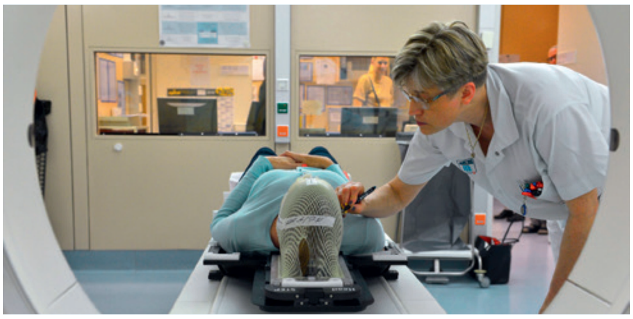
Nuclear Power

for Sustainable Development

7 AFFORDABLE AND CLEAN ENERGY

Ensure access to affordable, reliable, sustainable and modern energy for all



SUSTAINABLE DEVELOPMENT GOALS

IAEA

60 Years

Atoms for Peace and Development

Nuclear Power

for Sustainable Development

Access to affordable, reliable and clean energy is crucial for achieving sustainable development goals, from eradicating poverty through to advancing health and education, facilitating industrial development and reducing greenhouse gas emissions. Nuclear power — with other technologies — can provide the energy to ultimately achieve high living standards, good health, a clean environment and a sustainable economy.

ENERGY IN SUSTAINABLE DEVELOPMENT

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs – Brundtland Commission*[1]

Since the 1992 United Nations Conference on Environment and Development in Rio de Janeiro, there has been a growing recognition of the role of energy in achieving the goals of sustainable development. This role was at first reflected indirectly and implicitly in Agenda 21 from the Rio Conference and in the UN Millennium Development Goals for 2000–2015. More recently, the critical contribution of energy has been acknowledged explicitly, starting from the ninth meeting of the UN Commission on Sustainable Development (CSD-9, 2001)[2] and later in the Secretary-General's 2011 Sustainable Energy for All Vision Statement. This culminated in August 2015 with the UN Summit on Sustainable Development adopting a set of 17 global Sustainable Development Goals (SDGs), which include a dedicated goal on energy (SDG 7):

> *Ensure access to affordable, reliable, sustainable and modern energy for all*[3]

Realizing SDG7 is essential for achieving the full set of SDGs as illustrated in Figure 1.

Fig. 1. Ensuring access to affordable, reliable, sustainable and modern energy for all (SDG7) is central to achieving all 17 SDGs.

NUCLEAR POWER AND SUSTAINABLE DEVELOPMENT

A range of energy technologies can support the realization of SDG7 — including the specific target to ‘ensure universal access to affordable, reliable and modern energy services [by 2030]’ (Target 7.1) — and ultimately all the SDGs. A comparative approach is required to assess the compatibility of each technology option with the SDGs (IAEA 2016a).

Nuclear power provides nearly one third of low carbon electricity globally

Large scale deployment of nuclear power in the 1970s and 1980s has made it a key contributor to low carbon electricity worldwide (Fig. 2). Although a slowdown in construction of new plants since the 1990s contributed to a subsequent decline in the share of low carbon electricity, nuclear power has still saved 1.5–2 billion tonnes of greenhouse gas (GHG) emissions every year since 1990, or about 60 billion tonnes since 1970. Nuclear power has also provided access to affordable and reliable electricity, with its baseload operation contributing to economic performance, grid stability and reliability.

Nuclear power can help to provide electricity access to growing urban populations worldwide

The future contribution of nuclear power to sustainable development will mainly depend on choices made by governments, the capacity to deploy new plants given long planning and construction times, as well as issues of acceptance. On the one hand, many existing nuclear power plants (NPPs) are expected to be retired over the next few decades, potentially exacerbating the declining share of low carbon electricity (Fig. 2). On the other hand, nuclear power could support increasing electricity access for rapidly growing urban populations in developing countries: urban population is expected to grow by over 1 billion by 2030, while the total rural population remains stable (Fig. 3a). In urban locations larger NPPs can capitalize on existing infrastructure, while emerging technologies such as small modular reactors may suit niche remote or rural applications.

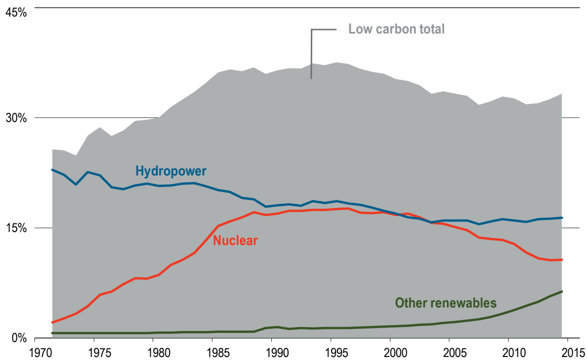


Fig. 2. Share of low carbon technology in global electricity generation.[4]

AFFORDABLE AND RELIABLE POWER FOR THE SDGs

Access to affordable and reliable forms of energy, including electricity, is essential for improving livelihoods

Challenges to achieving SDG7

The global community faces major challenges in ensuring access to affordable, reliable, sustainable and modern energy for all. More than 1 billion people currently lack access to electricity, with over 1 billion more requiring access by 2030 (Fig. 3a). Many also struggle with unaffordable or unreliable energy.

In addition, very few have access to energy that is truly sustainable: one illustration is high carbon dioxide (CO_2) emissions per unit of final energy consumed (Fig. 3b). Overcoming these challenges requires technologies that are more compatible with supplying affordable, reliable, sustainable and modern energy for all.

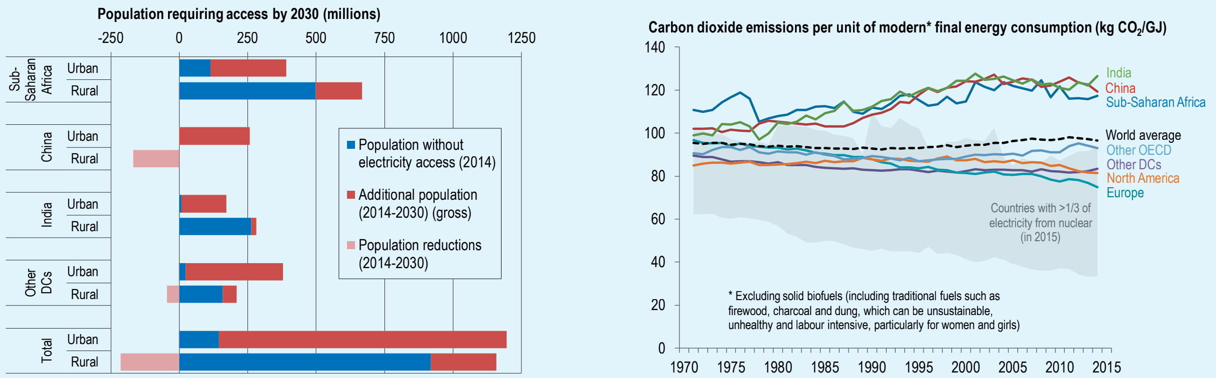


Fig. 3. (a) Population in developing countries (DCs) requiring electricity access by 2030,[5] *(b) CO_2 emissions per unit of final energy.*[4, 6]

and fostering development, thus contributing indirectly to achieving the SDGs (Fig. 1). The affordability of electricity is closely related to the cost of generation, together with the so-called 'system costs', which include costs of delivering electricity and maintaining a reliable grid. While costs are important, the ultimate price of electricity also depends on market structure and competition, the regulatory environment, subsidies and taxes.

With the right support nuclear power can provide affordable electricity for development

Figure 4 shows the costs of generating 1 megawatt-hour (MW·h) of electricity levelized over the lifetime of the power plant for new large scale electricity technologies. The cost ranges reflect regional and national differences related primarily to market structure and resource endowments. As illustrated, nuclear power is among the cheapest generation technologies, once in operation. It should also be noted that these estimates represent direct private costs and exclude social costs or benefits from externalities, such as avoided CO_2 emissions.

Similar to other capital intensive technologies, the generation cost of an NPP depends on the cost of capital (for instance, the costs in Figure 4 would be lower with a discount rate reflecting the social cost of capital, and higher with a rate reflecting a risky investment environment). These high capital costs also mean that the levelized cost of an NPP is sensitive to construction lead times and capacity factor variations. Furthermore, the financing of an NPP presents its own unique challenges with each plant costing US \$2–8 billion (or US \$1800–6200/kW)[8], requiring an investment environment that provides certainty, including via innovative contractual arrangements and well-designed public support. On the other hand, poorly targeted policy and market design can stifle necessary investment.

Nuclear power is a source of reliable baseload electricity

A reliable electricity supply is supported by baseload and dispatchable generators (such as nuclear, hydro, coal and gas) and storage, which can respond to changes in electricity load or contribute to frequency regulation. Nuclear generation also operates at a high capacity factor (about 90%) providing continuous reliable power. In contrast, intermittent generation sources, such as wind and solar, place additional requirements on the electricity system for load balancing and backup: the system costs for these technologies can be 3–10 times higher than for other generators, increasing sharply with market share (Fig. 5). However, despite these higher costs there may be cases where integrating small scale intermittent renewables can be less costly than expanding the transmission and distribution grid.[7]

SUSTAINABLE AND MODERN POWER

Access to sustainable and modern energy implies the provision of energy services in a way that preserves natural resources and biodiversity, and protects habitats and ecosystems. For achieving the SDGs this includes climate change mitigation, protection of ecosystems on land and in water, and avoiding the depletion of resources.

Is nuclear power a suitable option for climate change mitigation and protection of ecosystems?

Nuclear power, along with hydro and wind power, emits the lowest quantity of GHGs per unit of electricity on a life cycle basis (see Box overleaf and IAEA 2016b). As Figure 6

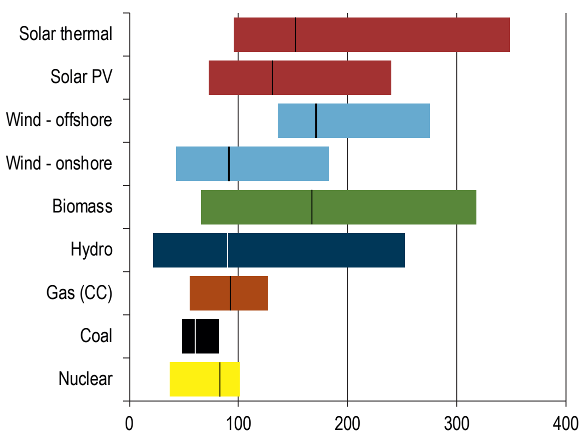


Fig. 4. Levelized costs of electricity generation (US $_{2013}$/MW·h) at 7% market discount rate.[8, 9] Bars indicate low, median and high estimates.

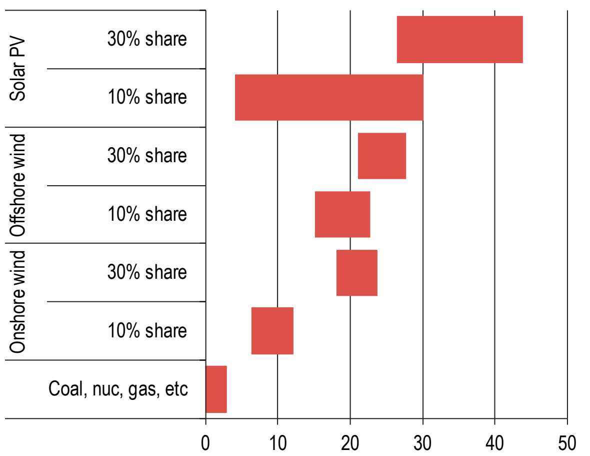


Fig. 5. Illustrative system costs in US \$/MW·h (including backup, balancing and grid).[8-10] Estimates are highly system and site specific, with costs potentially higher for specific configurations, or lower where there is excess capacity.

shows, GHG emissions are substantially higher for fossil technologies, including those with carbon capture and storage (CCS). The low carbon baseload power from nuclear can complement intermittent renewable options to ensure a reliable low carbon electricity supply.

Nuclear, hydro and wind power are among the lowest greenhouse gas emitters

For ecosystems, the main life cycle impacts from power production occur through acidification (deposition of acid chemicals, leading to impairment of freshwater, fisheries, soil, forests/vegetation) and eutrophication (increased concentrations of chemical nutrients, leading to excessive algal growth, and severe impairments to water quality). On a life cycle basis, fossil technologies have the greatest acidification potential, whereas nuclear power is among the technologies with the lowest acidification potential per unit of energy produced (Fig. 7).[12] The main sources of eutrophication from fossil based technologies originate from coal mining and transport, power plant waste treatment and emissions from combustion. In contrast, the eutrophication potential of NPPs is estimated to be among the lowest for all technologies.

Nuclear power has a very small impact on ecosystems compared to alternatives

How large is the water, land and resources footprint of nuclear power?

Power production competes for land and water with other activities, including agriculture, industry, the provision of clean water and sanitation, and environmental amenity. In general, sustainable energy technologies are those requiring lower water and land inputs. However, linkages between different SDGs mean that an integrated approach, such as the IAEA's Climate-Land-Energy-Water (CLEW) framework, may provide additional insights into synergies between land (and food), energy and water in specific development activities.

Nuclear power, like other thermal technologies, relies on substantial water inputs for cooling during operation

Life cycle assessment: comparing the sustainability of energy technologies

Some energy technologies, such as fossil fuel power plants, consume resources and generate emissions during operation. For others, such as solar photovoltaics, most of the emissions and resource use occur in the manufacturing process.

Life cycle assessment provides a consistent way to compare the full impact of producing a final product, in this case a kilowatt-hour (kW·h) of electricity, with different technologies. This approach accounts for all the impacts over the life of each technology, i.e. from 'cradle to grave'.

The life cycle impacts from **normal operation** of electricity technologies are explored over the next few pages. For all technologies, the impact of **accidents** outside normal operation can vary widely and arise across the life cycle (e.g. accidents in mining, manufacturing, transportation, construction, operation, decommissioning). Fatalities from accidents are discussed on page 6.

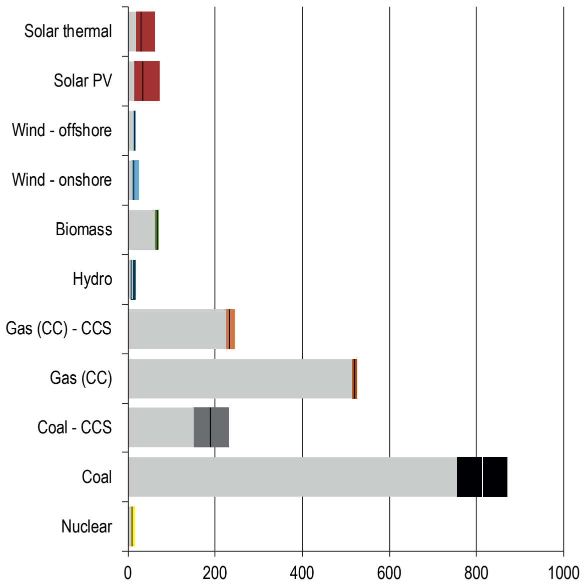


Fig. 6. Life cycle GHG emissions (in g CO_2-equivalent/kW·h) of electricity technologies, 2010.[9, 11] Coloured ranges show regional low, average and high estimates, which can also vary considerably from site to site.

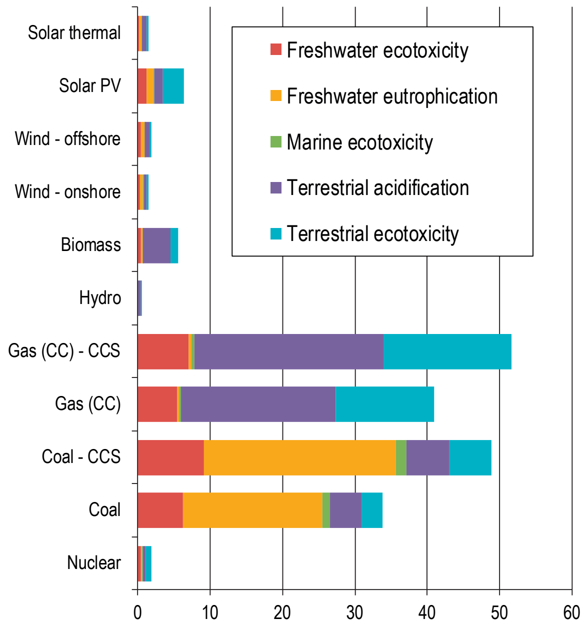


Fig. 7. Life cycle ecosystem impact (in species-year affected per 1000 TW·h) of electricity technologies, 2010 global average.[9, 11]

(Fig. 8), although a distinction should be made between water withdrawn (and later returned to its source) and water consumed (through evaporation, transpiration or incorporation into a product). Thermal plants with once-through cooling withdraw significantly more water than plants employing cooling towers, but consume (evaporate) less. Hydropower, biomass and solar thermal technologies consume significant quantities of water (with a large range for hydro and biomass based on topography, crop selection and climate).

The land footprint of nuclear facilities is among the lowest across the power technologies compared in Figure 9. Only combined cycle gas turbines (CCGTs) and offshore wind have a smaller average footprint. Coal, biomass and solar thermal technologies have the highest land requirements.

Nuclear power uses similar amounts of water as other thermal power plants (e.g. coal), but has very small land and resource requirements

In addition to sustainable land and water use, the preservation of natural resources (and reduction of material inputs) is central to the concept of sustainable development. In the power sector, aside from fuels, the major input materials comprise cement and metals (aluminium, copper, iron), as compared in Figure 10. Additional resources for specific technologies may include: rare earth metals for gearless wind turbines; special metals, silver and glass for CSP and PV[9]; and geological CO_2 storage sites for CCS.

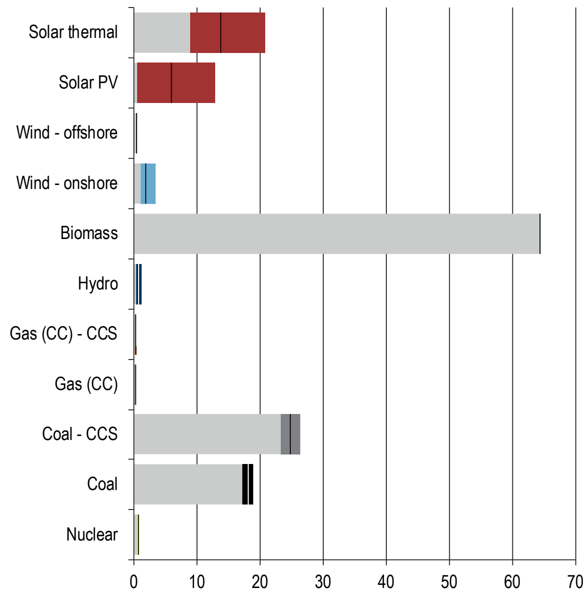


Fig. 9. Life cycle land occupation (m²-year/MW·h) required for the production of electricity.[9, 11] Coloured ranges show regional low, average and high estimates, which can also vary considerably from site to site.

The lowest requirements for structural materials are seen for fossil generators, nuclear and some hydropower plants. By contrast, concentrated solar tower technologies and inefficient hydropower installations have high material requirements. Although the fossil technologies are small consumers of structural materials, their total material use is much higher due to their fuel consumption.

While material requirements are relatively low for nuclear power, an additional consideration is the availability

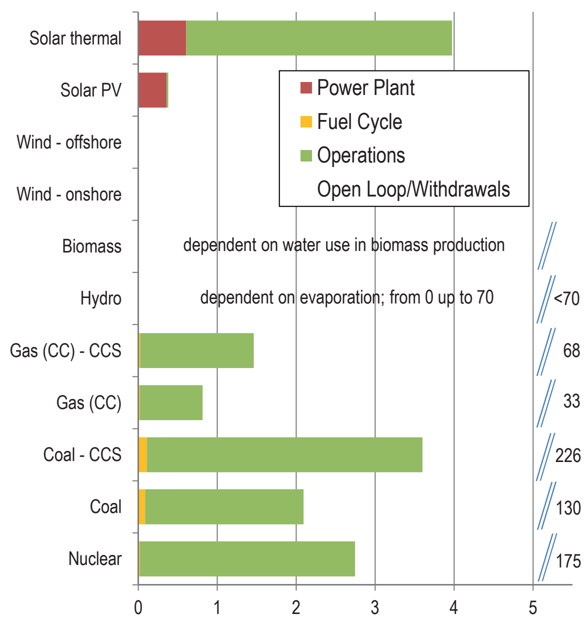


Fig. 8. Life cycle water consumption (in m³/MW·h) for electricity technologies.[13] Water used in operations (dark green) refers to cooling towers, while light green shows withdrawals for the alternative of once-through cooling.

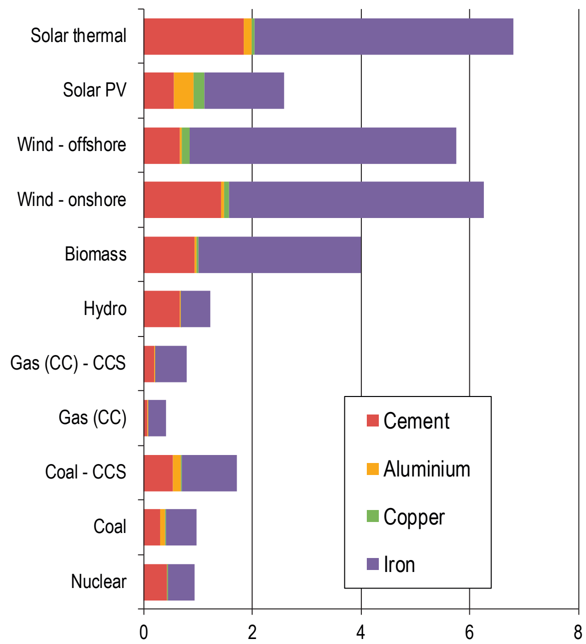


Fig. 10. Life cycle structural material requirements (g/kW·h) for electricity technologies, 2010 global average.[9, 11]

of uranium. Recent estimates of uranium resources available at a cost below US $130/kg U imply around 100 years of supply at current consumption rates, using a once-through fuel cycle, in which only a fraction of the energy content of the fuel is exploited (NEA/IAEA 2014). Using fast reactors in a closed fuel cycle could increase the resource lifetime to 6000 years.

HUMAN HEALTH AND NUCLEAR POWER

Good health and well-being are indirectly linked to SDG7. Medical facilities need affordable and reliable energy, whilst switching to sustainable and modern energy sources reduces death and illness from pollution. The World Health Organization estimates that outdoor and indoor particulate pollution from fuel combustion cause close to 7 million premature deaths annually.[11]

For the power sector, the main health effects arise from toxic emissions (such as metal leaching from coal mines) and particulate emissions from combustion. Figure 11 compares the impact of different technology options on human health measured in disability adjusted life years (DALYs), i.e. the number of years lost due to ill-health, disability or early death, per unit of electricity produced. Fossil generation options impose the largest burden on health per unit of output, with technologies employing carbon capture performing particularly poorly due to their lower efficiency, use of toxic solvents, and the release of compounds in the capture process. Nuclear power is among the best performers in terms of health, with solar, wind and hydro having lower impacts.

Nuclear power has low impacts on health, but maintaining and improving safety is crucial

An additional consideration for health is the impact of accidents. Accidents can be triggered by natural hazards, technological failures and human errors. A comprehensive assessment of severe accidents from different energy chains for 1970–2008 shows high fatality rates per unit of electricity output from coal.[14] Renewables, modern nuclear plants and hydropower in OECD countries have lower fatality rates (whereas hydro dam failures in non-OECD countries have led to numerous casualties). Despite the low rates for nuclear power, the potential exists for major accidents. Unlike with most other technologies, these accidents may cause substantial fatalities.[15] Major accidents also have wider social and health impacts when communities are forced to relocate. The accidents at Chernobyl and Fukushima (IAEA 2015) highlighted the importance of continuing efforts to improve safety (see below).

NUCLEAR POWER CHALLENGES AND OPPORTUNITIES

Compared to other electricity technologies, nuclear power has unique features that create additional opportunities and challenges for sustainable development. Nuclear technology also plays a role in sustainable development outside the energy domain, notably in the provision of medicine, food and clean water.[16]

Intergenerational challenges of nuclear power

While the use of all energy technologies has repercussions for future generations, nuclear energy imposes a requirement to isolate radioactive waste from the biosphere for millennia, despite possible technology options to reduce the quantity of waste. Key concerns for intergenerational equity include ensuring the safety and security of disposal facilities (in a way that does not require active measures by future generations) and ensuring a fair distribution of costs between present and future generations.[17]

Public perception

Irrespective of the economic and environmental performance of nuclear power, its contribution to the SDGs will ultimately be determined by political and public support. The general public has little direct experience with complex nuclear technologies, creating a situation where the benefits of nuclear power are unclear and risks can be exaggerated. To maintain and increase public support, decision makers need to

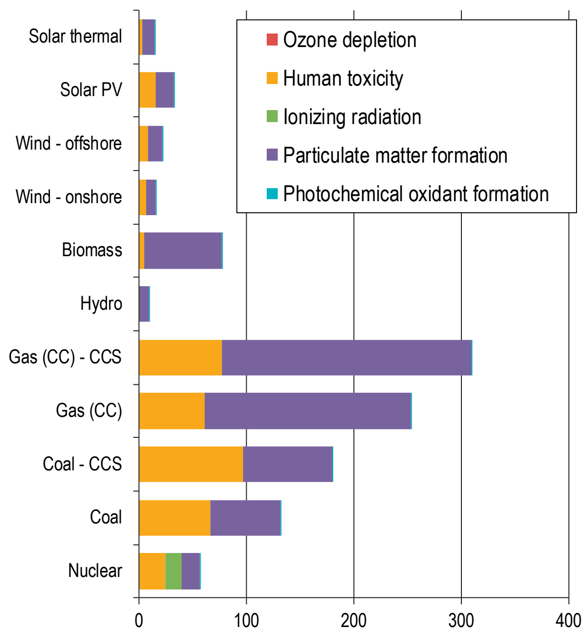


Fig. 11. Life cycle human health impact (in disability adjusted life years (DALY) per TW·h) of electricity technologies, 2010 global average.[9, 11]

better understand the factors governing perceptions of risk, provide tailored information, and ensure that transparent and participative processes lead to fair and consistent decision making.

Safety and non-proliferation

These public concerns about nuclear power are in many cases related to issues of safety, security and proliferation. While there has been a long term trend towards increasing safety in the nuclear industry, the Fukushima Daiichi accident in March 2011 prompted additional efforts. These include national, regional and international near term and long term actions, including the IAEA Action Plan on Nuclear Safety (2011), to evaluate and mitigate the safety vulnerabilities of NPPs to external hazards.

Nuclear power must not only be safe but also used exclusively for peaceful purposes, supported through safeguards measures (including activities of the IAEA and others) to build confidence and foster technical co-operation.

Overall, the emergence of inherently safe reactor designs (with passive safety features), improved methods of waste reduction and resource management with closed fuel cycles, and technologies that cannot be used to divert fissile material to weapons development could substantially address a number of the challenges unique to nuclear power.

OUTLOOK FOR NUCLEAR POWER AND THE SDGs

Several future scenarios for global nuclear power deployment have been explored by international agencies, non-governmental organizations and industry, as illustrated in Figure 12. The IAEA's (2017a) high estimate is similar to the International Energy Agency's (IEA) and World Energy Council's (WEC) ambitious climate change mitigation scenarios, reflecting nuclear power's low GHG emissions. Achieving these levels of deployment translates into construction rates of new plants close to the peak seen in the early 1980s, but sustained for decades. While global industrial and economic capacity is considerably larger today, this level of deployment will necessitate strong government support. Other IEA and WEC scenarios envisage moderate growth in nuclear capacity, above the IAEA's low estimate. An extreme possible future, in which the global community forgoes any role for nuclear in the SDGs, is reflected in the Greenpeace [r]evolution scenario.

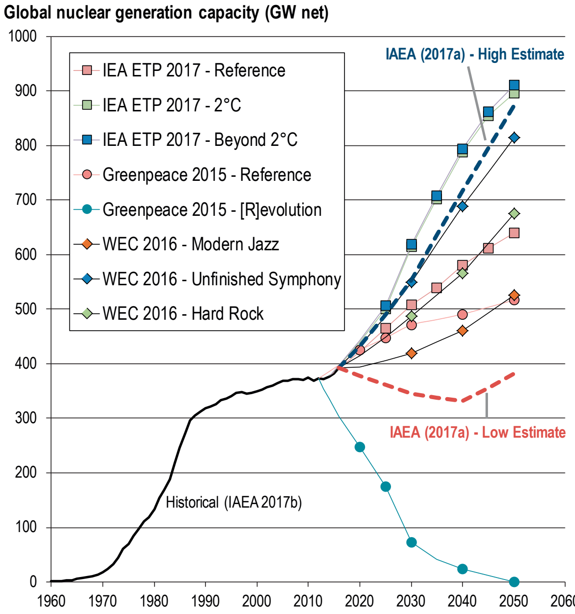


Fig. 12. Selected scenarios of global nuclear generation capacity, including the IEA's Energy Technology Perspectives (ETP), and the latest World Energy Council (WEC) and Greenpeace scenarios.[18-20]

Nuclear power can provide access to affordable, reliable and clean energy to support the SDGs

These scenarios illustrate the possible future global role of nuclear power, although there is uncertainty regarding technology and policy developments. Despite this uncertainty, the potential to contribute to SDG7 and hence other SDGs is clear given that nuclear power is a source of reliable, relatively low cost and low carbon electricity, compared to other generation technologies. Nuclear power production also has low land requirements, and imposes a relatively small burden on ecosystems and health. In addition, it is well suited to providing electricity for growing urban populations (increasing by over one billion by 2030), contributing directly to 'ensur[ing] universal access to affordable, reliable and modern energy services [by 2030]' (SDG7 Target 7.1). Nonetheless, the challenges to realising the potential of nuclear power, such as financing high capital costs, addressing public concerns and managing safety, waste disposal and proliferation, are not insignificant.

Ultimately, as acknowledged at CSD-9, the 'choice of nuclear energy rests with countries',[2] and will depend on how the opportunities and challenges of nuclear power correspond with national priorities for sustainable development.

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8. Based on IEA/NEA (2015), *Projected Costs of Generating Electricity*, 2015 Edition, International Energy Agency/Nuclear Energy Agency, Organisation for Economic Co-operation and Development.
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440+

reactors in operation

11%

of world's electricity

>30%

of world's low-carbon electricity

Department of Nuclear Energy

International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600-0; Fax: +43 1 2600-7

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