62% (Lund et al., 2010b) and in Indonesia it was 78% (Darma et al., 2010; data from their Table 1).

Table 4.7 | World installed capacity, electricity production and capacity factor of geothermal power plants from 1995 to 2009 (adapted from data from Bertani (2010).

Year	Installed Capacity (GW$_e$)	Electricity Production (GWh/yr)	Capacity Factor (%)
1995	6.8	38,035	63.5
2000	8.0	49,261	70.5
2005	8.9	55,709	71.2
2008-2009[1]	10.7	67,246	74.5

Note: 1. Installed capacity as of December 2009, and electricity production as of December 2008. Installed capacity in 2008 was 10.3 GW$_e$ and was used to estimate the capacity factor of 74.5% shown here.

The geothermal CF worldwide average increased significantly between 1995 and 2000, with a lower increase in the last decade. This lower increase can be partially explained by the degradation in resource productivity (temperature, flow, enthalpy or combination of these) in geothermal fields operated for decades, although make-up drilling can offset this effect. The complementary explanation is that in the last decade some operating geothermal turbines have exceeded their economic lifetime, and thus require longer periods of shut-down for maintenance or replacement. For instance, out of the 48 geothermal-electric power units of >55 MW$_e$ operating in the world in 2009, 13 (27%) had been in operation for 27 years or more (Bertani, 2010, Table IX). Moreover, 15 new power plants, with a combined capacity of 456 MW$_e$, started to operate during 2008, but their generation contributed for only part of the year (Bertani, 2010, Table X). Typical CFs for new geothermal power plants are over 90% (Hance, 2005; DiPippo, 2008; Bertani, 2010).

4.7.4 Levelized costs of geothermal electricity

The current LCOE for geothermal installations (including investment cost for exploration, drilling and power plant and O&M costs) are shown in Figure 4.8.

The LCOE is presented as a function of CF, investment cost and discount rates (3, 7 and 10%), assuming a 27.5-year lifetime and using the values for worldwide investment and O&M costs shown in Figure 4.7 for 2009 and as presented in Section 4.7.2 (Bromley et al., 2010). As can be expected, the main conclusions from the figure are that the LCOE is proportional to investment cost and discount rate, and inversely proportional to CF, assuming the same average O&M costs. When lower O&M costs can be achieved, as is currently the case in New Zealand (Barnett and Quinlivan, 2009), the resulting LCOE would be proportionally lower. For greenfield projects, the LCOE for condensing flash plants currently ranges from US cents$_{2005}$ 4.9 to 7.2/kWh and, for binary-cycle plants, the LCOE ranges from US cents$_{2005}$ 5.3 to 9.2/kWh, at a CF of 74.5%, a 27.5-year economic design lifetime, and a discount rate of 7% and using the

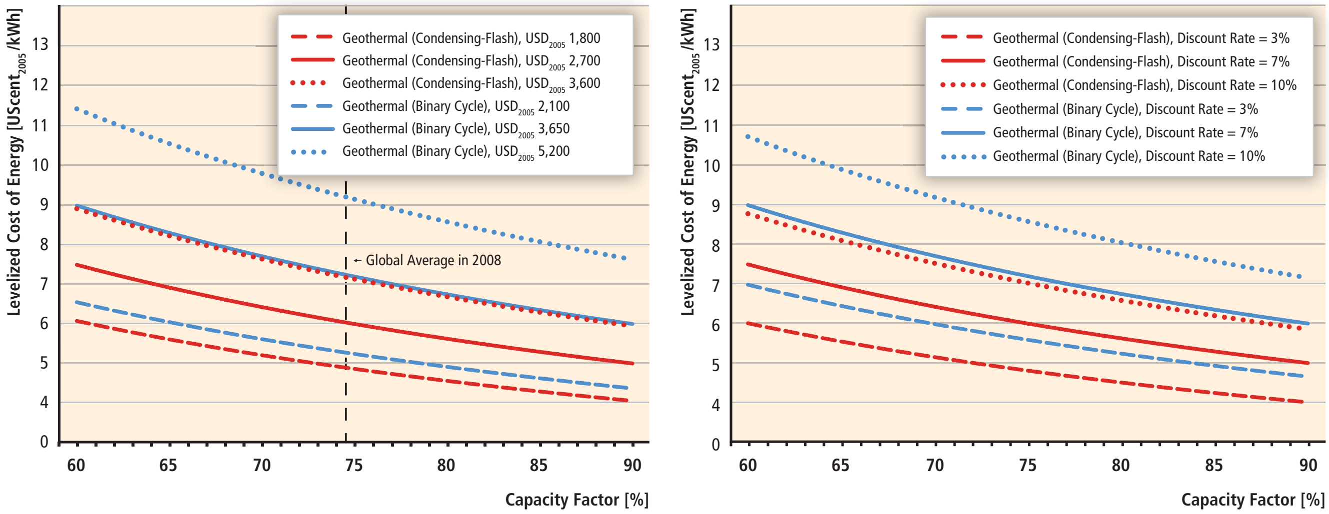


Figure 4.8 | Current LCOE for geothermal power generation as a function of (left panel) capacity factor and investment cost (discount rate at 7%, mid-value of the O&M cost range, and mid-value of the lifetime range), and (right panel) capacity factor and discount rate (mid-value of the investment cost range, mid-value of the O&M cost range, and mid-value of the lifetime range) (see also Annex III).

lowest and highest investment cost, respectively. Achieving a 90% lifetime average CF in new power plants can lead to a roughly 17% lower LCOE (Figure 4.8). The complete range of LCOE estimates, considering variations in plant lifetime, O&M costs, investment costs, discount rates and CFs, can vary from US cents$_{2005}$ 3.1 to 13/kWh for condensing flash plants and from US cents$_{2005}$ 3.3 to 17/kWh for binary plants (see also Annex III and Chapters 1 and 10).

No actual LCOE data exist for EGS, but some projections have been made using different models for several cases with diverse temperatures and depths (Table 9.5 in Tester et al., 2006). These projections do not include projected cost reductions due to future learning and technology improvements, and all estimates for EGS carry higher uncertainties than for conventional hydrothermal resources. The obtained LCOE values for the Massachusetts Institute of Technology EGS model range from US cents$_{2005}$ 10 to 17.5/kWh for relatively high-grade EGS resources (250°C to 330°C, 5-km depth wells) assuming a base case present-day productivity of 20 kg/s per well. Another model for a hypothetical EGS project in Europe considers two wells at 4 km depth, 125°C to 165°C reservoir temperature, 33 to 69 kg/s flow rate and a binary power unit of 1.6 MW$_e$ running with an annual capacity factor of 86%, and obtains LCOE values of US cents$_{2005}$ 30 to 37/kWh (Huenges and Frick, 2010).[17]

4.7.5 Prospects for future cost trends

The prospects for technical improvements outlined in Section 4.6 indicate that there is potential for cost reductions in the near and longer term for both conventional geothermal technology and EGS. Additionally, the future costs for geothermal electricity are likely to vary widely because future deployment will include an increasing percentage of unconventional development types, such as EGS, as mentioned in Section 4.8.

The following estimates are based on possible cost reductions from design changes and technical advancements, relying solely on expert knowledge of the geothermal process value chain. Published learning curve studies for geothermal are limited, so the other major approach to forecasting future costs, extrapolating from historical learning rates, is not pursued here. See Section 10.5 for a more complete discussion of learning curves, including their advantages and limitations.

Foreseeable technological advances were presented in Section 4.6. Those potentially having the greatest impact on LCOEs in the near term are: (a) engineering improvements in design and stimulation of geothermal reservoirs; and (b) improvements in materials, operation and maintenance mentioned in Section 4.6.3 as well as some from Section 4.6.1. These changes will increase energy extraction rates and lead to a better plant performance, and less frequent and shorter maintenance periods, all of which will result in better CFs. With time, more efficient plants (with CFs of 90 and 95%) are expected to replace the older ones still in operation, increasing the average CF to between 80 and 95% (Fridleifsson et al., 2008). Accordingly, the worldwide average CF for 2020 is projected to be 80%, and could be 85% in 2030 and as high as 90% in 2050.

Important improvements in drilling techniques described in Section 4.6.2 are expected to reduce drilling costs. Drilling cost reductions due to increasing experience are also based on historic learning curves for deep oil and gas drilling (Tester et al., 2006). Since drilling costs represent at least between 20 and 35% of total investment cost (Section 4.7.1), and also impact the O&M cost due to the cost of make-up wells, a lower LCOE can be expected as drilling cost decreases. Additionally, an increased success rate for exploration, development and make-up

17 Further assumptions, for example, about O&M costs, lifetime, CFs and the discount rate may be available from the references.

wells is also foreseeable. Nevertheless, these reductions are unlikely to be achieved in the near term, and were not included in projections for LCOE reductions by 2020. Other improvements in exploration, surface installations, materials and power plants mentioned in Sections 4.6.2 and 4.6.3 are likely, and should lead to reduced costs.

Based on those premises, future potential LCOEs were calculated for 2020. For greenfield projects the worldwide average projected LCOE for condensing flash plants with a distribution of investment costs ranges from US cents$_{2005}$ 4.5 to 6.6/kWh and for binary-cycle plants ranges from US cents$_{2005}$ 4.9 to 8.6/kWh, at a CF of 80%, 27.5-year lifetime and discount rate of 7%. Therefore, a global average LCOE reduction of about 7% is expected for geothermal flash and binary plants by 2020.

For projected future costs for EGS, a sensitivity analysis of model variables carried out in Australia obtained near-term LCOE estimates of between AU$ 92 and AU$ 110 per MWh, equivalent to US cents$_{2005}$ 6.3 and 7.5/kWh, which are slightly higher than comparable estimates from Credit Suisse (Cooper et al., 2010). Another model (Sanyal et al., 2007) suggested that the LCOE for EGS will decline with increasing stimulated volume and replication of EGS units, with increasing the maximum practicable pumping rate from a well, and with the reduced rate of cooling of the produced fluid (LCOE increases approximately US cents$_{2005}$ 0.45/kWh per additional degree Celsius of cooling per year), which in turn can be achieved by improving the effectiveness of stimulation by closely spaced fractures (Sanyal, 2010). Tester et al. (2006) suggested that a four-fold improvement in productivity to 80 kg/s per well by 2030 would be possible and that the projected LCOE values would range from US cents$_{2005}$ 3.6 to 5.2/kWh for high-grade EGS resources, and for low-grade geologic settings (180°C to 220°C, 5- to 7-km depth wells) LCOE would also become more economically viable at about US cents$_{2005}$ 5.9 to 9.2/kWh.[18]

18 Further assumptions, for example, about future O&M costs, lifetime, CFs and the discount rate may be available from the references.

4.7.6 Costs of direct uses and geothermal heat pumps

Direct-use project costs have a wide range, depending upon specific use, temperature and flow rate required, associated O&M and labour costs, and output of the produced product. In addition, costs for new construction are usually less than costs for retrofitting older structures. The cost figures given in Table 4.8 are based on a climate typical of the northern half of the USA or Europe. Heating loads would be higher for more northerly climates such as Iceland, Scandinavia and Russia. Most figures are based on cost in the USA (in USD$_{2005}$), but would be similar in developed countries and lower in developing countries (Lund and Boyd, 2009).

Some assumptions for the levelized cost of heat (LCOH) estimates presented in Table 4.8 are mentioned in Annex III. For building heating, assumptions included a load factor of 25 to 30%, investment cost of USD$_{2005}$ 1,600 to 3,900/kW$_{th}$ and a lifetime of 20 years, and for district heating, the same load factor, USD$_{2005}$ 600 to 1,600/kW$_{th}$ and a lifetime of 25 years. Thermal load density (heating load per unit of land area) is critical to the feasibility of district heating because it is one of the major determinants of the distribution network capital and operating costs. Thus, downtown high-rise buildings are better candidates than a single family residential area (Bloomquist et al., 2001). Generally, a thermal load density of about 1.2 x 10^9 J/hr/ha (120,000 J/hr/m^2) is recommended.

The LCOH calculation for greenhouses assumed a load factor of 0.50, and 0.60 for uncovered aquaculture ponds and tanks, with a lifespan of 20 years. Covered ponds and tanks have higher investment costs than uncovered ones, but lower heating requirements.

GHP project costs vary between residential installations and commercial/institutional installations. Heating and/or cooling large buildings lowers the investment cost and LCOH. In addition, the type of installation, closed loop (horizontal or vertical) or open loop using groundwater,

Table 4.8 | Investment costs and calculated levelized cost of heat (LCOH) for several geothermal direct applications (investment costs are rounded and taken from Lund, 1995; Balcer, 2000; Radeckas and Lukosevicius, 2000; Reif, 2008; Lund and Boyd, 2009).

Heat application	Investment cost USD$_{2005}$/kW$_{th}$	LCOH in USD$_{2005}$/GJ at discount rates of		
		3%	7%	10%
Space heating (buildings)	1,600–3,940	20–50	24–65	28–77
Space heating (districts)	570–1,570	12–24	14–31	15–38
Greenhouses	500–1,000	7.7–13	8.6–14	9.3–16
Uncovered aquaculture ponds	50–100	8.5–11	8.6–12	8.6–12
GHP (residential and commercial)	940–3,750	14–42	17–56	19–68

has a large influence on the installed cost (Lund and Boyd, 2009). The LCOH reported in Table 4.8 assumed 25 to 30% as the load factor and 20 years as the operational lifetime. It is worth taking into account that actual LCOH are influenced by electricity market prices, as operation of GHPs requires auxiliary power input. In the USA, recent trends in lower natural gas prices have resulted in poor GHP project economics compared to alternative options for heat supply, and drilling costs continue to be the largest barrier to GHP deployment.

Industrial applications are more difficult to quantify, as they vary widely depending upon the energy requirements and the product to be produced. These plants normally require higher temperatures and often compete with power plant use; however, they do have a high load factor of 0.40 to 0.70, which improves the economics. Industrial applications vary from large food, timber and mineral drying plants (USA and New Zealand) to pulp and paper plants (New Zealand).

4.8 Potential deployment[19]

Geothermal energy can contribute to near- and long-term carbon emissions reductions. In 2008, the worldwide geothermal-electric generation was 67.2 TWh_e (Sections 4.4.1 and 4.7.3) and the heat generation from geothermal direct uses was 121.7 TWh_{th} (Section 4.4.3). These amounts of energy are equivalent to 0.24 EJ/yr and 0.44 EJ/yr, respectively, for a total of 0.68 EJ/yr (direct equivalent method). The IEA (2010) reports only 0.41 EJ/yr (direct equivalent method) as the total primary energy supply from geothermal resources in 2008 (see Chapter 1); the reason for this difference is unclear. Regardless, geothermal resources provided only about 0.1% of the worldwide primary energy supply in 2008. By 2050, however, geothermal could meet roughly 3% of global electricity demand and 5% of the global demand for heating and cooling, as shown in Section 4.8.2.

This section starts by presenting near-term (2015) global and regional deployments expected for geothermal energy (electricity and heat) based on current geothermal-electric projects under construction or planned, observed historic growth rates, as well as the forecast generation of electricity and heat. Subsequently, this section presents the middle- and long-term (2020, 2030, 2050) global and regional deployments, compared to the IPCC AR4 estimate, displays results from scenarios reviewed in Chapter 10 of this report, and discusses their feasibility in terms of technical potential, regional conditions, supply chain aspects, technological-economic conditions, integration-transmission issues, and environmental and social concerns. Finally, the section presents a short conclusion regarding potential deployment.

19 Complementary perspectives on potential deployment based on a comprehensive assessment of numerous model-based scenarios of the energy system are presented in Chapter 10 and Sections 10.2 and 10.3 of this report.

4.8.1 Near-term forecasts

Reliable sources for near-term geothermal power deployment forecasts are the country updates recently presented at the *World Geothermal Congress 2010.* This congress is held every five years, and experts on geothermal development in several countries are asked to prepare and present a paper on the national status and perspectives. According to projections included in those papers, which are based on the capacity of geothermal-electric projects stated as under construction or planned, the geothermal-electric installed capacity in the world is expected to reach 18.5 GW_e by 2015 (Bertani, 2010). This represents an annual average growth of 11.5% between 2010 and 2015, based on the present conditions and expectations of geothermal markets. This annual growth rate is larger than the historic rates observed between 1970 and 2010 (7%, Table 4.4), and reflects increased activity in several countries, as mentioned in Section 4.4.

Assuming the countries' projections of geothermal-electric deployment are fulfilled in the next five years, which is uncertain, the regional deployments by 2015 are shown in Table 4.9. Note that each region has its own growth rate but the average global rate is 11.5%. Practically all the new power plants expected to be on line by 2015 will be conventional (flash and binary) utilizing hydrothermal resources, with a small contribution from EGS projects. The worldwide development of EGS is forecasted to be slow in the near term and then accelerate, as expected technological improvements lower risks and costs (see Section 4.6).

The country updates did not include projections for geothermal direct uses (heat applications, including GHP). Projecting the historic annual growth rate in the period 1975 to 2010 (Table 4.4) for the following five years results in a global projection of 85.2 GW_{th} of geothermal direct uses by 2015. The expected deployments and thermal generation by region are also presented in Table 4.9. By 2015, total electric generation could reach 121.6 TWh/yr (0.44 EJ/yr) while direct generation of heat, including GHP, could attain 224 TWh_{th}/yr (0.8 EJ/yr).

On a regional basis, the forecast deployment for harnessing identified and hidden hydrothermal resources varies significantly in the near term. In Europe, Africa and Central Asia, large deployment is expected in both electric and direct uses of geothermal, while in India and the Middle East, only a growing deployment in direct uses is projected with no electric uses projected over this time frame.

The existing installed capacity in North America (USA and Mexico) of 4 GW_e, mostly from mature developments, is expected to increase almost 60% by 2015, mainly in the USA (from 3,094 to 5,400 MW_e, according to Lund et al. (2010b) and Bertani (2010). In Central America, the future geothermal-electric deployment has been estimated at 4 GW_e (Lippmann, 2002), of which 12% has been harnessed so far (~0.5 GW_e). South American countries, particularly along the

Table 4.9 | Regional current and forecast installed capacity for geothermal power and direct uses (heat, including GHP) and forecast generation of electricity and heat by 2015.

REGION*	Current capacity (2010)		Forecast capacity (2015)		Forecast generation (2015)	
	Direct (GW_{th})	Electric (GW_e)	Direct (GW_{th})	Electric (GW_e)	Direct (TW_{th}/yr)	Electric (TWh_e/yr)
OECD North America	13.9	4.1	27.5	6.5	72.3	43.1
Latin America	0.8	0.5	1.1	1.1	2.9	7.2
OECD Europe	20.4	1.6	32.8	2.1	86.1	13.9
Africa	0.1	0.2	2.2	0.6	5.8	3.8
Transition Economies	1.1	0.08	1.6	0.2	4.3	1.3
Middle East	2.4	0	2.8	0	7.3	0
Developing Asia	9.2	3.2	14.0	6.1	36.7	40.4
OECD Pacific	2.8	1.2	3.3	1.8	8.7	11.9
TOTAL	**50.6**	**10.7**	**85.2**	**18.5**	**224.0**	**121.6**

Notes: * For regional definitions and country groupings see Annex II.

Current and forecast data for electricity taken from Bertani (2010), and for direct uses from Lund et al. (2010a), both as of December 2009. Estimated average annual growth rate in 2010 to 2015 is 11.5% for power and 11% for direct uses. Average worldwide capacity factors of 75% (for electric) and 30% (for direct use) were assumed by 2015.

Andes mountain chain, also have significant untapped—and under-explored—hydrothermal resources (Bertani, 2010).

For island nations with mature histories of geothermal development, such as New Zealand, Iceland, the Philippines and Japan, identified geothermal resources could allow for a future expansion potential of two to five times existing installed capacity, although constraints such as limited grid capacity, existing or planned generation (from other renewable energy sources) and environmental factors (such as national park status of some resource areas) may limit the hydro-thermal geothermal deployment. Indonesia is thought to be one of the world's richest countries in geothermal resources and, along with other volcanic islands in the Pacific Ocean (Papua-New Guinea, Solomon, Fiji, etc.) and the Atlantic Ocean (Azores, Caribbean, etc.) has significant potential for growth from known hydrothermal resources, but is market-constrained in growth potential.

Remote parts of Russia (Kamchatka) and China (Tibet) contain identified high-temperature hydrothermal resources, the use of which could be significantly expanded given the right incentives and grid access to load centres. Parts of other South-East Asian nations and India contain numerous hot springs, inferring the possibility of potential, as yet unexplored, hydrothermal resources.

Additionally, small-scale distributed geothermal developments could be an important base-load power source for isolated population centres in close proximity to geothermal resources, particularly in areas of Indonesia, the Philippines and Central and South America.

4.8.2 Long-term deployment in the context of carbon mitigation

The IPCC Fourth Assessment Report (AR4) estimated a potential contribution of geothermal to world electricity supply by 2030 of 633 TWh/yr (2.28 EJ/yr), equivalent to about 2% of the total (Sims et al., 2007). Other forecasts for the same year range from 173 TWh/yr (0.62 EJ/yr) (IEA, 2009) to 1,275 TWh/yr (4.59 EJ/yr) (Teske et al., 2010).

A summary of the literature on the possible future contribution of RE supplies in meeting global energy needs under a range of GHG concentration stabilization scenarios is provided in Chapter 10. Focusing specifically on geothermal energy, Figure 4.9 (left) presents modelling results for the global supply of geothermal energy in EJ/yr. About 120 different long-term scenarios underlie Figure 4.9 that derive from a diversity of modelling teams, and span a wide range of assumptions for—among other variables—energy demand growth, the cost and availability of competing low-carbon technologies, and the cost and availability of RE technologies (including geothermal energy).

Chapter 10 discusses how changes to some of these variables impact RE deployment outcomes, with Section 10.2.2 providing a description of the literature from which the scenarios have been taken. In Figure 4.9 (left) the geothermal energy deployment results under these scenarios for 2020, 2030 and 2050 are presented for three GHG concentration stabilization ranges, based on the AR4: Baselines (>600 ppm CO_2), Categories III and IV (440 to 600 ppm) and Categories I and II (<440 ppm), all by 2100. Results are presented for the median scenario, the 25th to 75th percentile range among the scenarios, and the minimum and maximum scenario results. Primary energy is provided as direct equivalent, that is, each unit of heat or electricity is accounted for as one unit at the primary energy level.[20]

The long-term projections presented in Figure 4.9 (left) span a broad range. The 25th to 75th percentile ranges of all three scenarios are 0.07

20 In scenario ensemble analyses such as the review underlying Figure 4.9, there is a constant tension between the fact that the scenarios are not truly a random sample and the sense that the variation in the scenarios does still provide real and often clear insights into collective knowledge or lack of knowledge about the future (see Section 10.2.1.2 for a more detailed discussion).

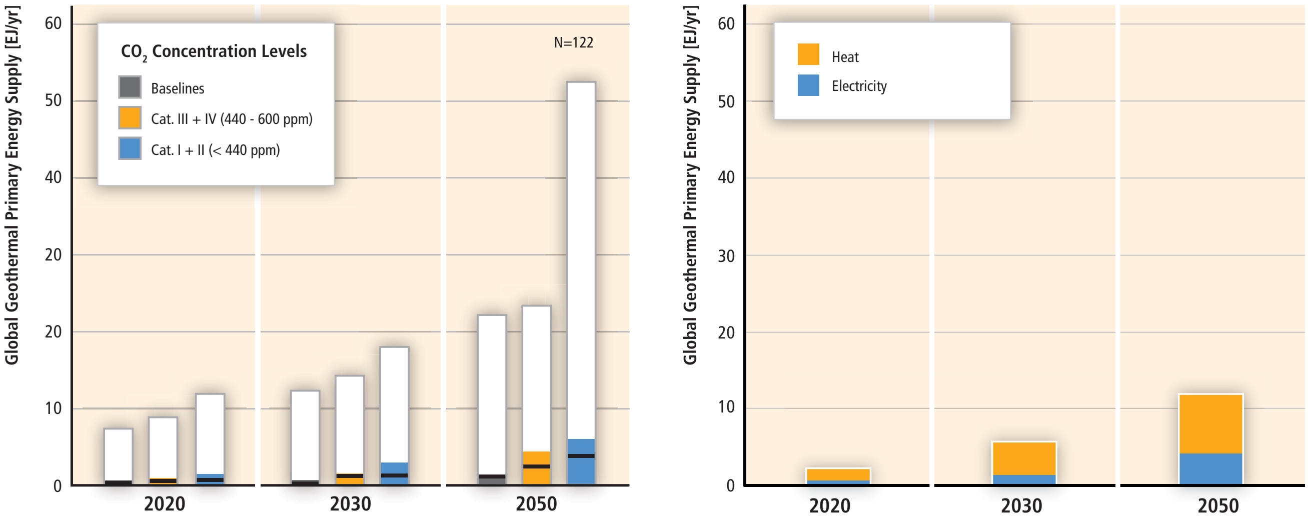


Figure 4.9 | Global primary energy supply of geothermal energy. Left panel: In long-term scenarios (median, 25th to 75th percentile range, and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration level in 2100; the specific number of scenarios underlying the figure is indicated in the right upper corner) (adapted from Krey and Clarke, 2011; see also Chapter 10). Right panel: Estimated in Section 4.8.2 as potential geothermal deployments for electricity and heat applications.

Table 4.10 | Potential geothermal deployments for electricity and direct uses in 2020 through 2050.

Year	Use	Capacity[1] (GW)	Generation (TWh/yr)	Generation (EJ/yr)	Total (EJ/yr)
2020	Electricity	25.9	181.8	0.65	2.01
	Direct	143.6	377.5	1.36	
2030	Electricity	51.0	380.0	1.37	5.23
	Direct	407.8	1,071.7	3.86	
2050	Electricity	150.0	1,182.8	4.26	11.83
	Direct	800.0	2,102.3	7.57	

Note: 1. Installed capacities for 2020 and 2030 are extrapolated from 2015 estimates at 7% annual growth rate for electricity and 11% for direct uses, and for 2050 are the middle value between projections from Bertani (2010) and Goldstein et al. (2011). Generation was estimated with an average worldwide CF of 80% (2020), 85% (2030) and 90% (2050) for electricity and of 30% for direct uses.

to 1.38 EJ/yr by 2020, 0.10 to 2.85 EJ/yr by 2030 and 0.11 to 5.94 EJ/yr by 2050. The scenario medians range from 0.39 to 0.71 EJ/yr for 2020, 0.22 to 1.28 EJ/yr for 2030 and 1.16 to 3.85 EJ/yr for 2050. The medians for 2030 are lower than the IPCC AR4 estimate of 2.28 EJ/yr, which is for electric generation only, although the latter lies in the 25th to 75th percentile range of the most ambitious GHG concentration stabilization scenarios presented in Figure 4.9 (left). Figure 4.9 (left) shows that geothermal deployment is sensitive to the GHG concentration level, with greater deployment correlated with lower GHG concentration stabilization levels.

Based on geothermal technical potentials and market activity discussed in Sections 4.2 and 4.4, and on the expected geothermal deployment by 2015, the projected medians for geothermal energy supply and the 75th percentile amounts of all the modelled scenarios are technically reachable for 2020, 2030 and 2050.

As indicated above, climate policy is likely to be one of the main driving factors of future geothermal development, and under the most favourable policy of CO_2 emissions (<440 ppm) geothermal deployment by 2020, 2030 and 2050 could be higher than the 75th percentile estimates of Figure 4.9, as a simple extrapolation exercise shows. By projecting the historic average annual growth rates of geothermal power plants (7%) and direct uses (11%) from the estimates for 2015 (Table 4.9), the geothermal deployment in 2020 and 2030 would reach the figures shown in Table 4.10 (see also Figure 4.9, right).

By 2050 the projected installed capacity of geothermal power plants would be between 140 GW_e (Bertani, 2010) and 160 GW_e (Goldstein et al., 2011), with one-half of them being of EGS type, while the potential installed capacity for direct uses could reach 800 GW_{th} (Bertani, 2010). Potential deployment and generation for 2050 are also shown in Table 4.10 and Figure 4.9 (right).

The total contribution (thermal and electric) of geothermal energy would be 2 EJ/yr by 2020, 5.2 EJ/yr by 2030 and 11.8 EJ/yr by 2050 (Table 4.10), where each unit of heat or electricity is accounted for as one unit at the primary energy level. These estimates practically double the estimates for the 75th percentile of Figure 4.9, because many of the approximately 120 reviewed scenarios have not included the potential for EGS development in the long term.

Future geothermal deployment may not follow its historic growth rate between 2015 and 2030. In fact, it could be higher (e.g., Krewitt et al., (2009) adopted an annual growth rate of 10.4% for electric deployment between 2005 and 2030), or lower. Yet the results from this extrapolation exercise indicate that future geothermal deployment may reach levels in the 75 to 100% range of Figure 4.9 rather than in the 25 to 75% range.

Note that for 2030, the extrapolated geothermal electric generation of 380 TWh/yr (1.37 EJ/yr) is lower than the IPCC AR4 estimate (633 TWh/yr or 2.28 EJ/yr).

Teske et al. (2010) estimate the electricity demand to be 25,851 to 27,248 TWh/yr by 2020, 30,133 to 34,307 TWh/yr in 2030 and 37,993 to 46,542 TWh/yr in 2050. The geothermal share would be around 0.7% of global electric demand by 2020, 1.1 to 1.3% by 2030 and 2.5 to 3.1% by 2050.

Teske et al. (2010) project the global demand for heating and cooling by 2020 to be 156.8 EJ/yr, 162.4 EJ/yr in 2030 and 161.7 EJ/yr in 2050. Geothermal would then supply about 0.9% of the total demand by 2020, 2.4% by 2030 and 4.7% by 2050.

The high levels of deployment shown in Figure 4.9 could not be achieved without economic incentive policies to reduce GHG emissions and increase RE. Policy support for research and development (subsidies, guarantees and tax write-offs for initial deep drilling) would assist in the demonstration and commercialization of some geothermal technologies such as EGS and other non-conventional geothermal resource development. Feed-in tariffs with confirmed geothermal prices, and direct subsidies for district and building heating would also help to accelerate deployment. The deployment of geothermal energy can also be fostered with drilling subsidies, targeted grants for pre-competitive research and demonstration to reduce exploration risk and the cost of EGS development. In addition, the following issues are worth noting.

Resource potential: Even the highest estimates for the long-term contribution of geothermal energy to the global primary energy supply (52.5 EJ/yr by 2050, Figure 4.9, left) are well within the technical potentials described in Section 4.2 (118 to 1,109 EJ/yr for electricity and 10 to 312 EJ/yr for heat, see Figure 4.2) and even within the upper range of hydrothermal resources (28.4 to 56.8 EJ/yr). Thus, technical potential is not likely to be a barrier in reaching more ambitious levels of geothermal deployment (electricity and direct uses), at least on a global basis.

Regional deployment: Future deployment of geothermal power plants and direct uses are not the same for every region. Availability of financing, water, transmission and distribution infrastructure and other factors will play major roles in regional deployment rates, as will local geothermal resource conditions. For instance, in the USA, Australia and Europe, EGS concepts are already being field tested and deployed, providing advantages for accelerated deployment in those regions as risks and uncertainties are reduced. In other rapidly developing regions in Asia, Africa and South America, as well as in remote and island settings where distributed power supplies are needed, factors that would affect deployment include market power prices, population density, market distance, electricity and heating and cooling demand.

Supply chain issues: No mid- or long-term constraints to materials supply, labour availability or manufacturing capacity are foreseen from a global perspective.

Technology and economics: GHP, district heating, hydrothermal and EGS methods are available, with different degrees of maturity. GHP systems have the widest market penetration, and an increased deployment can be supported by improving the coefficient of performance and installation efficiency. The direct use of thermal fluids from deep aquifers, and heat extraction using EGS, can be increased by further technical advances in accessing and fracturing geothermal reservoirs. Combined heat and power applications may also be particularly attractive for EGS and low-temperature hydrothermal resource deployment. To achieve a more efficient and sustainable geothermal energy supply, subsurface exploration risks need to be reduced and reservoir management needs to be improved by optimizing injection strategies and avoiding excessive depletion. Improvement in energy utilization efficiency from cascaded use of geothermal heat is an effective deployment strategy when markets permit. Evaluation of geothermal plants performance, including heat and power EGS installations, needs to take into account heat quality of the fluid by considering the useful energy that can be converted to electric power. These technological improvements will influence the economics of geothermal energy.

Integration and transmission: The site-specific geographic location of conventional hydrothermal resources results in transmission constraints for future deployment. However, no integration problems have been observed once transmission issues are solved, due to the base-load characteristic of geothermal electricity. In the long term, fewer transmission constraints are foreseen since EGS developments are less geography-dependent, even though EGS' resource grades can vary substantially on a regional basis.

Social and environmental concerns: Concerns expressed about geothermal energy development include the possibility of induced local seismicity for EGS, water usage by geothermal power plants in arid regions, land subsidence in some circumstances, concerns about water and soil contamination and potential impacts of facilities on scenic quality and use of natural areas and features (such as geysers) that might otherwise be used for tourism. Sustainable practices will help protect natural thermal features valued by the community, optimize water and land use and minimize adverse effects from disposal of geothermal fluids and gases, induced seismicity and ground subsidence.

4.8.3 Conclusions regarding deployment

Overall, the geothermal-electric market appears to be accelerating compared to previous years, as indicated by the increase in installed and planned power capacity. The gradual introduction of new technology improvements, including EGS, is expected to boost the deployment, which could reach 140 to 160 GW_e by 2050 if certain conditions are met. Some new technologies are entering the field demonstration phase to evaluate commercial viability (e.g., EGS), or the early investigation stage to test practicality (e.g., utilization of supercritical temperature and submarine hydrothermal vents). Power generation with binary plants permits the possibility of producing electricity in countries that have no high-temperature resources, though overall costs are higher than for high-temperature resources.

Direct use of geothermal energy for heating and cooling is competitive in certain areas, using accessible, hydrothermal resources. A moderate increase can be expected in the future development of such resources for direct use, but a sustained compound annual growth is expected with the deployment of GHP. Direct use in lower-grade regions for heating and/or cooling in most parts of the world could reach 800 GW_{th} by 2050 (Section 4.8.2). Cogeneration and hybridization with other thermal sources may provide additional opportunities.

Evidence suggests that geothermal supply could meet the upper range of projections derived from a review of about 120 energy and GHG-reduction scenarios. With its natural thermal storage capacity, geothermal is especially suitable for supplying base-load power. Considering its technical potential and possible deployment, geothermal energy could meet roughly 3% of global electricity demand by 2050, and also has the potential to provide roughly 5% of the global demand for heating and cooling by 2050.

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