WP/16/148

IMF Working Paper

Climate Mitigation in China:
Which Policies Are Most Effective?

by Ian Parry, Baoping Shang, Philippe Wingender, Nate Vernon, and Tarun Narasimhan

INTERNATIONAL MONETARY FUND

 WP/16/148

IMF Working Paper

Fiscal Affairs Department

Climate Mitigation in China: Which Policies Are Most Effective?

Prepared by Ian Parry, Baoping Shang, Philippe Wingender, Nate Vernon and Tarun Narasimhan

Authorized for distribution by Michael Keen and James Daniel

July 2016

Abstract

For the 2015 Paris Agreement on climate change, China pledged to reduce the carbon dioxide (CO_2) intensity of GDP by 60–65 percent below 2005 levels by 2030. This paper develops a practical spreadsheet tool for evaluating a wide range of national level fiscal and regulatory policy options for reducing CO_2 emissions in China in terms of their impacts on emissions, revenue, premature deaths from local air pollution, household and industry groups, and overall economic welfare. By far, carbon and coal taxes are the most effective policies for meeting environmental and fiscal objectives as they comprehensively cover emissions and have the largest tax base.

JEL Classification Numbers: Q48, Q54, Q58, H23

Keywords: Paris Agreement, carbon tax, China, air pollution, coal tax, emissions trading, incidence, welfare effects

Authors' E-Mail Addresses: iparry@imf.org; bshang@imf.org; pwingender@imf.org; nvernon@imf.org; and tnarasimhan@imf.org

Contents **Page**

Appendices

Appendix Table

EXECUTIVE SUMMARY

This paper develops a practical spreadsheet tool for evaluating a wide range of national level fiscal and regulatory policy options for reducing energy-related carbon dioxide (CO_2) emissions in China. The model, which captures fuel use in the power, transport, and other energy sectors out to 2030, with fuel responsiveness parameterized to empirical literature, estimates the impacts of mitigation policies on CO_2 emissions, revenue, premature deaths from local air pollution, household and industry groups, as well as their overall domestic welfare gains (domestic environmental benefits less welfare costs).

By far, the two most effective policies for reducing CO_2 emissions, raising revenue, and reducing local air pollution are carbon taxes (taxes on the carbon content of fuel supply) or a tax on coal use and either of these policies would be a straightforward extension of the existing resource tax (an excise tax currently applied to various minerals). In the baseline case, CO_2 taxes rising progressively from RMB 32.5 ($5)[1] per ton in 2017 to RMB 455 ($70) per ton by 2030 (applied to all fossil fuels or just coal) reduce CO_2 emissions by around 30 percent relative to baseline levels in 2030, raise revenues of over 3.0 percent of GDP, and reduce fossil fuel air pollution deaths by 33 percent in 2030, saving 3.7 million lives during 2017–30. More modest policy scenarios, with prices rising RMB 15 ($2.50) per ton in 2017 to RMB 227.5 ($35) achieve around two-thirds or more of these environmental and fiscal benefits.

An Emissions Trading System (ETS) applied to the power sector and large industrial CO_2 sources has about 60 percent of the environmental and (with auctioned allowances) about 50 percent of the fiscal impact of the carbon and coal tax policies, when assuming emissions price trajectories. A wide range of other policies—including taxes on road fuels and electricity and incentives for renewable generation, energy efficiency in different sectors, and lower emissions intensity of power generation—by themselves have much lower environmental benefits than the ETS and relatively small fiscal benefits.

The more aggressive carbon/coal tax scenarios yield annual net economic benefits approaching 5 percent of GDP in 2030 (due to the large domestic health benefits)—before even counting the global climate benefits. Net benefits under the equivalently scaled ETS are 2.2 percent of GDP, while they are less than 0.5 percent of GDP under almost all of the other policies. The environmental and fiscal benefits of the aggressive carbon/coal tax scenarios however are still well short of those generated by a policy that prices all environmental costs efficiently from a domestic and global perspective.

The relative ranking of different mitigation instruments (the main focus here) is generally robust to different scenarios for uncertain parameters, though inevitably the absolute impacts of individual policies are subject to significant uncertainty (e.g., due to uncertainty over future energy prices and fuel price responsiveness).

A carbon or coal tax imposes a disproportionately large burden on low income households—50 and 25 percent larger relative to their consumption for the first and second income deciles

---

[1] In this paper and its accompanying spreadsheet all prices and results are reported in constant 2015 prices.

compared with the tenth (top) income decile. However, recycling about 10 percent of the tax revenues can mitigate adverse impacts on the bottom two deciles, for example through reduced social security contributions and increased welfare and social spending (areas where China has been lagging relative to advanced and other middle income countries). An ETS with auctioned allowances is somewhat more regressive than carbon and coal taxes, and dramatically more regressive if allowances are freely allocated (with rents accruing to owners of capital).

A carbon or coal tax also imposes a relatively larger cost in industries most closely associated with traditional growth engines such as heavy manufacturing and construction. It also has a disproportionately smaller effect on services and labor-intensive industries which are less reliant on energy and have higher value added ratios. Notably, exporting sectors do not bear a disproportionate share of the tax burden when compared to other sectors in China. While costs would increase in comparison to producers in other countries without a carbon tax, these results suggest that mitigating fiscal measures to provide some support would not be overly costly.

Given the planned introduction of a nationwide ETS in 2017, possibilities for combining it with a carbon tax to ensure all emissions are subject to some form of pricing are worth exploring. This type of comprehensive carbon pricing addresses not only the negative externalities from pollution and promotes more sustainable and green growth, but can also support China's effort to rebalance its economy towards services and consumption-led growth.

I. INTRODUCTION

Over 190 countries submitted greenhouse gas (GHG) emission reduction pledges—so-called "Intended Nationally Determined Contributions" (INDCs)—for the December 2015 Paris Agreement on climate change.[2] The centerpiece of China's INDC is to:

- Achieve the peaking of carbon dioxide (CO_2) emissions around 2030 (making best efforts to peak early);
- Lower the CO_2 intensity of GDP by 60–65 percent from the 2005 level by 2030; and
- Raise the share of non-fossil fuels in primary energy (11 percent in 2014) to around 20 percent.[3]

INDCs are not legally binding (there are no penalties for non-compliance), however all countries are required to report (every two years starting in 2020) progress on INDCs, subject to a common external verification procedure, and to submit updated INDCs every five years, which are expected to be progressively more stringent. Like China, India also has an emissions intensity target, though for other large emitters, INDCs take the form of total emissions targets (Table 1).

[2] UNFCCC (2015).

[3] China's INDC also pledges to expand forest coverage, though this is beyond the paper's scope. Non-CO_2 greenhouse gases are also beyond our scope (and are not in China's INDC targets): in 2012 methane and nitrous oxide emissions were 19 and 6 percent respectively as large as CO_2 emissions (World Bank 2016).

Most previous assessments of CO_2 mitigation possibilities in China have focused on the technical feasibility of alternative fuels, new technologies, and future pathways at the industry and national level (see Appendix 1). While providing valuable information on the possible evolution of the energy system, it is important to look well beyond engineering analyses and consider the specific policy actions needed to achieve emissions goals through changes in producer and consumer behavior and to quantitatively evaluate different policy options across a broad range of metrics of concern to policymakers. This information helps policymakers understand the tradeoffs in policy choices, provides guidance on how to move forward on and update emissions pledges, and is needed for communicating the case for policy reform to stakeholders.

Table 1. Emissions Pledges Submitted for the 2015 Paris Agreement: Large Emitting Countries/Regions

Country/ region	Main mitigation pledge	Share of global emissions, 2012[a]
China	CO_2 peaking around 2030, lower CO_2 intensity of GDP 60-65%.	25.9
US	Reduce GHGs to 26-28% below 2005 levels by 2025.	16.0
EU	Reduce GHGs 40% below 1990 levels by 2030.	11.9
India	Reduce GHG intensity of GDP 33-35% below 2005 level by 2030.	6.2
Russia	Reduce GHGs 25-30% below 1990 levels by 2030.	5.2
Japan	Reduce GHGs 25% below 2005 levels by 2030.	3.9
Korea	Reduce GHGs 37% below baseline in 2030.	1.9
Canada	Reduce GHGs 30% below 2005 levels by 2030.	1.7
Brazil	Reduce GHGs 37% below 2005 levels by 2025.	1.4
Mexico	Reduce GHGs 25% below baseline in 2030.	1.4
Indonesia	Reduce GHGs 29% below baseline in 2030.	1.4
Australia	Reduce GHGs 26-28% below 2005 levels by 2030.	1.2

Note: [a] Refers to energy-related CO_2.

Sources: UNFCCC (2015), EIA (2016).

There is a bewildering array of alternative, national-level CO_2 mitigation instruments, and combinations of those instruments, including:

- An emissions trading system (ETS), which China is slated to adopt in 2017 for power sector, large industrial, and domestic aviation CO_2 emissions [4] (in total about half of energy-related CO_2);

- A carbon tax, taken here to mean a tax on the carbon content of all fossil fuel supply;

- Taxes on individual energy products such as coal, road fuels, electricity;

- Increased subsidies for renewables;

- Policies to reduce the CO_2 intensity of power generation; and

- Policies to increase the energy efficiency of electricity-using capital, vehicles, and other energy equipment.

From a purely economic perspective, carbon pricing—applied to all emissions, with a predictable price aligned to environmental objectives, and with revenues used productively—would ideally form the centerpiece of mitigation policy (e.g., Farid and others, 2016). But there are practical reasons (e.g., containing increases in energy prices) why policymakers may initially prefer a more limited form of carbon pricing, perhaps in combination with other instruments. Nevertheless, to make sound choices, policymakers need quantitative information on the following.

First, the effectiveness of different instruments at reducing CO_2 emissions, under alternative stringencies for those instruments and various plausible scenarios for the baseline evolution of the energy system (prior to policy changes).

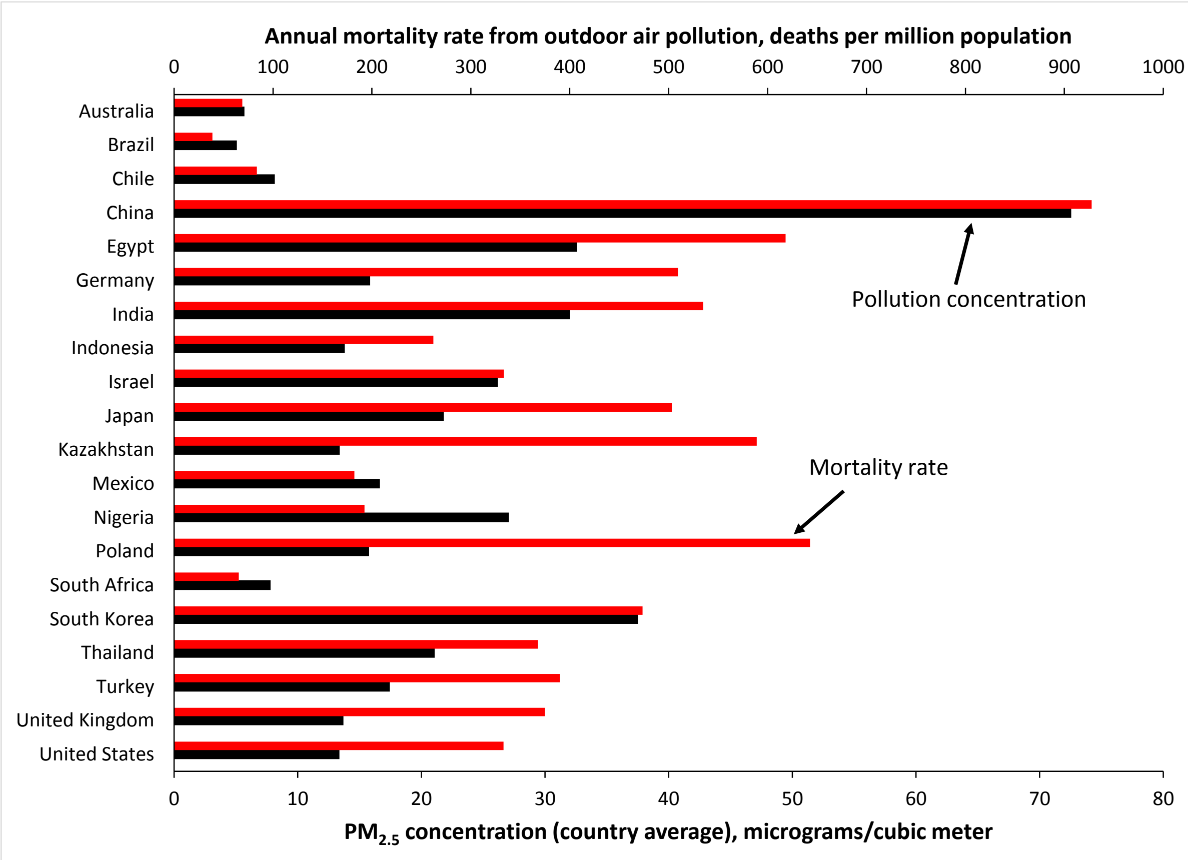
Second, the cost of mitigation policies on the economy, which is important to contain, not only for the policies' sake, but also for enhancing the prospects that policies are sustained and strengthened over time.

Third, the domestic public health impacts of policies, which are a very major concern given that local outdoor air pollution prematurely killed an estimated 0.9 people per 1,000 of the population in China 2010, or 1.2 million in total. Mortality rates, and average air pollution concentrations are much higher in China than in other selected countries (Figure 1). Although other measures (e.g., requirements for emissions control technologies) are being taken to reduce local air pollution from power generation, carbon mitigation policies could play an important complementary role to the extent they reduce coal use, especially beyond the power sector.

---

[4] See http://carbon-pulse.com/14353.

Figure 1. Outdoor Air Pollution Mortality Rates and Pollution Concentrations, Selected Countries, 2010



Notes: $PM_{2.5}$ is fine particulate matter (with diameter up to 2.5 micrometers) which is respirable and therefore most harmful to human health. Pollution concentrations are averages of regional concentrations (measured by satellite data) weighted by regional population shares. The mortality data is air pollution deaths (from fossil fuels and other sources) estimated in the Global Burden of Disease project, divided by country population.

Sources: Brauer and others (2012), IHME (2013), IMF (2016).

Fourth, *fiscal* impacts from emissions charges, which are potentially large given the relatively high dependency of the economy on coal. Coady and others (2015) estimate that full pricing for (global and domestic) environmental costs in China would have raised revenues of several percent of GDP in 2015.

Fifth, impacts on energy prices and the resulting *burdens on industry and household groups*, as this can critically influence the political acceptability of policy reform and compensation levels potentially needed for vulnerable groups.

This paper develops a practical spreadsheet tool [5] for evaluating the above types of policies against environmental, fiscal, and economic metrics. The main caveat is the inevitable uncertainty over key parameters (e.g., determining future emissions trends and the responsiveness of fuel use to policies), underscoring the importance of checking the robustness of policy comparisons.

The paper first describes the analytical framework for the spreadsheet model and policy scenarios with parameterization details provided in an Appendix. The main policy comparisons and sensitivity analyses are then presented. The following section provides some flavor of the distributional incidence of carbon pricing across household and industry groups. A final section summarizes the main implications for policy.

II. ANALYTICAL FRAMEWORK

A full accounting of the factors governing current and future energy use in China would require a numerical simulation model with considerable detail on a wide spectrum of existing and emerging technologies across the energy system, while also balancing demand and supply across markets for fuel, energy capital of different vintages, regions, and periods. Such models exist for a limited number of countries including China (see Appendix 1). However, often these models are not constructed to compare a broad range of mitigation instruments and do not always provide transparent intuition on the key factors determining the impact of policies or the sensitivity of results to uncertain parameters and changing economic conditions. They also require extensive data and time-consuming calibration that typically precludes their use by users outside of the teams producing them.

However, a great deal about environmental, fiscal, and economic impacts can still be learned from an aggregate-level (or 'reduced form') model parameterized such that energy projections and the responsiveness of energy products and emissions to policy is roughly consistent with that implied by far more disaggregated (or 'structural') models or empirical evidence. The model should contain the features most essential for comparing a wide range of economy-wide and sectoral policies including: distinguishing the main energy sectors (e.g., electricity, transport), fuel use within those sectors and trends (e.g., income growth) affecting future fuel use; distinguishing changes in energy efficiency from changes in the use of energy-consuming products; and the main environmental impacts (CO_2 and local air emissions). Because the purpose here is not to inform about how policies affect particular technologies, the turnover of energy capital, and regional energy markets, additional disaggregation is not needed. Instead, the purpose is to provide a practicable spreadsheet tool that easily accommodates policy modifications (e.g., to meet more stringent INDCs), alternative assumptions (e.g., for fuel price elasticities or future energy demand), and regular data updating, while linking to both a broader input/output model to indicate impacts of higher energy costs on manufacturing and service industries and household consumption data to indicate distributional impacts.

This section therefore develops and describes a multi-period model of fuel use in the power, road transport, and 'other energy' sectors (the latter representing an aggregation of direct fuel

[5] The tool is available online at www.imf.org/environment.

use by households and industry) and the price responsiveness of these fuels.[6] Each sector in the baseline case is described below, with notation summarized in Table 2, followed by a discussion of policy scenarios.

Table 2. Model Notation

Symbol	Description[a]
Fossil fuels	
p_t^i	Consumer price of fossil fuel i
τ_t^i	Excise tax for fossil fuel i (including any carbon charge)
$\hat{p}_t^i$	Pre-tax price (or supply cost) of fossil fuel i
Power sector	
Y_t^E	Electricity consumption/production
U_t^E	Use of electricity-consuming products/capital (not used in the parameterization)
h_t^E	Electricity consumption rate per unit of U_t^E (not used in the parameterization)
p_t^E	Consumer price of electricity
υ^E	Income elasticity of demand for electricity-using products
η^{UE}	Demand elasticity for electricity-consuming products with respect to energy costs
α^E	Annual rate of improvements in efficiency of electricity-using capital
η^{hE}	Elasticity of energy efficiency with respect to electricity costs
θ_t^{Ei}	Share of power generation from fuel i
g_t^i	Cost of generating a unit of electricity using fuel i
$\tilde{\epsilon}^{Ei}$	Conditional own-price demand elasticity for fuel i (from switching to other fuels)
F_t^{Ei}	Use of fuel i in electricity generation
ρ_t^{Ei}	Productivity of generation by fuel i
$\alpha^{\rho i}$	Annual rate of improvement in the productivity of generation by fuel i
k_t^{Ei}	Non-fuel unit cost of generation for fuel i
s_t^{EREN}	Generation subsidy for renewables
k_t^{ET}	Unit transmission costs for electricity
τ_t^E	Excise tax on electricity use (zero in the benchmark)
Transport sector	
F_t^{Ti}	Use of transportation fuel i (gasoline or diesel)
U_t^{Ti}	km driven by vehicles with fuel type i (not used in the parameterization)
h_t^{Ti}	Fuel use per vehicle km driven (not used in the parameterization)
υ^{Ti}	Income elasticity of demand for km driven in vehicle type i

[6] The approach avoids a lot of technical detail on, and derivations from, underlying household preferences over goods and firm production technologies.

	η^{UTi}	Elasticity of km driven in type i vehicles with respect to own per km fuel cost
	α^{hTi}	Annual decline in consumption rate of fuel i due to improving fuel economy
	η^{hTi}	Elasticity of consumption rate of fuel i with respect to fuel price
Other energy sector		
	F_t^{Oqi}	Use of fuel i by user group q (large or small users) in the other energy sector
	U_t^{Oqi}	Group q's use of other energy products consuming fuel i (not used in the parameterization)
	h_t^{Oqi}	Consumption rate for fuel i in other energy products used by group q (not used in the parameterization)
	v^{Oi}	Income elasticity of demand for other energy products using fuel i
	η^{UOi}	Demand elasticity for other energy products using fuel i with respect to fuel costs
	α^{hOi}	Annual decline in consumption rate of fuel i in other energy products due to improving efficiency
	η^{hOi}	Elasticity of consumption rate of fuel i in other energy products with respect to fuel price
Additional notation (including from Appendix C)		
	GDP_t	Gross domestic product
	$CO2_t$	Nationwide CO_2 emissions from fossil fuels
	μ^{CO2i}	CO_2 emissions factor for fuel i, or tons of CO_2 emitted per unit of fuel use
	REV_t	Revenue from energy taxes
	$MORT_t$	Mortality (number of premature deaths) from air pollution
	m_t^{Ei}	Air pollution mortality per unit of fuel i used in electricity sector
	m_t^{Ti}	Air pollution mortality per unit of fuel i used in transport sector
	m_t^{Oi}	Air pollution deaths per unit of fuel i used in other energy sector
	$VMORT_t$	Value per premature mortality from air pollution
	Γ_t^i	Distortion between social and private cost for fuel i (domestic environmental costs less taxes)
	β_t^i	Congestion and other km-related externalities associated with road fuel type i

Notes: [a] Subscript *t* denotes a value in time period *t*.

A. Energy Sectors

A discrete time period model is used where $t = 0...\bar{t}$ denotes a particular year. 0 is the current year, or more precisely, the most recent year for which data is available, while $\bar{t}$ is the last year of the projection period, taken to be 2030, China's target year for meeting its INDC (see above). Fossil fuels are first discussed, followed by how these and alternative fuels are used in the power, road transport, and other energy sectors.[7]

[7] Cross-price effects across the three sectors are not modelled as they are likely small for the time horizon due to products being poor substitutes for one another (e.g., higher prices for transport vehicles will have a minimal effect on the demand for fuels for space heating).

(i) Fossil fuels

Five fossil fuel products are distinguished—coal, natural gas, gasoline, road diesel and an aggregate of non-road oil products (e.g., for domestic aviation, petrochemicals)—where these fuels, indexed by i, are denoted by *COAL*, *NGAS*, *GAS*, *DIES*, and *OIL,* respectively. The consumer fuel price at time t, denoted p_t^i, is:

$$p_t^i = \tau_t^i + \hat{p}_t^i \qquad (1)$$

In (1), τ_t^i is the tax on fuel i including any excise or carbon charge applied to fuels, but not value added tax (VAT)[8]. $\hat{p}_t^i$ is the pre-tax fuel price or supply cost which is exogenous to the model perfectly elastic (for the most part, a reasonable longer run approximation). For fuels used in more than one sector, pre-tax prices and any taxes are taken to be the same across users in different sectors. All prices, for fuels and other products, are expressed in real (constant yuan) terms.

The model assumes full pass through of fuel prices into higher prices for electricity and other energy products consumed by households, which may ultimately be a reasonable approximation as China is in the midst of de-regulating the energy sector. In markets with regulated prices, it can be difficult to pin down how much of a new tax will be absorbed in losses for state owned enterprises as opposed to being passed forward in higher prices (though presumably most is passed forward).[9]

(ii) Power sector

Demand for electricity

Residential, commercial, and industrial electricity uses are aggregated into one economy-wide demand for electricity in year t, denoted Y_t^E,[10] and determined as follows:

$$Y_t^E = \left(\frac{U_t^E}{U_0^E} \cdot \frac{h_t^E}{h_0^E}\right) \cdot Y_0^E \qquad (2a)$$

$$\frac{U_t^E}{U_0^E} = \left(\frac{GDP_t}{GDP_0}\right)^{\upsilon^E} \cdot \left(\frac{h_t^E p_t^E}{h_t^E p_0^E}\right)^{\eta^{UE}} \qquad (2b)$$

$$\frac{h_t^E}{h_0^E} = (1+\alpha^E)^{-t} \cdot \left(\frac{p_t^E}{p_0^E}\right)^{\eta^{hE}} \qquad (2c)$$

---

[8] VAT effectively applies only to fuels consumed at the household level and, moreover, does little to reduce consumption of those fuels as it raises the price of all consumer goods by the same proportion (rather than raising the price of fuels relative to other consumer goods).

[9] The taxes discussed below might be viewed as an effective rate, equal to the nominal rate times the fraction of the tax that is passed forward.

[10] Disaggregation is not needed for the policy analysis as this does not consider taxes differentiated by type of electricity user.

In equation (2a), which infers the economy-wide demand for electricity, U_t^E represents usage of electricity-consuming products or capital, implicitly equal to the stock of electricity-using capital times the average intensity (e.g., fraction of the day) with which this capital is used. h_t^E is the electricity consumption rate (e.g., kWh per unit of capital usage), or the inverse of energy efficiency. Electricity consumption in a future year therefore differs from that in the current year due to proportionate changes in product usage and in energy consumption rates.

In equation (2b), product usage increases as (real) gross domestic product, denoted GDP_t, expands over time. υ^E denotes the (constant) income elasticity of demand for electricity-using products (i.e., the percent increase in use of these products per one percent increase in GDP) and implicitly incorporates any structural trends from broader rebalancing of the economy (see below). Product usage also varies inversely with proportionate changes in the cost of electricity per unit of use, which equals the user electricity price p_t^E times electricity consumption per unit of use. $\eta^{UE} < 0$ is the (constant) elasticity of demand for use of electricity-consuming products with respect to energy costs (i.e., the percent reduction in use per one-percent increase in unit electricity costs). A policy to increase energy efficiency without affecting the electricity price will therefore lead to increased usage of electricity-consuming products, offsetting some (albeit a minor portion) of the energy savings from greater efficiency—this is known as the 'rebound effect' (e.g., Gillingham and others, 2016).

In equation (2c), the electricity consumption rate declines (given other factors) at a fixed annual rate of $\alpha^E \geq 0$, reflecting autonomous technological improvements in energy efficiency. And higher electricity prices increase energy efficiency, implicitly through advancing adoption of more efficient technologies: η^{hE} is the elasticity of the energy consumption rate with respect to energy prices.

Note, from (2a–2c) that absolute data on U_t^E and h_t^E is not needed to implement the model.

The assumption of constant income and price elasticities, for this and other sectors, is common in the literature, at least at a given point in time. The notation also implies that elasticities do not vary across different periods, which may be reasonable when policies are introduced gradually and fully anticipated so that households and firms have ample time to adjust, but less reasonable for unanticipated and rapid policies, for which longer run responses, when capital stocks can turn over, significantly exceed shorter run responses. However, reducing the size of nearer-term behavioral response parameters in the spreadsheet model to implicitly reflect lagged adjustments does not really affect the main policy conclusions from the analysis.[11]

Mix of power generation fuels

Power generation fuels are classified into three carbon-containing fuels—coal, natural gas, and oil—and three non-carbon fuels—nuclear, hydro, and (non-hydro) renewables (wind, solar, biofuels)—where the latter three fuels are denoted by i = *NUC*, *HYD*, and *REN*. The share of

---

[11] Explicitly modelling dynamic capital adjustments would require a far more complex numerical simulation model, defeating the purpose of the flexible spreadsheet tool developed here.

electricity generated by fuel i at time t, denoted θ_t^{Ei}, and is negatively related to its per unit generation cost at time t, denoted g_t^i, and positively to the unit generation costs for other fuels as follows:

$$\theta_t^{Ei} = \theta_0^{Ei}\left\{\left(\frac{g_t^i}{g_0^i}\right)^{\tilde{\varepsilon}^{Ei}} + \sum_{j\neq i}\theta_0^{Ej}\left[1-\left(\frac{g_t^j}{g_0^j}\right)^{\tilde{\varepsilon}^{Ej}}\right]\Big/\sum_{l\neq j}\theta_0^{El}\right\} \tag{3}$$

where i, j, l = *COAL*, *NGAS*, *OIL*, *NUC*, *HYD*, *REN*. $\tilde{\varepsilon}^{Ei} < 0$ is the 'conditional' own-price elasticity of generation from fuel i with respect to generation cost. Conditional here (indicated by the ~) means the elasticity reflects the percent reduction in use of fuel i due to switching from that fuel to other generation fuels, for each percent increase in generation cost for fuel i, conditional on a given amount of electricity (generated from all fuels). The size of the conditional generation cost elasticity is moderately smaller than that of the full generation cost elasticity—the latter would also incorporate reduced demand for all generation fuels as higher electricity prices lower electricity demand. And generation cost elasticities are larger than corresponding fuel price elasticities as an increase in all (fuel and non-fuel) generation costs has a bigger impact on reducing generation from a particular fuel than an increase in fuel costs alone (see Appendix C).

According to equation (3) the generation share for fuel i is decreasing in its own generation cost and increasing in the generation cost of other fuels. In the latter case, the increase in generation share for fuel i is the reduction in generation share for fuel $j \neq i$ times the (initial) share of i in generation from all fuel alternatives to j.[12]

Use of fossil fuel i in power generation at time t, denoted F_t^{Ei}, is given by:

$$F_t^{Ei} = \frac{\theta_t^{Ei}\cdot Y_t^E}{\rho_t^{Ei}} \tag{4}$$

Fuel use equals the generation share times total electricity output and divided by ρ_t^{Ei}, which is the productivity of fuel use, that is, electricity generated per unit of F_t^{Ei}.

The total supply of power generation in each period is assumed equal to the total demand for electricity.

Prices and costs

Unit generation costs are given by:

$$g_t^{Ei} = \frac{p_t^i + k_t^{Ei}}{\rho_t^{Ei}}, \qquad \text{for } i = COAL,\ NGAS,\ OIL; \tag{5a}$$

---

[12] This is a neutral assumption implying, for example, that other generation fuels are scaled up in proportion as a coal tax reduces coal use. In practice, proportionate increases for nuclear and renewables might be greater than for hydro, though what matters for our purposes is the total increase in non-carbon fuels (rather than its composition between nuclear, renewables, and hydro).

$$g_t^{Ei} = \frac{k_t^{Ei}}{\rho_t^{Ei}} - s_t^{Ei}, \qquad \text{for } i\text{=}NUC, HYD, REN; \; s_t^i = 0 \text{ for } i\text{= } NUC, HYD \tag{5b}$$

$$\rho_t^{Ei} = (1+\alpha^{\rho i})^t \rho_0^{Ei} \tag{5c}$$

Here k_t^{Ei} denotes capital, labor and other non-fossil fuel costs. In (5a), unit generation costs for fossil fuels decline over time with productivity improvements (increases in ρ_t^{Ei}) which are assumed to reduce fuel and non-fuel costs by the same proportion. Similarly in (5b) productivity improvements lower generation costs, from non-fossil fuels. And renewables receive a subsidy of s_t^{EREN} per unit of generation (subsidies for other generation fuels are taken to be zero). In (5c), productivity of generation by fuel i potentially increases over time at rate $\alpha^{\rho i} \geq 0$ per year due to better production technologies and retirement of older, less efficient plants from the fleet.

Finally:

$$p_t^E = \sum_i q_t^{Ei} \theta_t^{Ei} + k_t^{ET} + \tau_t^E \tag{6}$$

The consumer price of electricity is the product of the generation shares and the per unit generation costs summed over generation fuels, plus unit transmission costs, k_t^{ET}, and any excise tax on electricity consumption, τ_t^E (zero in the baseline). As mentioned above, upstream taxes on fuel supply will be fully passed forward in higher electricity prices, implying an equivalency between taxing the carbon content of power generation fuels and taxing emissions at the point of combustion—the model does not allow for the possibility of reducing CO_2 emissions at the point of combustion through carbon capture and storage technologies, given the high carbon prices needed for these technologies to be viable.

(ii) Road transport sector

In the road transport sector, two vehicle classes are distinguished according to their fuel type, gasoline or diesel, denoted by *i* = *GAS* and *DIES* respectively—the former represents automobiles and motorbikes while the latter trucks and buses. Analogous to equations (1a)-(1c), gasoline and diesel fuel demand at time *t*, denoted F_t^{Ti} is given by

$$F_t^{Ti} = \left(\frac{U_t^{Ti}}{U_0^{Ti}} \cdot \frac{h_t^{Ti}}{h_0^{Ti}}\right) F_0^{Ti} \tag{7a}$$

$$\frac{U_t^{Ti}}{U_0^{Ti}} = \left(\frac{GDP_t}{GDP_0}\right)^{\upsilon^{Ti}} \cdot \left(\frac{h_t^{Ti} p_t^i}{h_0^{Ti} p_0^i}\right)^{\eta^{UTi}} \tag{7b}$$

$$\frac{h_t^{Ti}}{h_0^{Ti}} = (1+\alpha^{hTi})^{-t} \cdot \left(\frac{p_t^i}{p_0^i}\right)^{\eta^{hTi}} \tag{7c}$$

In equation (7a), U_t^{Ti} is vehicle usage or kilometers (km) driven by vehicles with fuel type i, implicitly equal to the number of vehicles on the road, times average km driven per vehicle. h_t^{Ti} is fuel use per vehicle km driven, or the inverse of average on road fuel economy.

In equation (7b), km driven in vehicle type i increases with GDP, according to the income elasticity of demand υ^{Ti}. And vehicle km varies inversely with proportionate changes in $h_t^{Ti} p_t^i$, or fuel costs per vehicle km, where $\eta^{UTi} < 0$ is the own-price elasticity for km driven with respect to per km fuel costs.[13]

In equation (7c), $\alpha^{Ti} \geq 0$ is an annual reduction in the fuel consumption rate due to autonomous improvements in vehicle fuel economy. Higher fuel prices also reduce fuel consumption rates (e.g., through promoting technologies to increase engine efficiency or lower vehicle, encouraging people to drive smaller vehicles) according to $\eta^{hTi} \leq 0$, the elasticity of the fuel consumption rate.

(iii) Other Energy Sector

The other energy sector reflects an aggregation of energy use outside the power and road transport sectors, including direct fuel usage in industry (steel, cement, refining, chemicals, construction, etc.), non-road transport, and residences. This sector is assumed to use coal, natural gas, (non-hydro) renewables, and (non-road) oil products.[14]

Given the need to distinguish economy wide-carbon policies from policies affecting only emissions from large industrial sources, the other energy sector is decomposed into consumption by large sources and small sources, with small sources being households and small firms with emissions below a certain threshold,[15] denoted by *q* = *LARGE*, *SMALL*, respectively. Use of fuel *i* in the other energy sector, by group *q*, at time *t*, denoted F_t^{Oqi}, is given by:

$$F_t^{Oqi} = \left(\frac{U_t^{Oqi}}{U_0^{Oqi}} \cdot \frac{h_t^{Oqi}}{h_0^{Oqi}}\right) F_0^{Oqi} \tag{8a}$$

$$\frac{U_t^{Oqi}}{U_0^{Oqi}} = \left(\frac{GDP_t}{GDP_0}\right)^{v^{Oi}} \cdot \left(\frac{h_t^{Oqi} p_t^i}{h_0^{Oqi} p_0^i}\right)^{\eta^{UOi}} \tag{8b}$$

$$\frac{h_t^{Oqi}}{h_0^{Oqi}} = (1 + \alpha^{Oi})^{-t} \cdot \left(\frac{p_t^i}{p_0^i}\right)^{\eta^{hOi}} \tag{8c}$$

where *i* = *COAL*, *NGAS*, *OIL*, and *REN*. The interpretation for equations (8a)-(8c) is analogous to that for the electricity and transport sectors with U_t^{Oqi} and h_t^{Oqi} denoting respectively, usage of products using fuel *i* at time *t* by group *q* and its fuel consumption rate. Parameters v^{Oi}, η^{UOi}, η^{hOi}, and α^{Oi} have analogous interpretations to previous notation and are taken to be the same across large and small users.

[13] The model abstracts from substitution between use of gasoline and diesel vehicles given the very different vehicle types and that the policy scenarios increase gasoline and diesel prices in roughly the same proportion.

[14] Given the focus on policies to reduce fossil fuels, the model does not capture (non-combustion) CO_2 emissions released, for example, during the cement-making process.

[15] A threshold of 26,000 tons of CO_2 has been suggested for participation in the ETS, though this has yet to be confirmed.

Given the more limited scope for substituting among different fuels used for very different products (compared with fuels producing a homogeneous product in the power sector), fuel switching possibilities are not modelled in the other energy sector.

(iv) Initial metrics for comparing policies and model solution

CO_2 emissions. Economy-wide CO_2 emissions from fossil fuel use at time *t*, denoted $CO2_t$, are given by

$$CO2_t = \sum_{ji} F_t^{ji} \cdot \mu^{CO2i} \tag{9}$$

where *j* = *E*, *T*, *O* denotes a sector and μ^{CO2i} is fuel *i*'s CO_2 emissions factor or tons of CO_2 emitted per unit of fuel use (zero for renewables, hydro, and nuclear).[16] There is significant variation in CO_2 emissions rates per ton of coal among different coal types, but this is not really the case when (as used here) emission rates are defined per unit of energy. The CO_2 emissions factors for fuels are fixed (given there is no carbon capture and storage).

Revenue. Aggregate tax revenue at time *t*, denoted REV_t, from taxes on fuels and electricity, and net of renewables subsidies, is given by:

$$REV_t = \sum_{ji} F_t^{ji} \cdot \tau_t^i + Y_t^E \cdot \tau_t^E - s_t^{EREN} \cdot \theta_t^{EREN} \cdot Y_t^E \tag{10}$$

Revenue is economy-wide use of fossil fuel products, times any tax on that product (excise or carbon charges), aggregated over fossil fuels, plus revenues from any excises on electricity consumption, less subsidies on renewable energy generation.

Air pollution mortality. Mortality, or total premature deaths from fossil fuel air pollution emissions, at time *t*, denoted $MORT_t$, is given by:

$$MORT_t = \sum_{ij} F_t^{ji} \cdot m_t^{ji} \tag{11}$$

m_t^{ji} is mortality per unit of fuel *i* used in sector *j* (zero for renewables, hydro and nuclear), which may differ by sector due to differing use of mitigation technologies during fuel combustion, and location of emissions sources to population centers.[17]

Economic welfare gains. Formulas for measuring the domestic welfare gains of policies are described in Appendix C. These are based on well-established second-order approximations (reflecting various triangles, rectangles, and trapezoids in fuel markets) from the literature (e.g.,

[16] These three fuels are assumed to have no environmental costs either. There are risks with nuclear power (e.g., radiation leaks from plant operation and waste storage) though these are not easily quantified and may be limited by appropriate safeguards.

[17] Local air pollution causes a range of other damages beyond mortality (morbidity, impaired visibility, building corrosion, crop damage, acidification of lakes) but previous studies suggest their combined damages are modest relative to mortality damages (e.g., NRC 2009, WB/SEPAC 2007).

Harberger 1964) and capture domestic environmental benefits (principally reduced local air pollution and, less importantly, reductions in congestion and other external costs of vehicle use) less economic welfare costs (distortions in fuel markets created by, or exacerbated by, new policies). Climate benefits are excluded from most of the calculations given their global nature and dispute over their value.

Model solution. A baseline scenario is first developed, using recent data on fuel prices and use in different sectors and projecting forward to 2030 using equations of the model and projections of energy prices and GDP. The impacts of policies are then calculated by computing policy-induced changes in fuel prices from any new explicit or implicit charges. The generation shares in the power sector are then calculated and the resulting electricity price. Electricity and fuel prices are then used in determining proportionate changes in energy efficiency, use of energy products, fuel demand across the three sectors, and hence the environmental, fiscal, and economic impacts just described.

B. Policies

A wide range of CO_2 mitigation policies are considered, including:

- A carbon tax, or tax on the supply of all fossil fuels in proportion to carbon content;
- An excise tax on coal;
- An ETS applied to power sector and large industrial CO_2 emissions;
- An excise tax on electricity generation;
- Increased subsidies for renewable power generation;
- A policy to reduce the CO_2 intensity of power generation;
- A policy to increase the efficiency of electricity-using capital;
- An increase in road fuel taxes;
- A policy to increase vehicle fuel efficiency; and
- A policy to increase efficiency (of large firms) in the other energy sector.

This subsection discusses the above policies, their specifics, and how they are modelled, with Table 3 providing a summary. Each policy is modelled in isolation though, as discussed below, the policies are largely additive in terms of their proportionate impacts on emissions. For each policy, a 'moderate' and 'aggressive' scenario is considered, and policy stringency increases progressively over time as, in practice, this allows firms and households more time to adjust. Later on, these policies are also compared with a fully efficient policy that comprehensively prices all external costs.

Carbon tax

A comprehensive tax on fossil fuel CO_2 emissions promotes the full range of emissions mitigation opportunities (switching to cleaner fuels, improving energy efficiency, conserving on usage of energy-consuming products) across all sectors of the economy. It also raises substantial revenue and, by reducing coal use (in particular), reduces deaths from local air pollution. Carbon taxes are straightforward to administer, for example, by integrating carbon charges into road fuel excises, (existing but currently minimal) resource taxes on coal extraction, and applying similar changes to natural gas and other oil products.[18]

The policy is modelled by incorporating into the tax for fuel i, a charge of $\tau_t^{CO2} \cdot \mu^{CO2i}$, for i = *COAL*, *NGAS*, *GAS*, *DIES*, and *OIL*, where τ_t^{CO2} is a uniform charge on CO_2 emissions in period t.

At present, although around 40 countries have some form of national carbon pricing, prices are often below RMB 65 ($10) per ton (WBG 2015, Figure 6),[19] which is well below estimates of the global climate damages from those emissions (Appendix C). Two carbon tax scenarios are considered, including a moderate case with the tax rate increasing in equal yearly increments of RMB 16.25 ($2.5) per ton from 2017 to reach RMB 227.5 ($35) per ton by 2030 and an aggressive case with a yearly increase of RMB 32.5 ($5) per ton reaching RMB 455 ($70) by 2030.

Excise on coal

Coal is by far the dirtiest fuel in terms of carbon emissions and local air pollution, so it is ironic that it has not been meaningfully taxed from an environmental perspective in any country. A simple coal excise tax is an effective way to cut CO_2 emissions in China, as this fuel currently accounts for around 80 percent of emissions. The coal tax rates considered here are analogous to the coal charges in the moderate and aggressive carbon tax scenarios, that is, they impose the same charges on coal used in the power and other energy sectors in different periods, but charges are not applied to other fossil fuels.

ETS for power and large industrial CO_2 emissions

This policy, building on regional pilot schemes, and which has been announced for China starting 2017 (though specifics are being determined), will cover emissions from power generators, large industrial sources, and domestic aviation, which amounts to about 50 percent of economy-wide CO_2 emissions.[20] If allowances are auctioned, the ETS raises revenues equal to the emissions price times the emissions cap.

---

[18] See, for example, Calder (2015) and Metcalf and Weisbach (2009).

[19] An exchange rate of RMB 6.5 per $1 is assumed.

[20] The specific industries include petro and other chemicals, building materials, iron and steel, non-ferrous metals, and paper (see http://carbon-pulse.com/14353).

To facilitate policy comparisons, the ETS is incorporated in the spreadsheet through its 'virtual tax' equivalent, that is, the emissions price that would be established by the cap. Given the equivalency in the model between upfront charges on fuel supply and emissions charges at the point of combustion, the ETS can be modelled in the same way as the carbon tax, but with charges applying only to power generation fuels and fuels used by large users in the other energy sector. The same emissions price trajectories are assumed as for the carbon tax. Given that the model is deterministic rather than stochastic, the variability of future prices under an ETS (or emissions uncertainty under a tax) are not considered.

Excise on electricity generation

Many countries impose excises on (mostly residential) electricity consumption for environmental and fiscal reasons. The environmental effectiveness of these policies is limited however, as they do not promote switching to cleaner generation fuels or reductions beyond the power sector.

Modest and aggressive scenarios for electricity taxes (applied to all electricity use) are considered here, with the tax rates matched to the increase in electricity prices under the modest and aggressive carbon tax scenarios in each period, but assuming the power generation mix in the baseline scenario.

Increased renewable generation subsidies

Here the focus is on renewables in power generation, given their greater potential for use in that sector compared with other sectors, though even in power generation there are limits to scaling up renewables (e.g., due to the intermittency of wind and solar power and the geographic mismatch between sites suitable for these plants and the location of population centers).

Subsidies for (non-hydro) renewables in power generation have limited effects on reducing CO_2 emissions, relative to directly pricing these emissions, as they do not promote some fuel switching possibilities (shifting from coal to natural gas and oil and from these fuels to nuclear and hydro), nor do they reduce electricity demand, or emissions beyond power.

Renewable power generation is commonly subsidized however—in China subsidies amounted to $7 billion in 2014, and are significantly higher than that in Germany, Italy, Spain, and the United States.[21] In principle, there is an economic rationale for combining carbon pricing with additional incentives for renewables if this addresses additional market barriers, such as the inability of firms developing, or pioneering use of, green technologies to capture spillover benefits to other firms from their own 'learning-by-doing' experiences. These technology spillovers are not incorporated in the spreadsheet model, though whether they warrant substantial renewable deployment incentives is not entirely clear [22] and any incentives should phase out as new technologies

[21] From IEA (2015). For more detail on country-level renewables policies see REN21 (2015).

[22] The case for subsidizing R&D into renewable technologies appears to be more solid than for subsidizing deployment of these technologies (e.g., Dechezleprêtre and Popp 2016, Löschel and Schenker 2016).

mature and penetrate the market. Renewable subsidies are mainly evaluated here by their effectiveness at achieving emissions targets.[23]

Moderate and aggressive policy scenarios are considered which increase the subsidy for renewables generation by 50 percent and 150 percent respectively above baseline levels in all periods from 2017 onwards (in the latter case renewable generation costs are almost driven to zero).

Reducing CO_2 intensity in the power sector

An alternative policy to reduce the CO_2 intensity of power generation is simply to regulate a standard for CO_2 per unit of generation. To be cost effective in a model (unlike the present one) with differences in mitigation costs across power generators, generators with relatively dirty portfolios of plants should be allowed to fall short of the standard by purchasing credits from relatively clean generators who exceed the standard.

One fiscal analog of this policy is a tax/subsidy scheme involving taxes on relatively dirty generators (in proportion to the difference between the average CO_2 per kWh across their plants and a pivot point emission rate) and subsidies for relatively clean generators (in proportion to the difference between the pivot point emission rate and their average CO_2 per kWh), where the pivot point emission rate can be chosen such that the policy is revenue-neutral. Both the regulation and the tax/subsidy scheme reward all opportunities for shifting from away from higher carbon fuels thereby reducing the average emission rate per unit of power generation (e.g., Krupnick and others 2010). But unlike carbon pricing, these policies have a relatively small impact on electricity prices as they do not involve the pass through of tax revenues (or allowance rents) in higher prices.

Yet another fiscal analog of these policies is a carbon tax applied to the emissions content of power generation fuels with all the revenues used to finance a subsidy per unit of power generation (e.g., Bernard and others 2007). This is how the policy is modelled here, with the carbon tax rates chosen to mimic those in the modest and aggressive carbon tax scenarios.

Increasing the efficiency of electricity-using capital

Regulations are commonly used to raise the efficiency of electricity-using products and capital. Besides their environmental benefits, it is sometimes suggested that these policies address an additional market failure due to the private sector undervaluing the discounted energy savings from higher energy efficiency, though the evidence on this is mixed (e.g., Allcott and Wozny

[23] Allowing greater subsidies to accelerate the rate of technological improvement in renewable generation in the model would enhance, but only moderately, their environmental effectiveness.

2013, Helfand and Wolverton 2011) and this possibility is not incorporated into the present model.[24]

The policy scenario considered here implicitly improves the efficiency of all electricity-using products and capital (e.g., appliances, lighting, buildings, heating and cooling equipment), and (somewhat unrealistically) in a cost-effective way, meaning the cost of the last ton of CO_2 reduced is equalized across all products.[25] The policy is modelled by applying a virtual tax in each period to the electricity price in equation (2c), thereby reducing the electricity consumption rate, but not applying it to the price in equation (2b), hence usage of electricity-using products increases slightly in response to the lower per unit costs (the rebound effect). The virtual tax on the electricity consumption rate is chosen to be the same as in the electricity tax scenarios.

Higher road fuel taxes

China already imposes significant road fuel excises, amounting to RMB 2.6 ($0.40) per liter for gasoline in 2014 and RMB 2.5 ($0.38) per liter for road diesel (see below). Road fuel taxes are the most effective policies for reducing fuel use, and hence vehicle CO_2 emissions, as they encourage improvements in fuel economy and reductions in vehicle use.

A modest fuel tax increase scenario is considered where the tax increase for gasoline and diesel each year corresponds to the extra charges for these fuels in the aggressive carbon tax scenario. An aggressive policy is also considered where the tax increases in each period are double those in the modest road fuel tax scenario.

Vehicle fuel economy policies

New passenger vehicles have been regulated in China since 2005, the latest standards targeting new vehicle fuel consumption of 5 liters per 100km (48 miles per gallon) by 2020 (UNEP 2015). On road fuel consumption is higher, as older vehicles on the road drag down the average (due to their being subject to less stringent standards when they came on the market and deteriorating efficiency with aging). Heavy-duty vehicles (trucks and buses), which are responsible for diesel fuel consumption, are (as in most other countries) not subject to regulation.[26]

The focus here is on higher fuel economy policies for gasoline vehicles as modelled by a virtual tax that increases the gasoline price in equation (7c) determining the gasoline consumption rate,

---

[24] Allowing for this market failure could imply that, up to a point, policies to increase energy efficiency could have net economic benefits (before even counting environmental benefits), though these are small relative to the net benefits from directly pricing emissions (e.g., Parry, Evans, and Oates 2014).

[25] In reality, policy will be less efficient as some products and capital may be difficult to regulate (e.g., smaller appliances, audio and entertainment equipment, industrial processes such as assembly lines) and (in the absence of extensive credit trading provisions), the incremental cost per ton of CO_2 reduced may differ substantially across different energy efficiency programs.

[26] Implementing regulations for heavy trucks, for example, is complicated given that fuel economy is very sensitive to the weight of freight (see Harrington 2012).

but not applying the tax to the fuel price in the vehicle usage equation (7b) (vehicle usage increases slightly from the rebound effect). In the moderate fuel economy scenario, the virtual tax rate matches that in the aggressive fuel tax case and in the aggressive fuel economy scenario it is twice as large.

Increasing efficiency (of non-renewables) for large firms in the other energy sector

The last policy considered increases the energy efficiency of fossil fuel-using capital for large users in the other energy sector (but not small users who are more difficult to regulate). As above, the policy is modelled by applying a virtual tax in each period to the price of coal, natural gas, and oil products in equation (8c), thereby reducing the energy consumption rate, but not applying it to the price in equation (8b), hence usage of products consuming (non-fossil) energy increases slightly through the rebound effect. The virtual tax on the other energy consumption rate in (9c) is chosen to imply the same increase in fuel price as under the corresponding modest and aggressive carbon tax scenarios.

Table 3. Policy Scenarios

Policy and description	**Stringency**	
	Modest	**Aggressive**
Carbon tax: charge on all fuels equal to CO_2 emission factor times CO_2 tax	CO_2 charge increases RMB 16.25/ton per year 2017–2030	CO_2 charge increases RMB 32.5/ton per year 2017–2030
Coal excise: charge on coal equal to CO_2 emission factor times the CO_2 tax	Same CO_2 charge as modest carbon tax	Same CO_2 charge as aggressive carbon tax
ETS: charge on power sector fuels and large other energy users equal to CO_2 emission rate times CO_2 tax	Same CO_2 charge as modest carbon tax	Same CO_2 charge as aggressive carbon tax
Electricity tax: unit tax on all power generation	Tax rate equals electricity price increase under modest carbon tax at baseline generation mix	Tax rate equals electricity price increase under aggressive carbon tax at baseline generation mix
Renewable generation subsidy: increases in the baseline rate of subsidy for renewable generation	Subsidy increased by 50 percent over baseline level from 2017–2030	Subsidy increased by 150 percent over baseline level from 2017–2030
Reducing CO_2/kWh from electricity: tax on power generation CO_2 with revenues financing per kWh subsidy	Same CO_2 charge as modest carbon tax	Same CO_2 charge as aggressive carbon tax
Efficiency standard for electricity: reduces electricity consumption rate	Same virtual tax on electricity consumption rate as in the modest electricity tax.	Same virtual tax on electricity consumption rate as in the aggressive electricity tax

Road fuel taxes: an increase in road fuel excises above baseline levels	Same tax increase as in aggressive carbon tax	Twice the tax increase as in aggressive carbon tax
Efficiency standard for transport: reduces fuel consumption rate of gasoline vehicles	Same virtual tax on gasoline consumption rate as in the aggressive road fuel tax	Twice the virtual tax on gasoline consumption rate as in the aggressive road fuel tax
Efficiency standard for large industry: reduces energy consumption rate for large industrial sector	Same virtual tax on fossil fuel consumption rate as in the modest carbon tax	Same virtual tax on fossil fuel consumption rate as in the aggressive carbon tax

III. Results

This section begins by discussing the various projections in the baseline scenario. The heart of the section is a comparison of the previously described policy scenarios across a range of metrics. A brief sensitivity analysis is then presented followed by a comparison of policies to an idealized policy (defined below) that fully prices all environmental costs.[27]

A. Baseline Projections

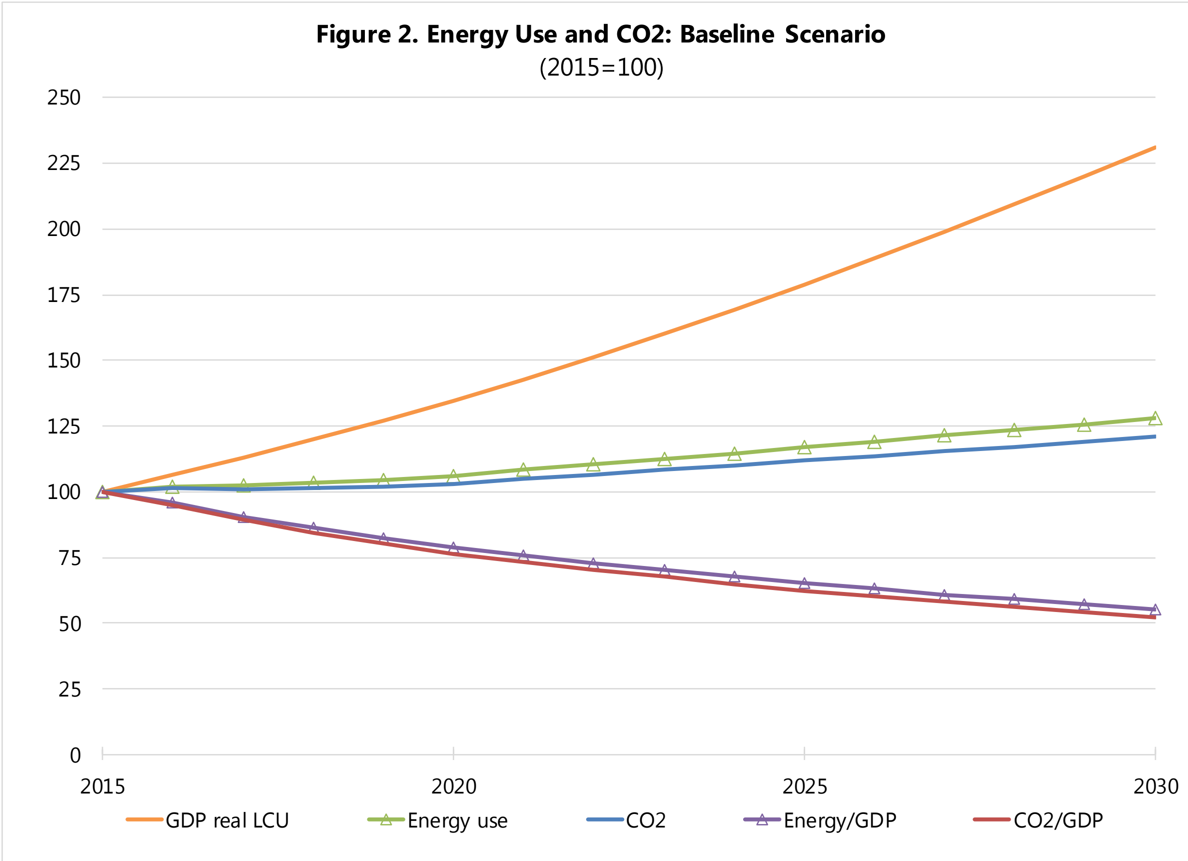
The baseline projections assume no new (or tightening of existing) policies beyond those that are implicit in observed data for 2013 aside from regulations that progressively reduce local air emission rates. Policy scenarios are then considered relative to this baseline. Inevitably, these projections are sensitive to different assumptions—particularly with regard to future international energy prices—underscoring the importance of sensitivity analyses.

Figure 2 shows baseline projections of energy and CO_2 emissions trends. GDP expands by 131 percent between 2015 and 2030 (from IMF projections), while total energy consumption increases by 27 percent, implying a 45 percent decline in the energy to GDP ratio. CO_2 emissions per unit of energy decline moderately, implying a slightly larger decline (48 percent) in the CO_2 intensity of GDP. Overall CO_2 emissions are projected to keep increasing (rather than peaking) in the absence of new policies and are 21 percent higher in 2030 compared with 2015.[28]

---

[27] The data underlying the figures below is available from the accompanying spreadsheet.

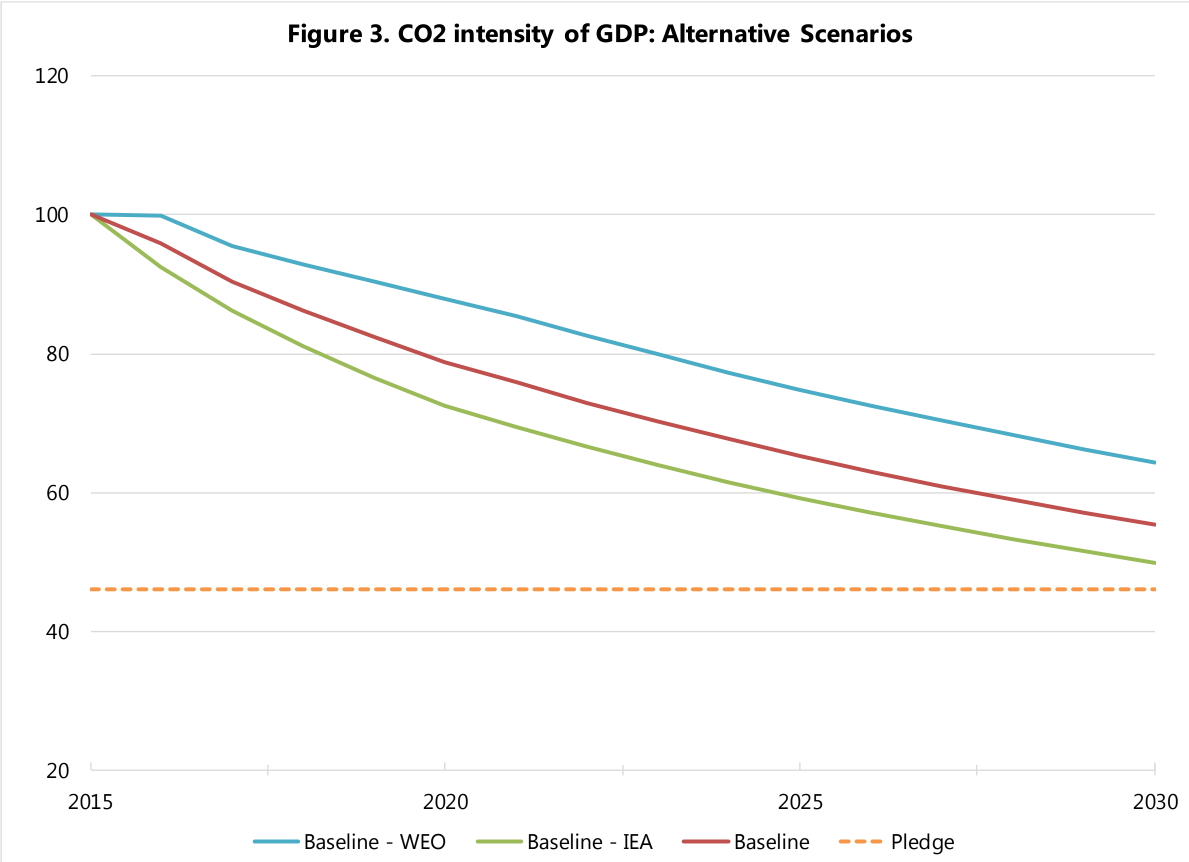
[28] These energy demand and CO_2 projections are broadly consistent with those from the range of energy models for China summarized in Mischke and Karlsson (2014), Figures 2 and 3—GDP growth is moderately larger in the present model, though this is offset by a faster decline in the energy intensity of GDP. Green and Stern (2016) project a similar decline in the energy intensity of GDP but a somewhat larger decline (20 percent) in the CO_2 intensity of energy by 2030.



Source: From above equations and parameter assumptions in Appendix B.

Figure 3 illustrates the sensitivity of the projected CO_2 to GDP intensity to different energy price projections. The baseline case splits the difference between price projections of the International Energy Administration (IEA) where oil, coal, and natural gas prices rise to about 250, 150 and 80 percent above 2015 levels by 2030, and (extrapolated) projections from IMF (2016), which are based on futures markets, and where oil and coal prices in 2030 are 80 and 20 percent higher respectively in 2030 relative to 2015 levels, and natural gas prices are about 20 percent lower. Under alternative energy price projections, the CO_2 intensity of GDP in 2030 varies between 49 and 64 percent of its 2015 level—the former case is not quite sufficient to meet China's INDC which requires reducing the CO_2 intensity to 46 percent of the 2015 level.[29]

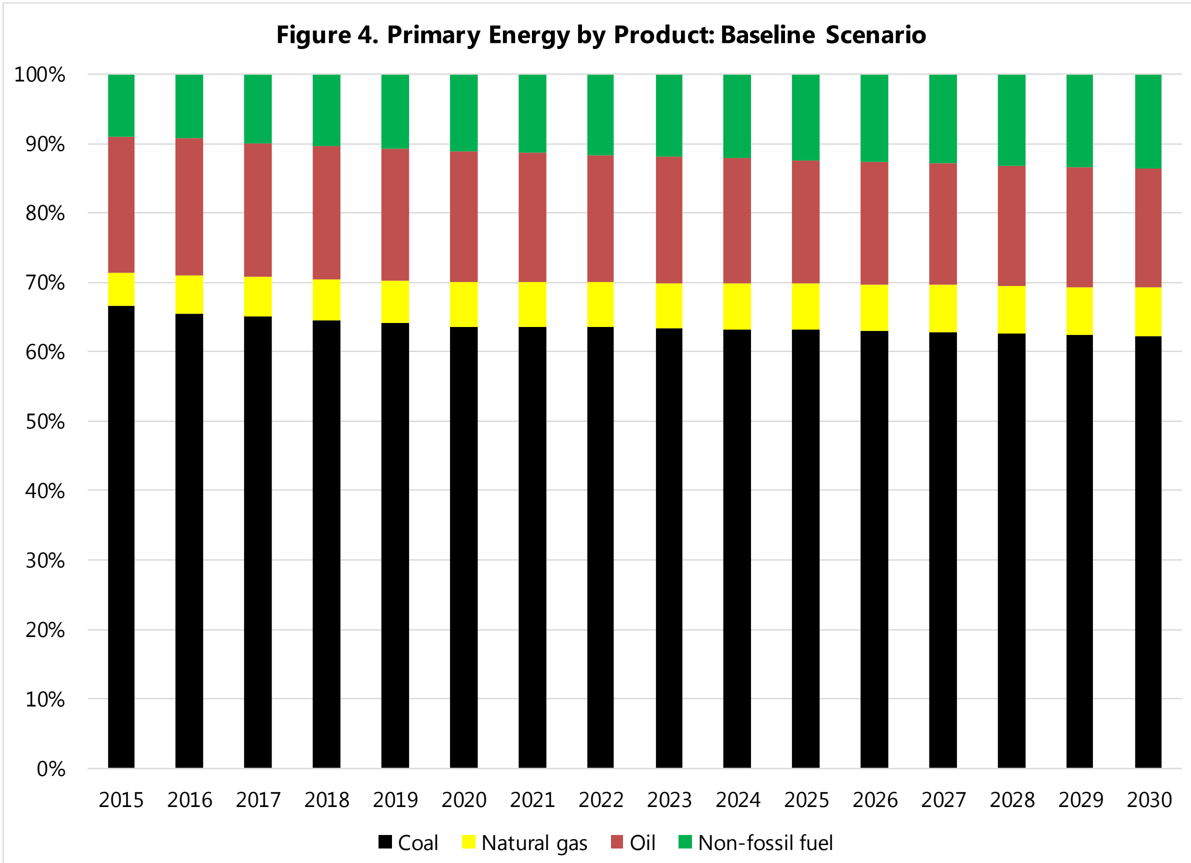
[29] For comparison, with the IEA price scenarios economy-wide CO_2 emissions in 2030 are about 5 percent higher than projected in the IEA (2015) pp. 635 'Current Policies Scenario'. In our baseline base, emissions are 18 percent higher than in IEA (2015).



Note: WEO prices refer to energy price projections underlying the IMF (2016) World Economic Outlook while IEA prices are from IEA (2015). The baseline case splits the difference between the two sets of energy price projections.

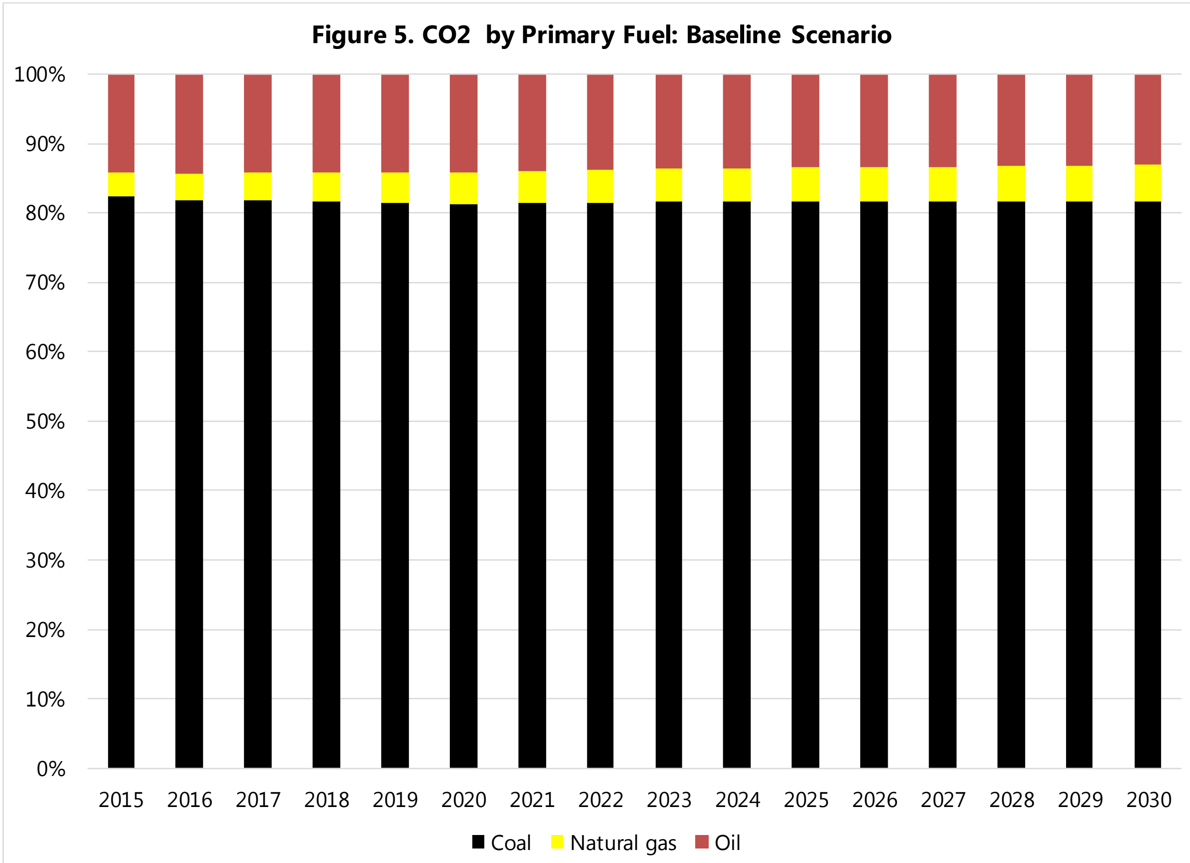
Source: From above equations and parameter assumptions in Appendix B.

As indicated in Figure 4, the composition of primary energy use in the baseline changes moderately—non-fossil fuel energy rises from 9 percent in 2016 to 13 percent, while the coal share falls from 66 percent in 2015 to 63 percent in 2030. New policies are needed to shift energy consumption more substantially away from coal (and raise the share of non-fossil fuels in primary energy).



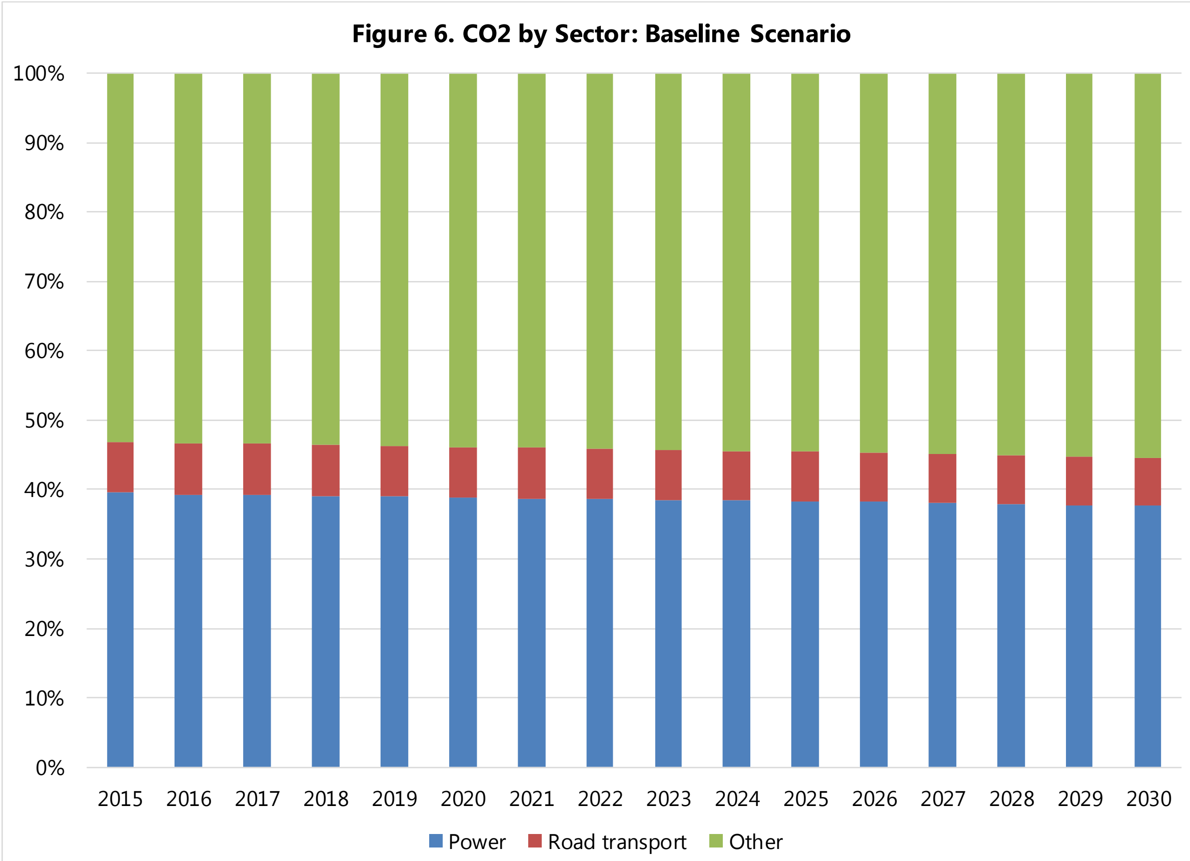
Source: From above equations and parameter assumptions in Appendix B.

Figure 5 indicates CO_2 emissions by fuel product in the baseline. Given its high carbon intensity (about 70 percent greater per unit of energy than for natural gas and 40 percent greater than for gasoline) coal accounts for a disproportionately larger share, 82 percent in 2015, of CO_2 emissions than it does for primary energy, while natural gas accounts for 3 percent and (road and non-road) oil products for 14 percent. The CO_2 emissions shares change moderately in the baseline out to 2030.



Source: From above equations and parameter assumptions in Appendix B.

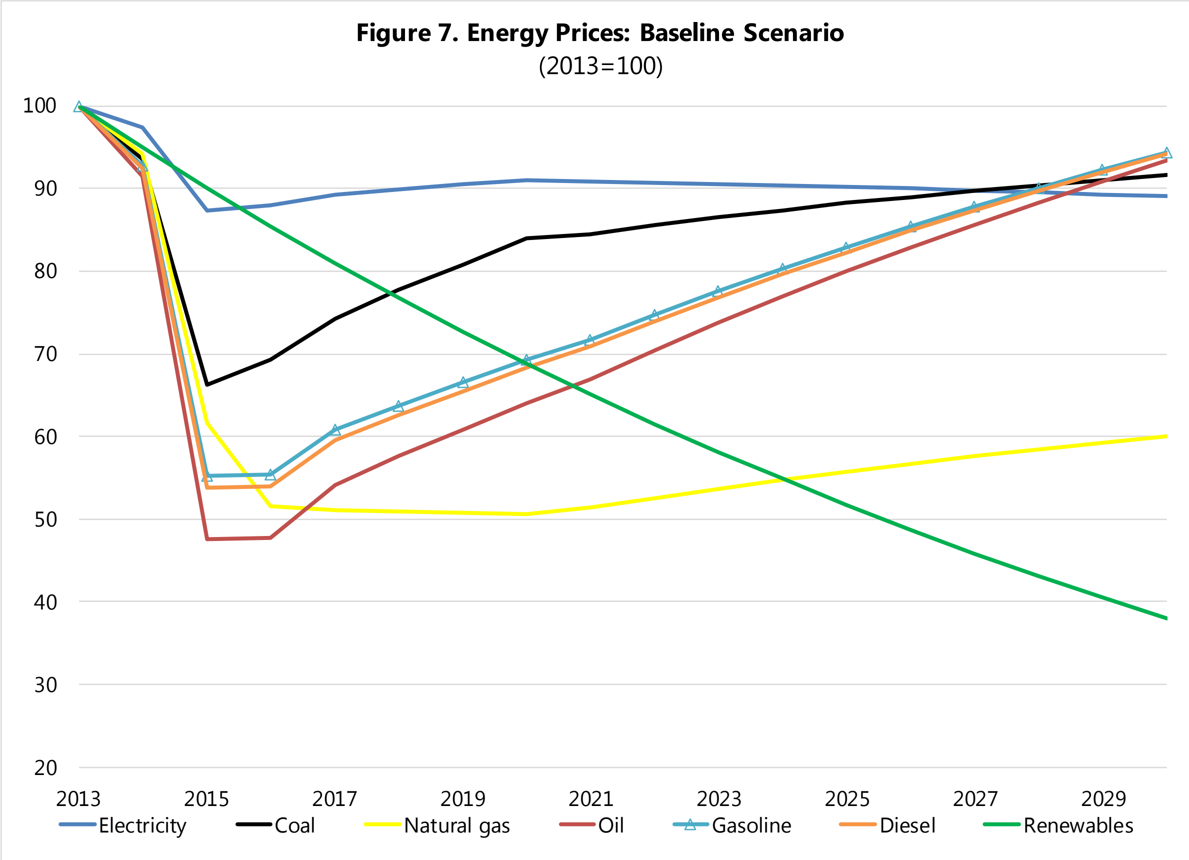
In terms of sectors, electricity accounts for 40 percent of CO_2 emissions in 2015, the transportation sector 7 percent, and the other energy sector 53 percent, and there is little change in these shares (see Figure 6) in the baseline given, for example, similar assumptions about income elasticities across sectors.



Source: From above equations and parameter assumptions in Appendix B.

Figure 7 indicates (real) energy price trends in the baseline. All fossil fuel prices decline sharply between 2013 and 2016—by 62 percent for crude oil,[30] about 31 percent for coal, 48 percent for natural gas, 45 percent for road fuels, and 12 percent for electricity—and thereafter rise slowly (or remain about flat for electricity) but are still well below 2013 levels in 2030. Renewables prices, as proxied by power generation costs, fall by over 50 percent during the period (based on an assumed annual productivity growth rate of 4.5 percent).

[30] China recently introduced a domestic oil price floor of RMB 260 ($40) per barrel but this is non-binding in our scenarios.

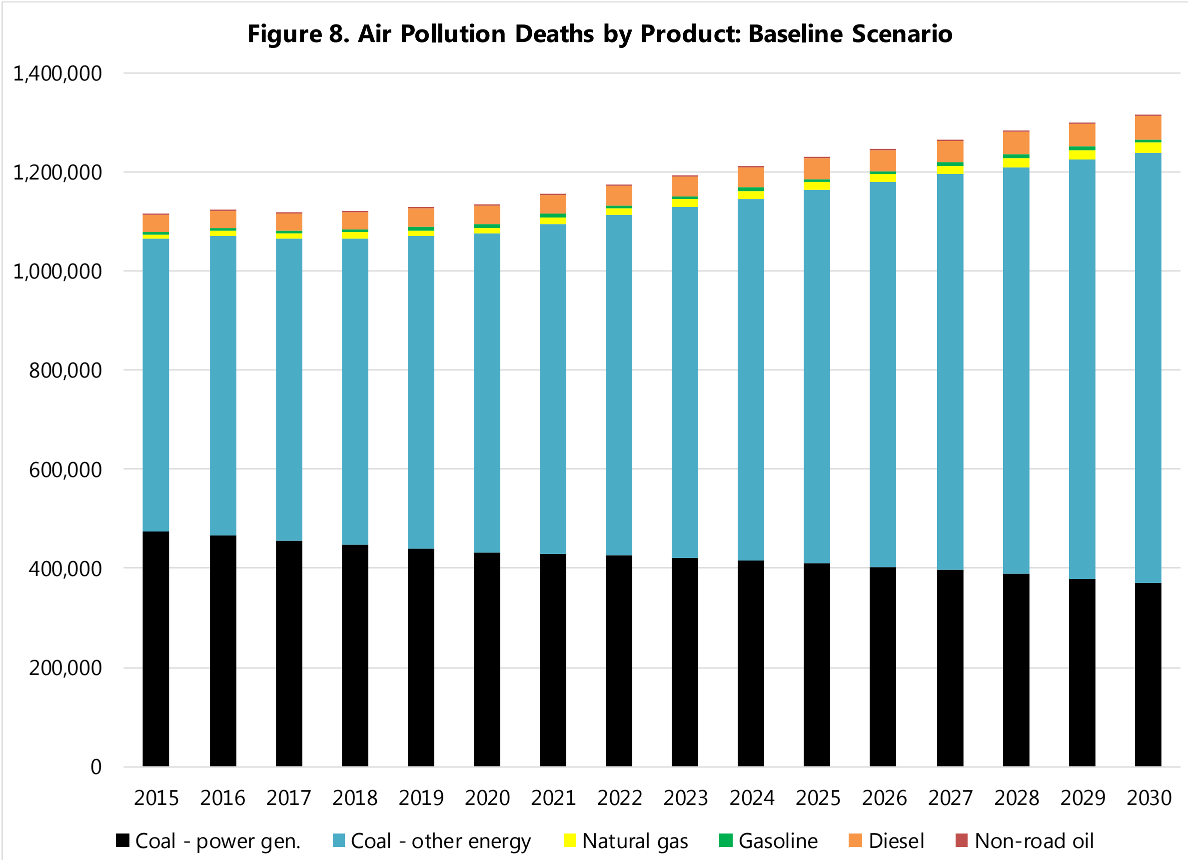


Note: Renewables prices are renewable power generation costs.

Source: Fossil fuel prices are a simple average of IMF (2016) and IEA (2015) projections.

Finally, Figure 8 shows estimated annual deaths from fossil fuel air pollution in the baseline, broken down by fuel product (using data in Parry and others 2014). Total deaths are 1,122,092 in 2015[31] and rise by 18 percent to 1,322,230 by 2030, as increased coal use and rising population exposure to urban pollution more than offset declining emission rates. In 2015, 53 percent of deaths are from coal combustion in the power sector and 42 percent from coal use in the other energy sector, however the share of power sector coal in total deaths drops to 28 percent by 2030 due to greater deployment of control technologies at coal plants which roughly halves the industry average air pollution emission rate by 2030.

[31] This excludes outdoor air pollution deaths from non-fossil emissions sources (e.g., agriculture, plastics, refrigerants, landfills, mining).



Source: From above equations and parameter assumptions in Appendix B.

B. Policy Comparison

This subsection compares the impact of different policies on CO_2 emissions, revenue, air pollution deaths, and economic welfare, relative to the baseline outcome, for both the moderate and aggressive policy scenarios.

(i) CO_2 emissions

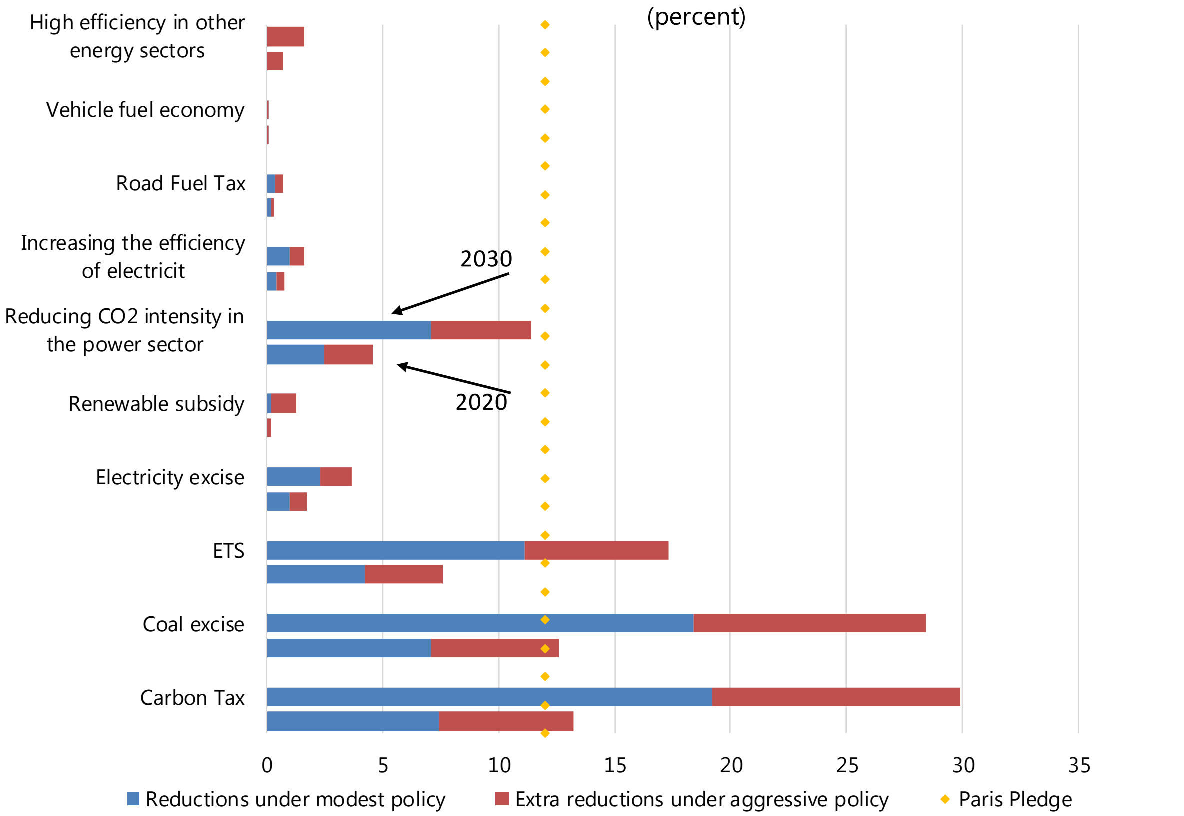
Figure 9 indicates the percent reduction (relative to the baseline level in the corresponding year) in CO_2 emissions in 2020 and 2030 under each policy and each policy scenario and Figure 10 indicates the breakdown of the CO_2 reductions by fuel type and sector, for the moderate policies in 2020.

As shown in Figure 9, the carbon tax is the most effective policy for reducing energy-related CO_2 emissions, reducing them by 13 percent and 30 percent below baseline levels in 2020 and 2030 in the aggressive case, and by 7 percent and 19 percent in those years in the moderate case. As mentioned above, the moderate tax in 2030 (RMB 237 or $35) is easily sufficient to meet China's emissions intensity target, indicated by the dashed line in Figure 9 (though this finding is sensitive to alternative assumptions). These results are driven by reductions in coal use, which account for 97 percent of the total reductions in Figure 10. Doubling the carbon tax has a less than proportionate impact on emissions reductions in Figure 9, given the standard assumption that fuel demand curves are convex (rather than linear).

The coal tax is only slightly less effective than the carbon tax, reducing emissions by 95–96 percent of the reductions under the carbon tax across years and stringency scenarios. This small difference reflects the relatively small emissions reductions forgone from failing to charge for CO_2 from natural gas and oil (Figure 10).

Figure 9. Carbon Emissions Reductions in 2020 and 2030

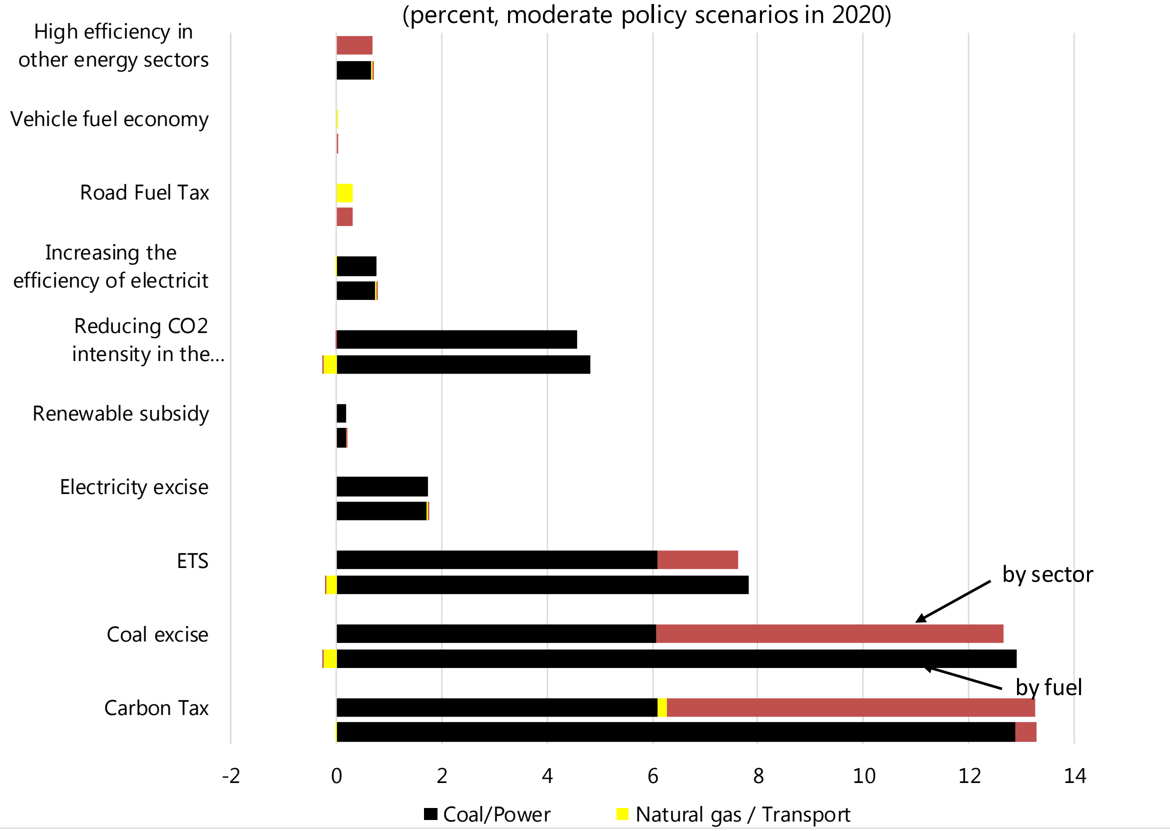
(percent)



Notes: Bars indicate percent reductions in fossil fuel CO_2 emissions relative to baseline emissions in that year.

Source: From above equations and parameter assumptions in Appendix B.

Figure 10. CO2 Reductions By Product and Sector
(percent, moderate policy scenarios in 2020)



Source: From above equations and parameter assumptions in Appendix B.

The ETS has intermediate effectiveness, reducing emissions by about 57 percent of the reductions under the carbon tax across years and stringency scenarios. The ETS produces the same CO_2 reductions from the power sector as does the carbon tax, but only a quarter of those from the other energy sector (Figure 10), as it does not cover small users in this sector, and none from road transportation.

The power sector CO_2/kWh intensity standard has about 30–40 percent of the effectiveness of the carbon tax cross years and scenarios. The electricity excise has about 12 percent of the effectiveness of the carbon tax, or put another way, about 12 percent of the emissions reductions under the carbon tax comes from reductions in electricity demand. This reduction is split about equally between improvements in energy efficiency and less usage of electricity-using capital—hence the policy to increase the efficiency of electricity-consuming products has about 5 percent of the effectiveness of the carbon tax.[32]

The road transportation policies have very limited effectiveness (for reasons already noted), and the same applies for the enhanced subsidy for renewable generation (as this builds off a small

[32] The rebound effect offsets about 10 percent of the energy savings from higher efficiency in the power sector, and similarly in the transport and other energy sectors.

base) and the efficiency policy for the other energy sector (which applies only to large firms accounting for one quarter of emissions in this sector).

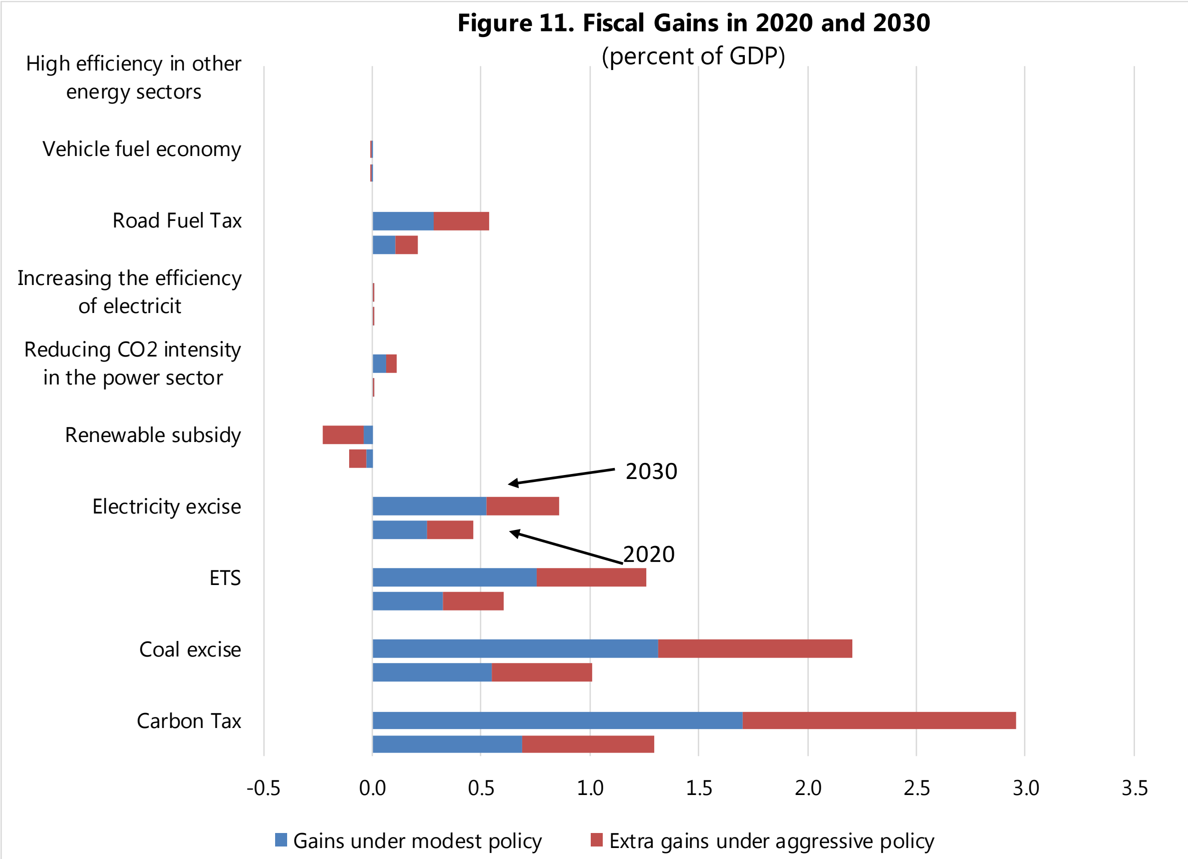
In terms of meeting the Paris pledge to reduce the CO_2 intensity of GDP 60 percent below 2005 levels by 2030, the only moderate policies to reach this target are the carbon and coal taxes (though the moderate ETS almost reaches it). Further, the aggressive ETS and regulations on CO_2 intensity in the power sector achieve, or just miss, the pledged reduction while all other policies are well short. As underscored in Figure 3 however, these findings are sensitive to different baseline scenarios.

(ii) Revenue

As indicated in Figure 11, the carbon tax also has the greatest fiscal benefit, raising revenues of 1.7 percent and 3.0 percent of GDP in 2030 in the modest and aggressive scenarios. Although carbon tax rates are 3.5 times as high in 2030 compared with 2020, revenues are only about a third to a half higher relative to GDP because the baseline CO_2 to GDP ratio is 50 percent lower in 2030 and the higher carbon taxes have a bigger impact on eroding the tax base.

Again the coal tax is not too far behind, raising revenues of about 74-79 percent of those under the carbon tax across years and stringency scenarios (prior to behavioral responses, the coal tax covers 85 percent of the emissions, and hence 85 percent of the tax base, compared with the carbon tax).

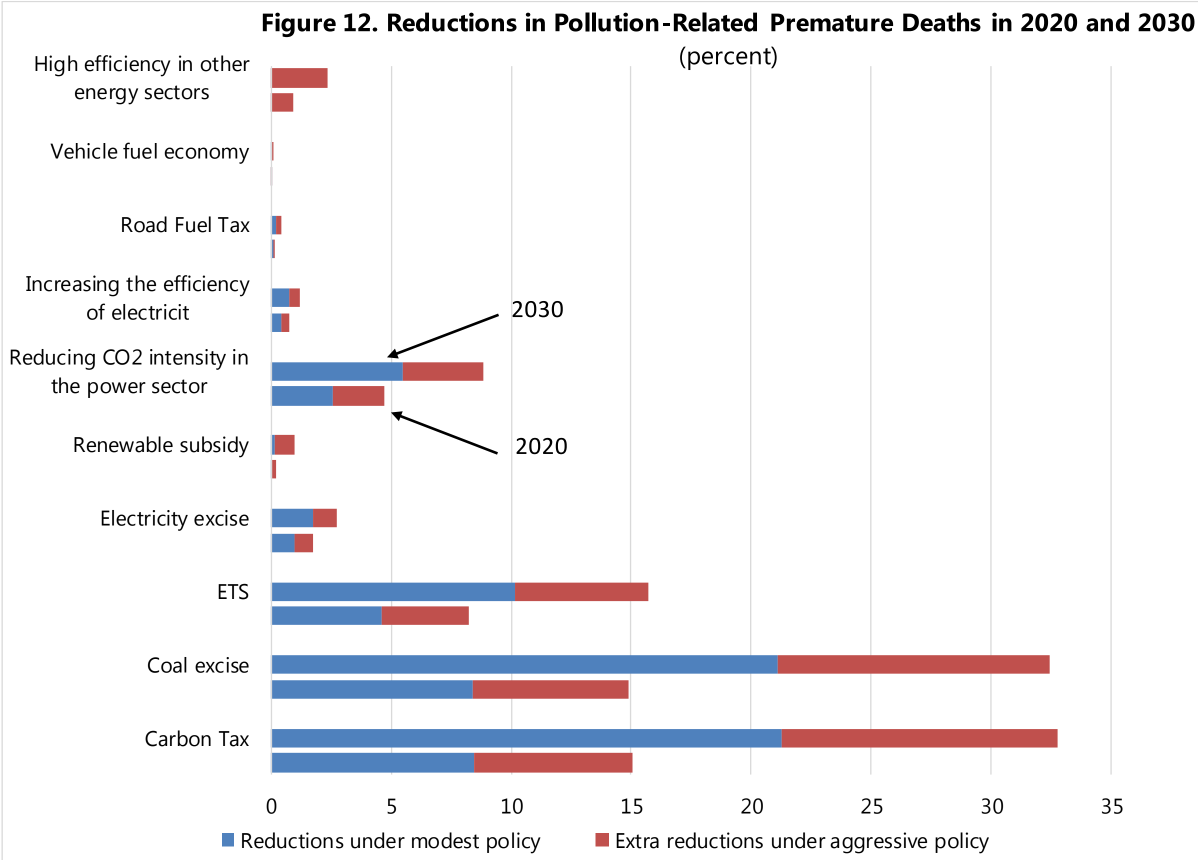
The ETS—if allowances are auctioned—and the electricity tax are intermediate cases, raising revenues of about 45 and 30 percent respectively compared with that from the carbon tax across years and stringency scenarios (the ETS, for example, fails to raise revenue from road transportation and small users in the other energy sector). Road fuel taxes raise about 18 percent of the revenue raised from the carbon tax (after accounting for the erosion of the tax base for pre-existing road fuel taxes). Policies to reduce the CO_2 intensity of power generation and to improve energy efficiency in the power and other energy sectors have no revenue impacts. The renewable generation subsidy loses revenue, as does the vehicle fuel economy policy (which erodes the tax base of prior fuel taxes) but the losses are relatively small (less than 0.25 percent of GDP).



Source: From above equations and parameter assumptions in Appendix B.

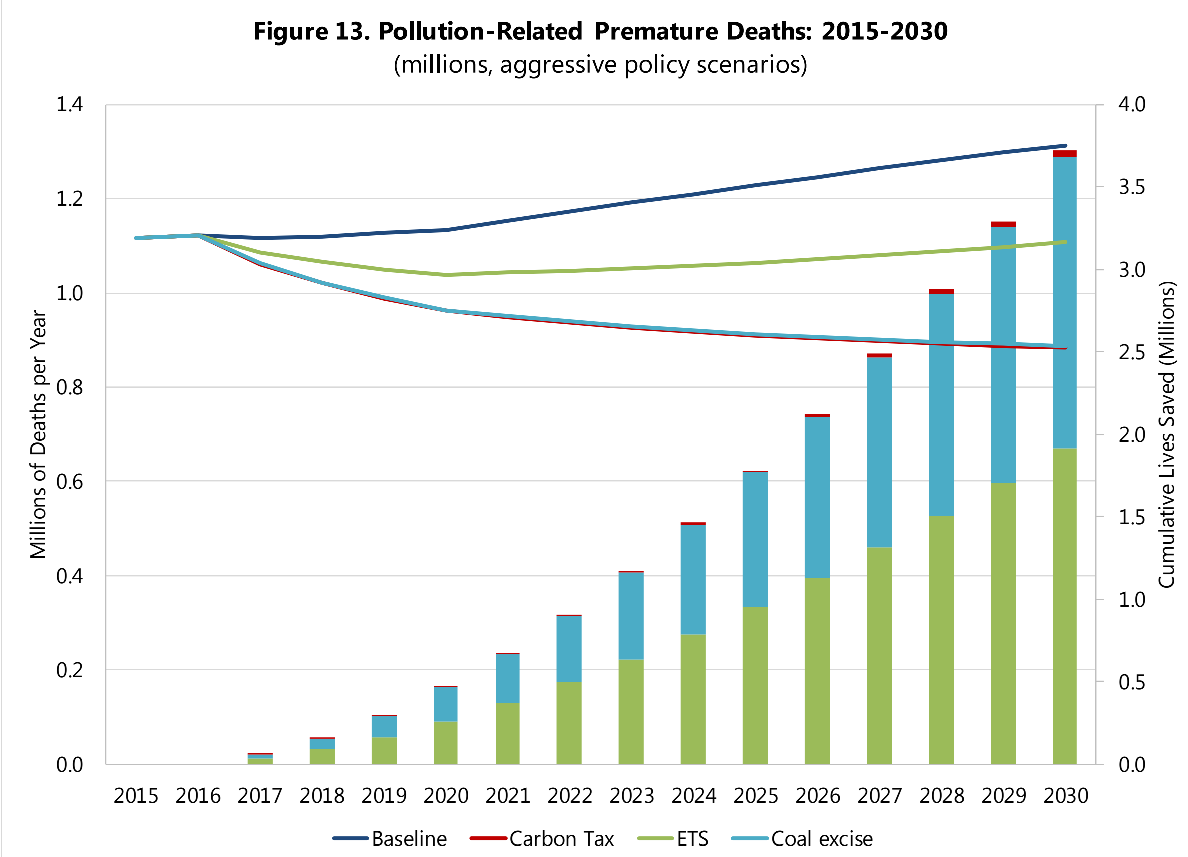
(iii) Local air pollution deaths

As indicated in Figure 12, the percentage reduction in air pollution deaths in 2020 and 2030 for the major CO_2 mitigation policies are fairly similar to the percentage CO_2 reductions in Figure 9. For example, the modest carbon tax and coal tax both reduce deaths by about 9 percent in 2020 and 22 percent in 2030, while the aggressive versions of these taxes reduce deaths by 33 percent in 2030. The ETS reduces deaths between 5 and 20 percent across years and scenarios.



Source: From above equations and parameter assumptions in Appendix B.

More interesting perhaps is Figure 13 showing the time profile of air pollution deaths under selected policies in the aggressive scenarios. Lives saved (the difference between deaths in the baseline and under different policies) progressively increases over time as policies become more stringent. Cumulated over the 2017 to 2030 period, the carbon and coal taxes save about 3.7 million lives and the ETS about 1.9 million.



Note: Columns indicate the incremental increase in cumulative deaths prevented (e.g., the green bar indicates the additional lives saved by the coal excise tax relative to the ETS from 2015 onwards).

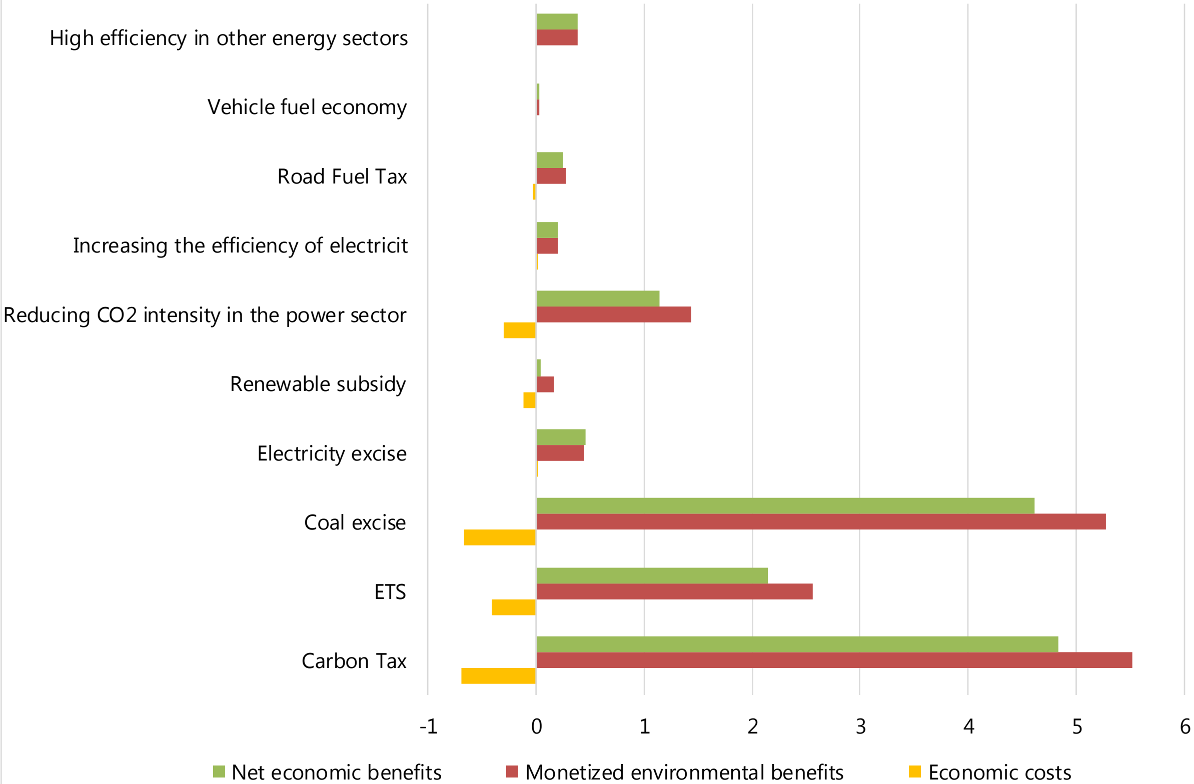
Source: From above equations and parameter assumptions in Appendix B.

(iv) Domestic welfare benefits and costs

Figure 14 indicates the economic welfare costs, monetized domestic environmental benefits (excluding global climate benefits), and net welfare benefits (environmental benefits less economic costs) of the various mitigation policies, focusing on the aggressive scenarios for 2030. The environmental benefits essentially reflect the value of lower air pollution mortality (congestion and other environmental benefits of reduced vehicle use are included but are very small in relative terms).

Not surprisingly, the carbon tax and coal tax perform far better than other policies, causing costs of about 0.7 percent of GDP but generate domestic environmental benefits approaching 6 percent of GDP, leaving a net welfare gain approaching 5 percent of GDP. Net welfare gains are 2.2 percent of GDP under the ETS, 1.2 percent under the policy to reduce the CO_2 intensity of power generation, and 0.5 percent of GDP or less under all other policies.

Figure 14. Domestic Economic Benefits and Costs in 2030
(percent of GDP, aggressive policy scenarios)



Source: From above equations, formulas in Appendix C, and parameter assumptions in Appendix B and D.

C. Sensitivity Analyses

Table 4 presents some sensitivity analysis for the carbon tax, coal tax, ETS, and CO_2/kWh reduction policy for the moderate policy scenarios, varying parameters across ranges of values in Appendix Table B1 and baseline energy price projections.

The percent reduction in CO_2 emissions under different policies is obviously sensitive to fuel price elasticities—for example, if the magnitude of fuel price elasticities is 50 percent larger than assumed in the central case, the percent reductions in CO_2 under different polices are increased by about 30–40 percent. Baseline energy prices also matter—with IEA (2015) price projections, the percent CO_2 reductions under different policies are roughly a third smaller (as carbon charges have a smaller proportional impact on fuel prices). Changing income elasticities for energy products affects the baseline level of future CO_2 emissions but has essentially no effect on the policy-induced percent reductions in CO_2.

Revenue gains from fiscal policies as a percent of GDP are sensitive, but only moderately so, to different income elasticities, price elasticities, and productivity trends (as these all have some effect on the future size of tax bases relative to GDP).

Cumulative lives saved under policies over the 2017–30 period vary significantly with all of the sensitivity cases in Table 4 as they affect either baseline deaths and/or policy responsiveness. For example, under the low fuel price elasticity scenario the carbon and coal taxes save around 3.4 million lives (50 percent more than in the central case), while lives saved from these policies drops to just over 1.5 million under a lower scenario for baseline deaths from air pollution. Welfare gains (calculated as a present discounted value over the 2017–30 period and expressed as a percent of 2015 GDP) vary significantly in absolute terms under alternative parameter scenarios but the relative welfare gains from policies are fairly robust—in all cases in Table 4 the ETS achieves about half of the welfare gains from the carbon and coal tax, and the policy to lower CO_2/kWh in the power sector achieves about 25–35 percent of these gains.

Table 4. Sensitivity Analysis: Moderate Policy Scenarios in 2030

		CO2 reduction (%)				Revenue gain (% of GDP)				Cumulative lives saved (millions)				PDV of welfare gain (% of 2015 GDP)			
		Carbon tax	Coal excise	ETS	Reducing CO2/kWh for power	Carbon tax	Coal excise	ETS	Reducing CO2/kWh for power	Carbon tax	Coal excise	ETS	Reducing CO2/kWh for power	Carbon tax	Coal excise	ETS	Reducing CO2/kWh for power
Central case		19.3	18.4	11.1	7.1	1.7	1.3	0.8	0.1	2.3	2.3	1.2	0.6	33.6	32.5	16.3	8.8
Income elasticities	Low	19.2	18.4	11.1	7.0	1.3	1.0	0.6	0.1	1.9	1.9	1.0	0.5	28.0	27.0	13.6	7.3
	High	19.3	18.5	11.2	7.1	2.2	1.7	1.0	0.1	2.8	2.7	1.4	0.8	40.4	39.1	19.6	10.5
Price elasticities	Low	10.0	9.7	6.2	4.2	1.8	1.4	0.8	0.1	1.1	1.1	0.6	0.4	15.7	15.3	8.2	4.9
	High	26.2	24.9	15.1	9.8	1.6	1.2	0.7	0.0	3.4	3.3	1.7	1.0	49.3	47.4	24.0	12.9
Productivity growth	Low	19.0	18.1	11.0	6.1	1.9	1.4	0.8	0.1	2.4	2.4	1.2	0.6	40.1	38.9	22.0	12.6
	High	19.6	18.9	11.4	7.3	1.5	1.2	0.7	0.1	2.2	2.2	1.1	0.6	32.0	30.9	15.5	8.4
Mortality rates	Low	19.3	18.4	11.1	7.1	1.7	1.3	0.8	0.1	1.5	1.5	0.8	0.4	21.4	20.5	10.6	5.8
	High	19.3	18.4	11.1	7.1	1.7	1.3	0.8	0.1	2.7	2.7	1.6	1.0	40.0	38.9	22.7	13.8
Energy price projections	WEO	24.7	23.5	13.7	9.7	1.9	1.5	0.9	0.2	3.5	3.5	1.7	1.1	51.7	49.9	24.1	15.3
	IEA	15.8	15.2	9.3	6.0	1.5	1.2	0.7	0.1	1.6	1.6	0.9	0.5	24.2	23.4	12.0	6.6

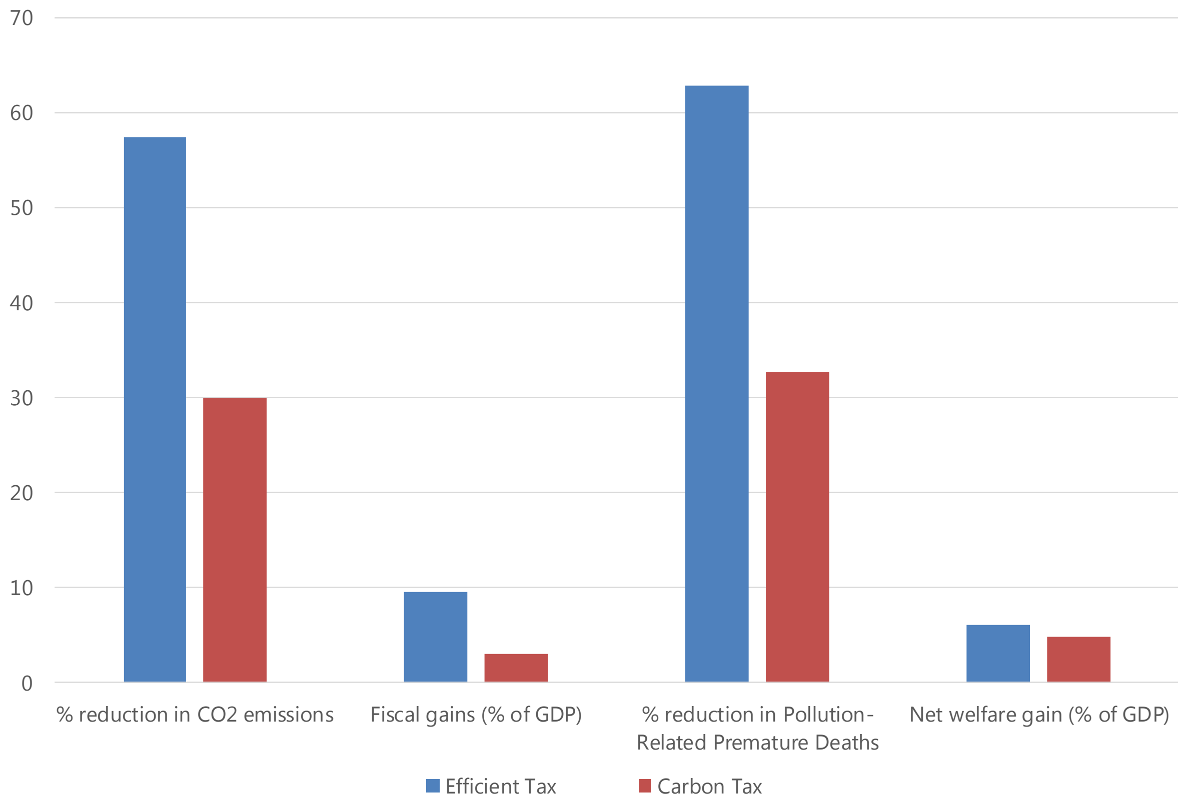
Source: From above equations, formulas in Appendix C, and parameter assumptions in Appendix B and D.

D. Comparison with a Fully Efficient Policy

Finally, Figure 15 compares the performance of the aggressive carbon tax in 2030 with that of an economically ideal policy that comprehensively charges fossil fuels according to estimates of global and domestic environmental costs (see Appendix D and E for details). (The performance of other policies relative to the fully efficient policy can be inferred from this graph and their performance relative to the aggressive carbon tax in the preceding figures). The purpose of this exercise is to explore to what extent there would be additional environmental, fiscal, and economic benefits from going beyond the policies considered above.

The fully efficient policy imposes, most notably, much higher taxes on coal (to reflect the domestic air pollution costs) than the aggressive carbon tax. It reduces CO_2 emissions in 2030 by 58 percent below baseline levels, reduces air pollution deaths by 63 percent, raises revenue of 8.5 percent of GDP, and generates a net domestic welfare gain (again, excluding global climate benefits) of 6.2 percent of GDP.[33] The aggressive carbon tax achieves 52 percent of the CO_2 reductions as under the fully efficient policy, 52 percent of the air pollution deaths, 79 percent of the domestic welfare gains, and 35 percent of the fiscal benefits. Therefore, even the aggressive policies considered above produce environmental, fiscal, and economic benefits that fall well short of those under a fully optimized pricing reform.

Figure 15. Performance of A Fully Efficient Policy in 2030



IV. Incidence of Energy Pricing Reform

Energy pricing reform will affect the economy and Chinese households through several channels. The economic impact will vary across industries and regions and will affect employment and earnings of different households differently. Through the higher production costs, energy and carbon pricing will also affect the return to capital and the associated capital income accrued by individuals. Finally, energy pricing reform will affect consumer prices. This in turn can be separated in direct and indirect effects (Arze del Granado, Coady, and Gillingham 2012). These effects are analyzed below.[34]

---

[33] A cautionary note here is that the uncertainties surrounding the effects of such dramatic policy changes are especially large.

[34] Regional analyses as well as full general equilibrium effects on production, labor, income and consumption are beyond the scope of this paper.

A. Incidence of a Carbon Tax on Households

The policy scenario consists a tax of $2.50/ton of carbon emitted in 2017 with equal increases every year through 2030. Given the static nature of our incidence analysis, we consider the effects of the tax at the sectoral and household level using projected energy price levels that will be reached in 2020. This exercise can easily be replicated for other years as well. For simplicity, we maintain the economic structure and consumption patterns of 2012, the latest year for which the national input-output table and household survey data are available to us. The expected rebalancing of the Chinese economy will lead to a different economic structure than the one observed in 2012. For example, car ownership is expected to increase for lower and middle income households. This would in turn lead to higher gasoline consumption for households throughout the income distributions. However as long as rebalancing otherwise reduces the energy budget shares for all household groups in roughly the same proportion, the current exercise should provide useful indicative results for policy analysis.

The impact of a carbon tax on consumer prices can be separated into a direct effect and an indirect effect. The direct effect is caused by higher prices for energy products consumed directly by households for cooking, heating, lighting and private transportation. The indirect effect comes from a higher cost of energy as input into the production of a broader range of goods and services consumed by households. The size of the two impacts depends on the relative share of household consumption spent directly on energy products and how energy intensive is the total consumption basket. If higher-income households have relatively more energy intensive consumption than the consumption patterns of lower-income groups, then the total impact of a carbon tax will be increasing in income levels.

As discussed in Anand and others (2013) the direct impact of a carbon tax, expressed as a percentage of total household consumption, can be calculated as:

$$\text{Direct Impact} = \text{Budget Share} * \text{Percentage Increase in Fuel Price}$$

If the budget share for a certain energy product is 5 percent for example, a 10 percent increase of this fuel price will result in a decrease in real income for the household equivalent to 0.5 percent. This estimate of the direct impact implicitly assumes that households do not substitute away from the product being taxed, i.e. that quantities of fuel consumed directly do not change. It is therefore often interpreted as either an estimate of the short-run impact (i.e., before households can adjust fuel consumption) or as an upper-bound of the long-run estimate.[35]

Assessing the direct effect of a carbon tax requires detailed information on household spending by type of products. The China Family Panel Studies (CFPS)[36] provides data on household

---

[35] Incidence with pre-existing market distortions should ideally be measured by the consumer surplus loss trapezoid. The direct impact measure is very close to the first order losses we estimate—e.g., only a 5 percent difference between the two for a policy change that reduces fuel consumption by 10 percent.

[36] See www.isss.edu.cn/cfps/EN.

expenditures for 25 aggregated categories of goods and services. The latest year available for the survey is 2012 and includes information from a nationally representative sample of more than 13,000 households throughout China.[37] The data are used to calculate expenditures and budget shares for each product. The budget share is calculated by dividing expenditure on individual goods and services by total household consumption.[38] Figure 16 below presents the budget share for households' direct consumption of energy for each consumption decile. Households at the bottom of the income distribution spend a substantially higher share of their total expenditure on energy, around 10 percent for the lowest decile. Higher income and consuming households instead spend around 4 percent of total household expenditures directly on energy.

The composition of energy consumption also differs across consumption groups with lower-income groups allocating a relatively higher share of energy expenditure to coal, electricity, heating and natural gas. Higher-income groups spend more on gasoline. The relatively large spending shares on electricity by lower income groups' is an interesting feature of these data in China and differs from the patterns in many developing economies where access to electricity is usually low for poor households with correspondingly low spending on electricity. Energy needs are then met by relying on other energy sources such as kerosene (Arze del Granado and others 2012). The decreasing share of electricity is in fact closer to what in observed in advanced economies, in particular the United States (Morris and Mathur 2015).

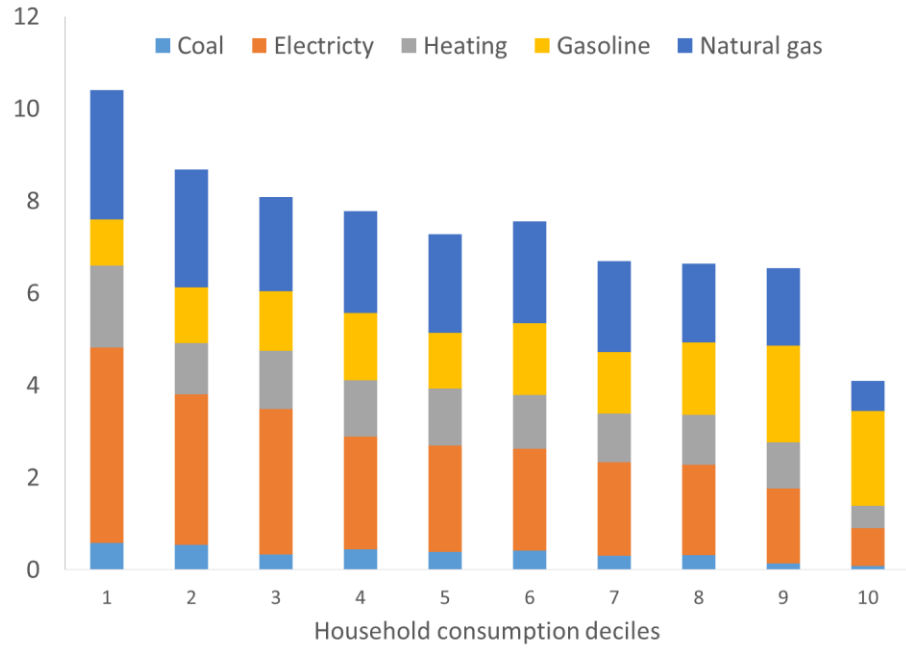
Finally, Figure 16 also shows sharp differences between the energy shares of households in the 9th and 10th deciles, and between households in the 1st and 2nd deciles. These large drops are mostly due to a denominator effect from very low consumption levels for households in the bottom decile and very high overall consumption levels for households in the top decile. When plotting energy spending per capita or per household instead, one finds strongly increasing patterns across the distribution. These drops are therefore the result of the high levels of income and consumption inequality in China.

---

[37] The CFPS is conducted by the Institute of Social Science Survey at Peking University. The survey covers about 95 percent of the Chinese population in 25 provinces. Income distribution and poverty studies have found the CFPS to be consistent with other large-scale nationally representative household surveys in China. Zhang and others (2014) find that poverty levels are much higher in these surveys than those reported in official statistics. Xie and others (2014) find the sex–age structure of the 2010 CFPS survey closely tracks the 2010 Census.

[38] Spending on electricity is estimated from electricity consumption taken from the CFPS and average residential electricity prices by province taken from Fridley and others (2014).

Figure 16. Composition of Household Energy Expenditure by Income Group, 2012
(in percentages of total household expenditure)



Source: IMF Staff estimates based on the CFPS 2012.

In addition to a real income loss that is directly due to higher energy prices, an assessment of a carbon tax needs to take into account the indirect effects through the price increase of other goods and services purchased by households. To estimate this indirect impact, we use the approach developed by Coady and Newhouse (2006), which assumes that increases in energy production costs are fully and immediately passed forward onto the domestic output prices of goods and services.

Estimating the price increases across a broad set of consumption items also requires information on the structure of production in China. This is typically found in input-output tables which provides the share of different inputs in the production cost structure. We use China's national input-output table for 2012, the latest version published by the National Bureau of Statistics. The table is disaggregated into 139 sectors and we make use again of the assumption of zero input demand price elasticity. As was the case for household demand for energy products, this means that our estimates of pass through to input and consumer prices should also be interpreted as short-term impacts or upper-bounds on long-term impacts. In quantitative terms given the price increases we are studying, this approximation seems reasonable for our purposes.

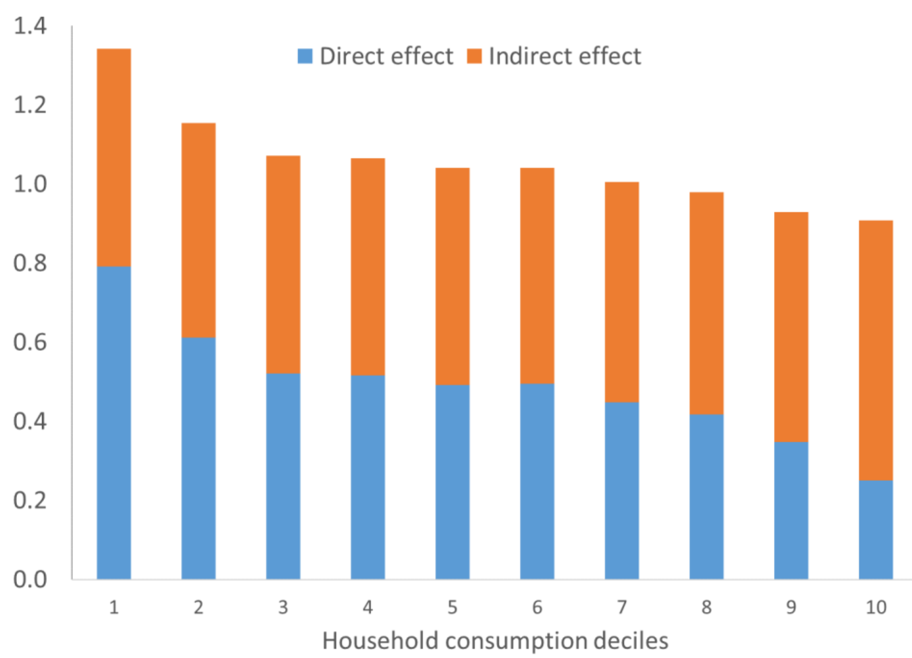
A modest $2.50/ton annual increase for a carbon tax would result in a rate of $10/ton of CO_2 in 2020. In turn, this would lead to first round effects on the price on energy products given our model's parameters. Specifically, we find that compared to baseline the price of coal in 2020 would be 23 percent higher, the price of electricity 6 percent higher, the price of natural gas 6 percent higher and the price of gasoline 3 percent higher. These price hikes would have a direct effect on households' purchasing power as illustrated by Figure 17. They would also lead to higher prices for most of the consumption basket of Chinese households through indirect effects.

The goods and services most impacted by energy price increases from a carbon tax include water, furniture, transport, communications and cars. These price increases are a function of the production technology and relative energy intensity as measured in the input-output table. While these consumption categories would be expected to see the highest consumer price increases, they don't necessarily have the highest share in the average consumption basket. The real income loss described above requires the price change to be multiplied by the relative consumption share of the goods and services affected. Because they constitute much larger consumption shares on average, the indirect impact from food, medical expenses, clothing, cigarettes and alcohol would have the largest impact on households' purchasing power.

The total impact of higher energy prices on real household incomes, and how it varies across the distribution of household consumption, is presented in Figure 17. We find that on average, the introduction of a modest carbon tax would increase consumer prices on average by around 1.1 percent by the year 2020. The size of the impact varies systematically across household consumption groups. Once again we find that the total effect is regressive, i.e., lower income households bear a larger relative burden from the introduction of the tax than households with higher consumption levels. The main reason is that electricity prices rise substantially and low income households have significantly higher budget shares for electricity.

Figure 17. Impact of a Carbon Tax, 2020

(in percent of total household consumption)



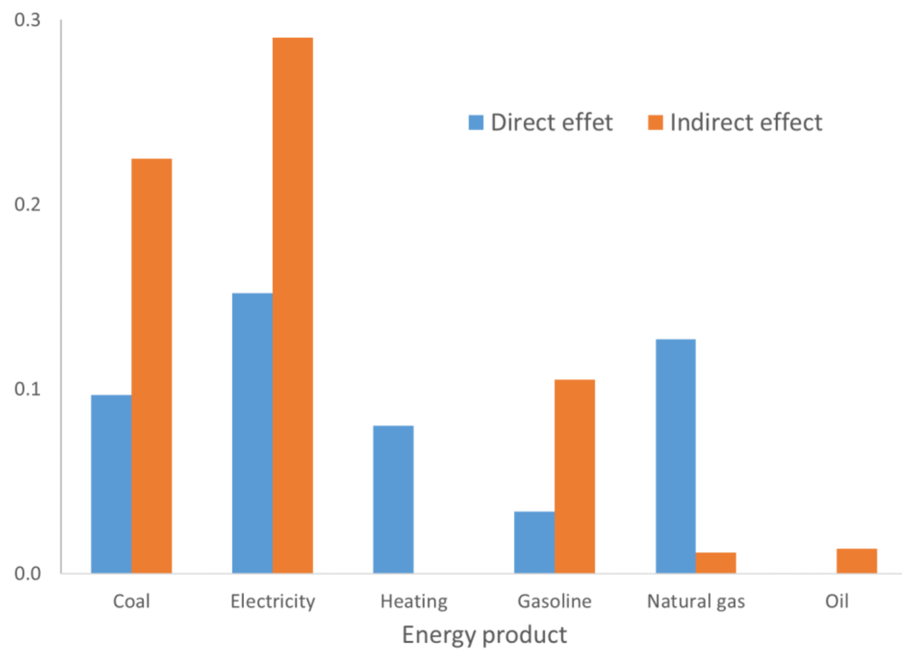
Source: IMF Staff estimates based on the 2012 CFPS and NBS 2012 Input-output table.

Figure 17 also shows that the regressivity of the carbon tax is entirely due to the direct price effect. This is consistent with the energy consumption patterns presented in Figure 16 where electricity, heat, coal, natural gas and coal consumption are higher for low income households. The indirect effect of the carbon tax is in fact increasing in household income levels, albeit at a slower rate than the reduction of the direct effect. This implies that richer households tend to consume more energy-intensive goods and services.

Another way of looking at the incidence of a carbon tax is to examine the direct and indirect effects by energy product (Figure 18). While the price of coal would increase substantially under a carbon tax due to a high emission rate, its direct impact on a broad consumer price index weighted across all consumer goods would be more limited. This is because coal is a small share of the price index. The price of electricity on the other hand would have a very large negative impact on real incomes since electricity consumption is such a large share of household spending, especially for the lowest income deciles. In addition, as an input for many goods and services consumed by households, its price increase would lead to a large indirect effect on households' purchasing power. Figure 18 also shows that the direct effect of natural gas price increase would be substantial. As would be the indirect effect of gasoline prices, mainly due to higher transportation costs.

Figure 18. Impact of a Carbon Tax by Energy Product

(percent change compared to baseline)



Source: IMF Staff estimates based on the 2012 CFPS and NBS 2012 Input-output table.

The incidence analysis of the other reforms discussed above reveal broadly similar patterns throughout the household income distribution. All the reform packages analyzed have a regressive impact on consumption, with the aggressive carbon tax having the largest while regulatory measures have the most benign impact. The absolute cost imposed on households is also in line with the aggregate welfare costs estimates shown in Figure 14.

We have thus far used household consumption (per person) to assess the distributional impact of consumer price changes of a carbon tax. This measure provides a reasonable approximation of individuals' welfare and lifetime income potential and it is widely used for policy analysis. An alternative measure is to look at household incomes. Individuals and households differ in terms of how much they save, due to factors such as savings rate, the rising wage profile over the lifecycle or temporary income shocks such as health or unemployment. Therefore, in any given year an individual's consumption might differ substantially from her current income if she is able to draw down her savings, borrow or receive public or private transfers. Using income instead of consumption could therefore potentially lead to different conclusions regarding the incidence of a carbon tax in China. Nevertheless, a similar graph using household current income both to rank households by income level and normalize the price impact faced by consumers yields qualitatively similar results. This confirms the regressive impact of the introduction of a carbon tax in China.

While it is broadly accepted that consumption is a better proxy for permanent income, in practice only current income may be observed by the government. This could lead to some targeting issues. To assess the potential scope leakage of government transfers, we present in Figure 19 a further breakdown of the data to measure the incidence of a carbon tax. The figure shows the average loss of real consumption due to consumer price increases using two alternative definition of quantiles: household consumption per capita and household income per capita. The blue line shows a similar effect documented above in Figure 18: households that are better off in terms of total consumption per person also bear a relatively lower burden from a carbon tax. The dashed orange line uses household income instead and in this case, the regressivity is not as apparent. While the lowest income households do face a higher-than-average burden, the difference is more muted. Moreover, households with the highest incomes in fact face the largest relative loss of purchasing power due to increases in energy prices.[39]

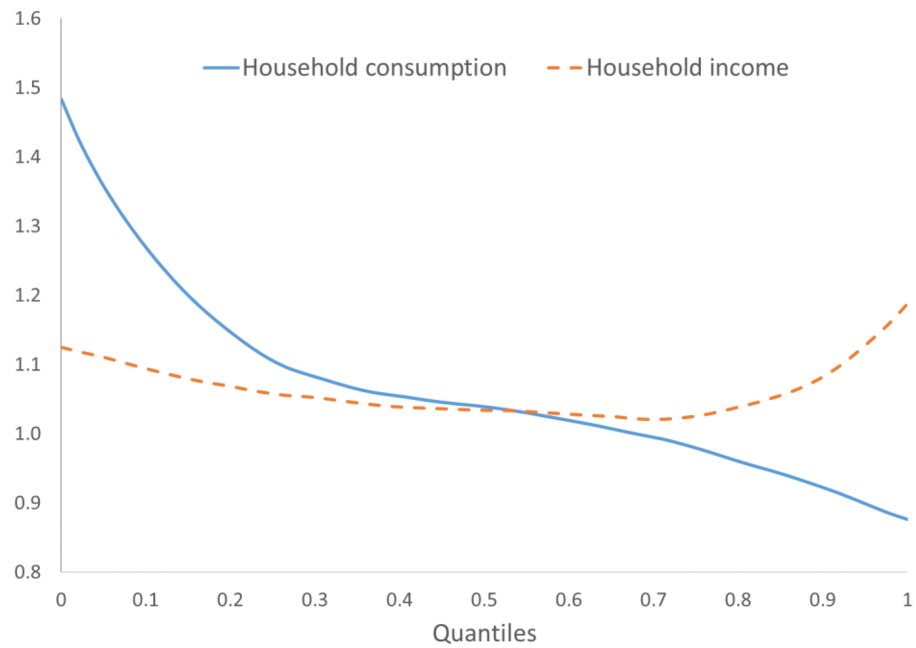
A potentially important insight of these findings is that is that if government wishes to use fiscal transfers to compensate the poorest, care should be given in the identification of the neediest households. In particular, only using current income as the basis for compensation might transfer more resources to income-poor households that in fact don't face such a large loss in purchasing power as a share of their total consumption as revealed by Figure 19. In addition to such potential leakage, targeting households based on aggregate consumption or current income net of savings can be quite data intensive and challenging. It might therefore be important to complement income-based eligibility requirements for transfer programs with other indicators of

[39] The difference between the two curves is unclear and might be due to the very high savings rate of Chinese households, especially among higher incomes. Underreporting of income might also explain some of this divergence. Further breakdowns of these effects reveal that the difference in the degree of progressivity operates almost entirely through the direct impact of energy prices. This result also differs from the United States. Morris and Mathur (2015) use broadly similar methodologies and find that the regressivity of a carbon tax is higher when using income as a measure of socioeconomic status

financial deprivation such as asset tests, home ownership status, age, etc. to mitigate the adverse effects of higher energy prices following the introduction of a carbon tax in China.

Figure 19. Distributional Impact of a Carbon Tax: Consumption vs. Income

(in percent of total household consumption)



Source: IMF Staff estimates based on the 2012 CFPS and NBS 2012 Input-output table.

The introduction of a carbon tax will change the price paid by consumers for goods and services. It will also have an impact directly on household incomes. This channel however is not as straightforward to estimate. For example, the effects are likely to vary systematically across industries and regions. Workers and business owners will also experience different effects as the return to capital and labor are likely to diverge. The simplistic assumption of no demand price elasticity would also be inadequate in a more general equilibrium framework. Still another crucial factor when analyzing the impact on incomes is the use of revenues generated from a carbon tax. The regressive impact documented above can be mitigated to an extent by targeted cuts in social security contributions or increases in welfare and social spending to compensate the poorest households. This is also a potentially important design difference between a carbon tax and an emission trading system (ETS). In particular, if emissions rights are not auctioned but simply given to polluters, as was the case for several pilot programs in China (WBG 2015), then these emission rights constitute economic rents that will accrue to the owners of the capital benefitting from the windfall gains. Higher income households overwhelmingly benefit from these rents through the receipt of dividends and capital gains.[41] The revenue generation and potential for recycling is therefore an important advantage a carbon tax offers compared to an ETS.

[41] Parry (2004).

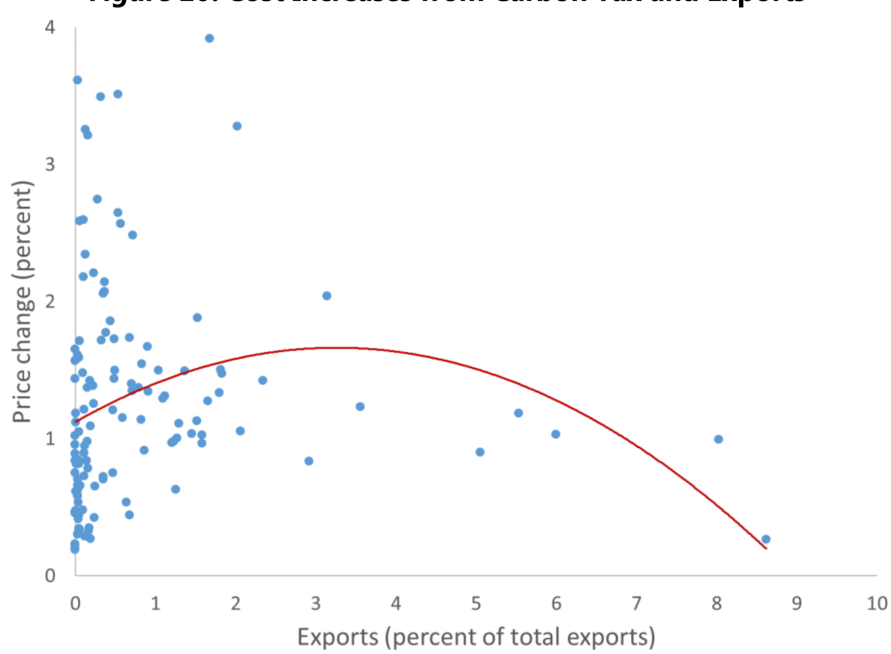
B. Sectoral Incidence

Increasing energy prices will have non-negligible effects on cost, production and the competitiveness of the Chinese economy. This is particularly true for coal given its outsize contribution to China's energy production. However, as just discussed without a general equilibrium model in which firms and individuals adjust demand and supply in response to price changes, it is difficult to evaluate the full effects of introducing a carbon tax. The use of revenues from a carbon tax, estimated to be around 1.7 percent of GDP per year under a modest policy scenario, is also crucial element of this exercise. In some cases, revenue recycling in the form of a corporate income tax cut or border carbon adjustment can offset some of the negative impacts on industry costs and competitiveness.

The introduction of a carbon tax will increase production costs across all industries. An important policy consideration is whether energy intensive and trade-exposed sectors will be relatively hard hit by such cost increase. This would obviously have important macroeconomic implications as decreased competitiveness would hurt Chinese exports and lower growth. This decrease in exports in addition will also lead to carbon leakage as production that leaves China would likely migrate to a jurisdiction without a carbon tax and therefore with lower production costs.

To assess the extent to which a moderate carbon tax would increase cost across industries, we plot in Figure 20 the estimated increase in sectors' costs against their respective contribution to the country's total exports. The figure shows that while there is no clear pattern emerging, the sectors that contribute most to total exports are also among those that would face the smallest cost increase from higher energy prices. Most of the hardest hit sectors are in fact those that with small export shares.

Figure 20. Cost Increases from Carbon Tax and Exports



Source: IMF Staff estimates based on the NBS 2012 Input-output table.

Table 4 lists the 10 sectors most and least impacted by the introduction of a carbon tax based on energy intensity of production estimated from the input-output coefficient matrix. All the sectors listed in the top panel are heavy industries associated with the 'old growth' model. In contrast, sectors that would experience the smallest cost increase are overwhelmingly in the service sector or in the consumer goods sectors such as tobacco and fishery. These results suggest that a carbon tax would also promote the rebalancing of the Chinese economy from heavy manufacturing, investment and real estate to services and consumption-led growth.

Table 5. Estimated Cost Increase from Moderate Carbon Tax, 2020

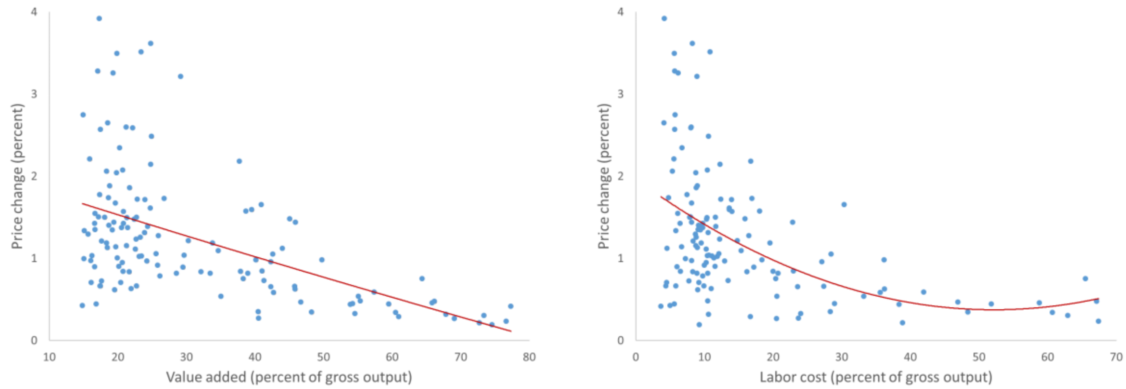
Sectors Most Affected	***Cost Increase***
Basic Chemical Raw Materials	3.9
Cement, Lime And Gypsum	3.6
Brick, Stone And Other Construction Materials	3.5
Fertilizer	3.5
Steel Flat-Rolled Products	3.3
Steel, Iron And Cast	3.3
Graphite And Other Non-Metallic Mineral Products	3.2
Chemical Fiber Products	2.7
Composites	2.6
Ferroalloy Products	2.6
Sectors Least Affected	
Real Estate	0.19
Capital Market Services	0.21
Social Security	0.23
Wholesale And Retail	0.27
Insurance	0.27
Monetary And Financial And Other Financial Services	0.29
Education	0.30
Tobacco Products	0.32
Entertainment	0.33
Fishery Products	0.34

Source: IMF Staff estimates based on the NBS 2012 Input-output table.

Similar results can also be easily estimated for sectors' share of value added and labor intensity. Panel a) in Figure 21 displays a strongly negative correlation between cost increases from a moderate carbon tax and the degree of value added by sector. This again suggest that a carbon tax would promote rebalancing by affecting relatively less the cost structure of sectors with high value added. We find a similar pattern for labor share of total output by sector in panel b). This suggests that labor intensive sectors would benefit more in relative terms, thereby promoting a rising share of labor and household income.

Figure 21. Sectoral Cost Increase and Rebalancing Indicators

a) Value Added Ratio b) Labor Intensity



Source: IMF Staff estimates based on the NBS 2012 Input-output table.

V. Administrative and Design Issues

A carbon tax imposed at the point of entry (hereafter called an upstream tax) in the economy would be the simplest way to design and administer the tax. The tax would be imposed either at the mine mouth or processing plant (where coal is washed and debris and waste is removed). The grading of coal for commercial purposes would also be the natural point where carbon content would be measured for purposes of assessing the tax base. For petroleum products, the tax would be levied at the refinery or gas processing plants. Import fuel would be taxed at the border.

An important advantage of an upstream tax is that it would build off the administrative structures already in place for China's Resource tax. An important change however would require the tax to either be converted back to a specific amount or to add an amount in RMB per unit in addition to the ad valorem structure recently introduced. This is because the externality-correcting tax should reflect the damages incurrent for use of the resource. These damages do not vary with the nominal value of coal or petroleum products, but are fixed in terms of quantities used. The tax should therefore reflect this fundamental feature of carbon emissions. Finally, a pure carbon tax would apply to the measured carbon content of fossil fuel and would therefore vary by geography and type of fuel. A coal excise on the other hand would simply apply to some quantity of the resource without taking into account the chemical composition of the mineral.

An upstream tax also has the benefit of requiring fewer points of collection and taxpayers responsible for remitting the tax. The alternative of taxing either combustion or consumption downstream on the other hand would involve far more taxpayers, transactions and taxable events. There are currently in China approximately 11,000 coal mines, but the government's restructuring plans for the sector will involve about 4,300 coal mines closures over the few years. There are far fewer coal preparation plants, petroleum refineries and gas processing plants. This would contrast, by orders of magnitude, with the number of transactions the tax administration would have to monitor in order to collect a carbon tax downstream. Another alternative would be to monitor the emissions of a select number of large emitters. This is the case of the European trading program and the ETS that will be introduced in China in 2017. However, measuring emissions is technically much more challenging than measuring carbon content of fuel before combustion (Calder 2015). This requires a high level of technical expertise that is typically not found in tax administrations. Because of the high costs of monitoring, trading systems usual only focus on large emitters. In China, this means that the ETS covers only half of all carbon emissions. An upstream tax would cover all the carbon emitted and thereby improve the effectiveness of measures aimed at curbing emissions.

VI. USE OF REVENUES

A well-designed carbon tax has the potential to generate significant revenues for the government. Over the next 15 years of so, a moderate carbon tax would collect close to 1.7 percent of GDP. Some of these revenues could be used to alleviate the impact of the tax on industries and regions most affected by the cost increases. This could be done for example through corporate income tax rebates. While such measures would undo to some extent the carbon-reducing incentives of the tax, the magnitudes involved to compensate energy-intensive exporting industries would not be very large as evidence by Figure 20.

As is often the case in many countries, energy pricing reform would also result in a particularly large burden on the less well off. Carbon tax revenues could be used to reduce tax the high rates that are effectively imposed on low income earners through high rates of social security contributions (de Mooij et al. 2016). Further, some of these revenues could also be used to increase social spending for vulnerable groups in areas such as health care, education and pensions, programs where China has been lagging relative to OECD countries and other middle income countries (Lam and Wingender 2015). Health care spending is also expected to increase dramatically solely as a result of demographic trends. Policy commitments to expand education and pension coverage would significantly add to the spending. A carbon tax could therefore be an important source of revenue to support this important reform program.

Finally, some of the revenues could be transferred to local governments in regions affected by higher costs associated with coal production in particular. The economic and structural transformation that would follow a re-pricing of energy and coal would impose potentially large costs concentrated in a few localized areas. Given the current limited resources at local government's disposal, revenue-sharing of a carbon tax could be beneficial to support social services and income support programs.

VII. CONCLUSION

The analysis in the paper indicates that a carbon tax (or coal tax) would be the most effective policy for reducing CO_2 emissions, raising revenue, and reducing local air pollution. For example, a modest carbon tax of RMB 15 per ton in 2017 of carbon rising to RMB 227.5 in 2030 should easily enable China to meet its emission reduction pledges for the Paris Agreement, while also saving an estimated 3 million lives during this period from lower local air pollution levels. Moreover, by contributing to coordinated efforts from the international community to slow global warming, such a tax will also reduce the negative impacts climate change will have in China, such as higher occurrence of natural disasters to which coastal areas are particularly vulnerable (World Bank and Development Research Center of the State Council 2013).

Such a tax would have the advantage of building on the existing structure of the resource tax. A carbon tax would be designed just as an excise, but with rates determined based on quantities of carbon as opposed to value of the fossil fuel. The carbon tax should also be introduced in a phased-in manner. With the rate increases announced in advance, firms and consumers would have time to adapt and undertake mitigation measures, such as the development of clean sources of energy like wind and solar or the construction of more efficient buildings.

Although China is planning to implement an ETS on the power sector and large industrial carbon emitters in 2017, this policy could be combined with a carbon tax on fuel supply to promote the full range of environmental and (with auctioned allowances) fiscal opportunities (the latter being important to provide revenues for compensating sectors and households vulnerable to energy price increases). Rebates for the tax could be provided to firms covered under the ETS to avoid disproportionately burdening them relative to emissions sources outside of the trading sector, though for practical purposes this may not be too important initially if emissions allowance prices are relatively modest.

A wide range of other policies considered—including taxes on road fuels and electricity and incentives for renewable generation, energy efficiency in different sectors, and lower emissions intensity of power generation—all have much lower environmental benefits than and at best relatively small fiscal benefits. These results highlight the importance for the government to rely on prices and markets to achieve the highest yields from environmental reform.

Overall, carbon pricing (through a tax or a tax-ETS combination) can address not only the negative externalities from pollution but will also promote more sustainable and greener growth. Given that sectors most dependent on coal and energy are heavy industries associated with the 'old growth' model, a carbon price set at a moderate but effective rate will support China's effort to rebalance its economy towards high value-added services and consumption-led growth.

APPENDIX A. PRIOR LITERATURE ON CLIMATE POLICY OPTIONS FOR CHINA

There are a number of engineering models of the energy system in China focusing on technological pathways for reducing future CO_2 emissions, for example, Mischke and Karlsson (2014) review 18 models developed by Chinese universities. The projections from these models serve as a useful check on the baseline projections in the present analysis (with some caveats about very recent structural shifts in the Chinese economy and reductions in energy prices). However, the models generally do not incorporate the impacts of specific mitigation policies and the key behavioral response assumptions implicit in the models are not always transparent.

Green and Stern (2016) also provide baseline projections for China using extrapolations of very recent trends in the energy intensity of GDP and the emissions intensity of energy, rather than an explicit structural model. Their CO_2 emissions projections, which emphasize structural changes in the economy, are lower than in the present analysis (see Appendix B and Section 3).

As regards modelling of specific carbon mitigation policies, Cao and others (2013) provide a sophisticated analysis of a carbon tax in China using a model that integrates a detailed treatment of air pollution damages into an economic-energy model incorporating capital dynamics and disaggregating 33 different industries. With similar assumptions about the price responsiveness of coal use, our results on the long run effectiveness of carbon taxes on reducing future CO_2 emissions are consistent in a broad sense, as are the reductions in deaths from less local air pollution.[42] The present analysis differs from Cao and others (2013), both in terms of scope and modelling approach. The focus here is on a broad range of fiscal and regulatory carbon mitigation instruments (well beyond carbon taxes) and these policies are also evaluated against a broader range of metrics (beyond emissions and public health effects). And the modelling strategy is highly simplified, given the goal of providing a user-friendly spreadsheet tool to readily accommodate updating and additional policy and sensitivity analysis.

The present analysis, in terms of its comparison of multiple instruments against multiple metrics, is closest in spirit to that in Krupnick and others (2010) who simulated a wide range of policies and policy combinations to reduce U.S. CO_2 emissions and oil consumption. Besides focusing on another country, that study also employed a far more sophisticated modelling approach, based on a variant of the U.S. Department of Energy's National Energy Modelling System (NEMS), with each model simulation run by a consultancy firm specializing in the use of NEMS. The qualitative rankings of many policies in terms of their effectiveness at reducing CO_2 are consistent with those here, though this is not surprising given that effectiveness depends on the range of behavioral responses for reducing emissions exploited by different policies.

Finally, the International Energy Agency (IEA) makes annual forecasts for China in its *World Energy Outlook*. Our baseline projections are compared with those in their latest report (IEA 2015) (see Section IIIA).

---

[42] Cao and others (2013) caution that chronic mortality effects of air pollution—which are the much larger component—are far more speculative than the acute effects, as the former is based pollution exposure/mortality relationships estimated for the United States rather than China (both chronic and acute mortality is implicit in the present analysis). However a recent study by Burnett and others (2013) suggests that (albeit limited) evidence on this relationship for other countries is broadly consistent with that for the United States.

APPENDIX B. MODEL PARAMETERS

Quantity and price data are taken from the IEA and the IMF respectively, and behavioral response parameters are based on empirical literature. Data for each sector is described below and is summarized in Table B1. Where there is significant uncertainty for parameters, a range of values is considered for sensitivity analysis.

Table B1. Parameter Values

Parameter, units	Baseline or central value (applied in year 2013)	Range for sensitivity analysis (if appropriate)
Primary fuel prices and taxes (in units of year 2013 RMB)		
$\tilde{p}_0^{COAL}$, RMB/GJ	29 ($4.40)	
$\tilde{p}_0^{NGAS}$, RMB/GJ	119 ($18.25)	
$\tilde{p}_0^{GAS}$, RMB/liter	6.1 ($0.94)	
$\tilde{p}_0^{DIES}$, RMB/liter	6.3 ($0.97)	
$\tilde{p}_0^{OIL}$, RMB/barrel	676 ($104)	
τ_0^{COAL} , RMB/GJ	0	
τ_0^{NGAS} , RMB/GJ	0	
τ_0^{GAS} , RMB/liter	1.04 ($0.16)	
τ_0^{DIES} , RMB/liter	0.85 ($0.13)	
τ_0^{OIL} , RMB/barrel	0	
Power sector		
Y_0^E , ktoe	386,971	
υ^E	.5	.25 to .75
η^{UE}	-.25	-.1 to -.4
η^{hE}	-.25	-.1 to -.4
α^E	.01	.005 to .015
θ_0^{ECOAL}	.76	
θ_0^{ENGAS}	.02	
θ_0^{EOIL}	.001	
θ_0^{ENUC}	.02	
θ_0^{EREN}	.04	
θ_0^{EHYD}	.17	
$\tilde{\epsilon}^{ECOAL}$	-.6	-.35 to -.85
$\tilde{\epsilon}^{ENGAS}$	-.6	-.35 to -.85
$\tilde{\varepsilon}^{EOIL}$	-.6	-.35 to -.85
$\tilde{\varepsilon}^{ENUC}$	-.6	-.35 to -.85
$\tilde{\epsilon}^{EREN}$	-.6	-.35 to -.85
$\tilde{\varepsilon}^{EHYD}$	-.6	-.35 to -.85
F_0^{ECOAL} , ktoe	930,333	
F_0^{ENGAS} , ktoe	7,790	
F_0^{EOIL} , ktoe	559	

	ρ_0^{ECOAL}, GWh/TJ	0.73	
	ρ_0^{ENGAS}, GWh/TJ	0.71	
	ρ_0^{EOIL}, GWh/TJ	0.79	
	ρ_0^{ENUC}, GWh/TJ	0.84	
	ρ_0^{EREN}, GWh/TJ	0.42	
	ρ_0^{EHYD}, GWh/TJ	0.28	
	$\alpha^{\rho COAL}$	.005	0 to .01
	$\alpha^{\rho NGAS}$	.02	.01 to .03
	$\alpha^{\rho OIL}$	.005	0 to .01
	$\alpha^{\rho NUC}$	.02	.01 to .03
	$\alpha^{\rho REN}$	.045	.03 to .06
	$\alpha^{\rho HYD}$	.005	0 to .01
	k_0^{ECOAL}, $/kWh	.03	
	k_0^{ENGAS}, $/kWh	.007	
	k_0^{EOIL}, $/kWh	0.03	
	k_0^{ENUC}, $/kWh	0.08	
	k_0^{EREN}, $/kWh	0.2	
	k_0^{EHYD}, $/kWh	0.07	
	s_0^{EREN}, $/kWh	.03	
	k_0^{ET}, $/kWh	.05	
Transport sector			
	F_0^{TGAS}, ktoe	96,471	
	F_0^{TDIES}, ktoe	170,729	
	υ^{TGAS}	.6	.4 to .8
	υ^{TDIES}	.6	.4 to .8
	η^{UTGAS}	-.25	-.1 to -.4
	η^{UTDIES}	-.25	-.1 to -.4
	η^{hTGAS}	-.25	-.1 to -.4
	η^{hTDIES}	-.25	-.1 to -.4
	α^{TGAS}	.01	.005 to .02
	α^{TDIES}	.01	.005 to .02
Other energy sector			
	$F_0^{OLARGECOAL}$, ktoe	231,413	
	$F_0^{OSMALLCOAL}$, ktoe	782,548	
	$F_0^{OLARGENGAS}$, ktoe	13,469	
	$F_0^{OSMALLNGAS}$, ktoe	103,409	
	$F_0^{OLARGEOIL}$, ktoe	3,514	
	$F_0^{OSMALLOIL}$, ktoe	243,092	
	$F_0^{OLARGENREN}$, ktoe	0	
	$F_0^{OSMALLNREN}$, ktoe	219,993	
	υ^{OCOAL}	.5	.25 to .75
	υ^{ONGAS}	1.0	.75 to 1.25
	υ^{OOIL}	.5	.25 to .75
	υ^{OREN}	1.0	.75 to 1.25

	η^{UOCOAL}	-.25	-.1 to -.4
	η^{UONGAS}	-.25	-.1 to -.4
	η^{UOOIL}	-.25	-.1 to -.4
	η^{UOREN}	-.25	-.1 to -.4
	η^{hOCOAL}	-.25	-.1 to -.4
	η^{hONGAS}	-.25	-.1 to -.4
	η^{hOOIL}	-.25	-.1 to -.4
	η^{hOREN}	-.25	-.1 to -.4
	α^{OCOAL}	.005	0 to .01
	α^{ONGAS}	.02	.01 to .03
	α^{OOIL}	.005	0 to .01
	α^{OREN}	.045	.03 to .06

(i) Fossil Fuels

Fuel prices and taxes/subsidies. Pre-tax prices for coal, natural gas, gasoline, diesel, and oil products for 2013 are from an IMF data based on international prices. These prices are then projected forward to 2030 based on splitting the difference between IMF[43] and IEA (2015) projections of international commodity price indices for coal, natural gas, and crude oil.

Also from IMF sources, pre-tax excises for gasoline and diesel are RMB 1.0 ($0.16) and RMB 0.85 ($0.13) per liter, while there are no other significant excises (or subsidies) for other fossil fuel products.

(ii) Power Sector

Electricity consumption. From IEA (2015), total electricity consumption in China in 2013 is 386,971 kilotons of oil equivalent (ktoe).[44]

Income elasticity of demand for electricity-using products. Empirical studies for different countries suggests a range for this elasticity of around 0.5–1.5.[45] However, China is currently undergoing an important, partial transition away from energy-intensive industries to services, suggesting that demand for energy products will increase by substantially less than in proportion to GDP growth.[46] This trend can be accounted for in the model by choosing a lower value for the income

[43] See www.imf.org/external/pubs/ft/weo/2015/02/weodata/weoselagr.aspx. The indices (based on futures prices) are for Australian thermal coal; Indonesian liquefied natural gas in Japan; and an average of Brent, West Texas Intermediate, and Dubai Fateh spot crude oil prices.

[44] Generation, rather than consumption, is what matters for fuel use and emissions, though the difference between them (reflecting electricity exports and imports) is well below 1 percent.

[45] For example, Jamil and Ahmad (2011), Table 1, report 26 estimates of long-run income elasticities for electricity from 17 studies, almost all of them lying within the above range.

[46] See, for example, GCEC (2014), Green and Stern (2016), Grubb and others (2015), and IMF (2015).

elasticity of electricity and other industrial energy products. A baseline value of 0.5 is used for the income elasticity for electricity which (along with other assumptions) produces projections of future energy intensity that are about in the middle of projections from other studies (see Section IIIA). A range of 0.25-0.75 is used for sensitivity analysis.

Price elasticities for electricity. A simple average across the 26 estimates of long-run electricity demand elasticities reported in Jamil and Ahmad (2011) is about -0.5, and nearly all estimates lie within a range of about -0.15 to -1.0.[47] A recent study for China by Zhou and Teng (2014) suggests an elasticity of -0.35 to -0.5. Evidence for the United States suggests the long-run price elasticity for electricity demand is around -0.4, with about half the response reflecting reduced use of electricity-consuming products and about half improvements in energy efficiency (e.g., Myers and others 2009, Parry and others, 2014, Sanstad and McMahon 2008). Baseline values of -0.25 are assumed for both the usage and energy consumption rate elasticities, each with ranges of -0.1 to -0.4, implying a total electricity demand elasticity of -0.5, with range -0.2 to -0.8.

Annual rate of efficiency improvement for electricity-using products. This parameter (which is of modest importance for the results) is taken to be 0.01 in the baseline,[48] with range 0.005 to 0.015.

Generation shares. These are obtained from IEA (2016) by the electricity produced from each fuel type divided by total electricity production.

Own-price elasticities for generation fuels (conditional on total electricity output). The price responsiveness of coal (in the power and other energy sector) is the most critical parameter determining the effectiveness of major CO_2 mitigation policies. Short run coal price elasticities among eight studies for various advanced countries, China, and India summarized in Trüby and Paulus (2012), Table 5, are around -0.15 to -0.35 (aside from one study where the elasticity is -0.6). For the United States, simulations from a variant of the US Department of Energy's National Energy Modeling System (NEMS) model in Krupnick and others (2010), suggest a coal price elasticity of around –0.15 (with fuel switching rather than reduced electricity demand accounting for over 80 percent of the response).[49] On the other hand, Burke and Liao (2015) report a coal price elasticity for China of -0.3 to -0.7 for 2012 using a panel of province-level data. A baseline coal price elasticity of -0.35 is assumed here, with range -0.2 to -0.5.

However, the elasticities in equation (3) are defined with respect to (full) generation costs rather than fuel costs and can be obtained by dividing the fuel price elasticity by the share of fuel costs in generation costs, which is taken to be 0.6 in 2013 (see below). This gives (approximately) a generation cost elasticity of -0.6 with range -0.35 to -0.85.

[47] See Madlener and others (2011) for further discussion of the literature and broadly similar findings.

[48] This is consistent with similar assumptions for China in Cao and others (2012), pp. 389–90.

[49] NEMS tends to be less price responsive than other models and the above simulation was for a carbon tax which also raises natural gas prices and dampens the reduction in coal use.

Evidence to parameterize other generation cost elasticities is less solid, though the results are generally not very sensitive to different values. For simplicity, the same baseline generation cost elasticity, and range, is assumed for other generation fuels as for coal.

Fossil fuel consumption. This is consumption of coal, natural gas and oil in power generation, taken from IEA (2016). Electricity produced from a particular fossil fuel, divided by that fuel's consumption, gives the productivity of that fuel.

Annual rate of productivity improvement. Productivity improvements at power plants reflect improvements in technical efficiency and retirement of older, less efficient plants. For coal, annual average productivity growth during 2003 to 2013 was 2 percent, though IEA (2015) Figure 2.16 projects sharply lower productivity growth in the future (e.g., because average coal plant efficiency in China has now surpassed that in advanced countries): a baseline annual productivity growth rate of 0.5 percent is assumed for both coal (to be approximately consistent with IEA 2015) as well as oil and hydro, with a range of 0 to 1.0 percent used for sensitivity analysis. For natural gas and nuclear, there is likely more room for productivity improvements and baseline annual growth rate of 2 percent is assumed (with range 1 to 3 percent). For renewables, annual productivity growth from 2003 to 2013 was the most striking at 6 percent, though this seems unlikely to be sustainable out to 2030—a productivity growth rate of 4.5 percent is used in the baseline case for this fuel, with range 3 to 6 percent.

Non-fuel generation costs. For coal plants these are taken to be two-thirds as large as 2013 fuel costs,[50] or RMB 0.18 ($0.028) per kWh. For natural gas plants (which have low fixed and high variable costs), non-fuel generation costs are taken to be one quarter of those for coal plants.

Renewables subsidy. This is obtained by dividing subsidy outlays on renewables (RMB 45.5 ($7) billion—see Figure 1) by renewable generation in 2013 (208 GWh), which yields a subsidy of RMB 0.2 ($0.03) per kWh.

Power transmission cost. This is taken to be 60 percent of the electricity generation cost in 2013, or RMB 0.63 ($0.05) per kWh.[51]

(iii) Road Transport Sector

Fuel use. From IEA (2015), consumption of road gasoline and diesel was 96,471 ktoe and 170,729 ktoe respectively in 2013.

Income elasticity of demand for vehicle miles. Estimates of this parameter are typically between about 0.35 and 0.8, although a few estimates exceed unity (Parry and Small 2005). A value of 0.6 is used here, with range 0.4 to 0.8.

---

[50] Based on Cao and others (2013), pp 341 (after accounting for differences in coal prices).

[51] This is approximately consistent with Cao and others (2013), pp. 343.

Price elasticities. Numerous studies have estimated motor fuel (especially gasoline) price elasticities for different countries and some studies decompose the contribution of reduced vehicle miles from improvements in average fleet fuel efficiencies. Based on this literature, a value of -0.25 is used, with range -0.1 to -0.4, for each of these elasticities, and for both gasoline and diesel—the total fuel price elasticities are therefore -0.5 with range -0.2 to -0.8.[52]

Annual rate of decline in vehicle fuel consumption rates (from technological improvements). These are set at 1 percent, with range 0.5 to 2 percent a year (e.g., Cao and others 2013).

(iv) Other Energy Sector

Fuel use. We assume 50 percent of fuel consumption in IEA (2016) from mining and quarrying, iron and steel, chemical and petrochemical, non-ferrous metals, paper, pulp and print, and non-metallic minerals is by large firms, to be consistent with projections that an ETS would cover about 50 percent of economy-wide CO_2 emissions.[53]

Income and price elasticities for other energy products. Evidence on income and price elasticities for fuels used in the industrial and residential sectors is more limited and, based on judgement, similar assumptions are made as for the power and transport sectors.

The same baseline value and range is used for goods produced with coal and oil as for the income elasticity for electricity products (given the structural shift away from heavy industry noted above), while a baseline value of 1.0, with range 0.75 to 1.25, is assumed for goods produced with natural gas and renewables. The central values and ranges for the usage and efficiency price elasticities for all fuels are taken to be the same as those for road fuels and electricity consumption.

Annual rate of productivity improvements. These are assumed to follow those for the same fuel as used in the power sector, reinforcing the structural shift towards cleaner energy sources.

(v) Miscellaneous

GDP growth. Projected GDP out to 2021 is from the IMF's World Energy Outlook. From 2022 onwards, real GDP growth is assumed to decrease linearly from 6 to 5 percent in 2030.[54]

---

[52] There is, however, significant variation among studies: for example, Sterner (2007) reports globally averaged (long-run) gasoline price elasticities (the sum of the two elasticities noted above) of around –0.7 while individual country estimates in Dahl (2012) are closer to about –0.25 on average (see Charap, da Silva and Rodriguez 2013 for further discussion). For a summary of evidence on the decomposition of the fuel price elasticities into the vehicle mileage and fuel efficiency responses see Parry and Small (2005). The responsiveness of fuel efficiency to taxation will be dampened in the presence of binding fuel economy regulations, though this issue is not relevant for the present analysis which compares policies in isolation (rather than jointly).

[53] NDRC (2014).

[54] IMF (2016) projects a growth rate of 5.7 percent for 2015-2020, though growth rates beyond that are expected to be a little lower (e.g., Green and Stern 2016).

Mortality rates from fuel combustion. Coal accounts for the vast majority of air pollution deaths from fossil fuel combustion in China. The problem is $PM_{2.5}$, fine particulate matter with diameter up to 2.5 micrometers, which is small enough to penetrate the lungs and bloodstream. These emissions are produced directly during fuel combustion and are also formed indirectly (and in greater quantities) from chemical reactions in the atmosphere involving sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions. China has taken steps to require new coal plants are fitted with flue-gas desulfurization (FGD) equipment, close small-scale (high polluting) plants, and require other existing plants are retrofitted with FGD. As of 2010, FGD equipment had been installed on around 80 percent of electric coal plants (Cao and others 2013, pp. 343), though even with these technologies plants still emit some SO_2, in addition to NO_x and (modest amount of) direct $PM_{2.5}$.

Air pollution mortality and damage estimates used are taken from Parry and others (2014), with some adjustments. Parry and others (2014) estimate that the average coal plant in China caused 10.4 air pollution deaths in 2010 per petajoule (PJ), or 0.435 deaths per ktoe, and the average coal plant with control technologies caused 5.3 deaths per PJ. These estimates are extrapolated from an air quality model for China by Zhou et al. (2006), after adjusting for changes in the average population exposure to coal plants emissions and changes in emission rates. In the absence of other factors, we assume the mortality rate from coal combusted at power plants and large industrial sources would converge linearly from 10.4 to 5.3 deaths per PJ between 2010 and 2030 (due to previously enacted environmental regulations). However, the share of the Chinese population residing in urban areas is projected to increase by about 25 percent between 2010 and 2030 (Cao and others 2013) and it is the urban population that is mostly exposed to air pollution. We therefore make a linear upward adjustment in this mortality rate each year to account for this, where the upward adjustment reaches 25 percent by 2030. For small-scale coal emissions, we assume the mortality rate is 10.4 deaths per PJ in 2010, rising in proportion to the rising share of the urban population.

Also based on Parry and others (2014), the mortality rates for natural gas, gasoline, diesel, and oil products for 2010 are taken to be 1.1 per PJ, 36 per billion liters, 124 per billion liters, and 20 per million barrels of other oil products, and again these are scaled up for the rising urban population (though even combined these fuels contribute only a small share to total mortality).

One caveat is that some evidence suggests people's channels for absorbing air pollution become saturated at very high outdoor pollution concentrations implying, paradoxically, that the health benefits from incremental reductions in fuel combustion are smaller at high pollution concentrations than at more moderate concentrations.[55] In this regard, our analysis may overstate the domestic health benefits of carbon mitigation policies as it assumes incremental benefits are the same, regardless of pollution concentrations.

---

[55] That is, the relationship between mortality and pollution concentrations may start to flatten out at severe pollution concentrations (e.g., Burnett and others 2013).

APPENDIX C. FORMULAS FOR MEASURING DOMESTIC BENEFITS AND COSTS OF POLICIES

The economic welfare costs and benefits of policies are measured using applications and extensions of long-established formulas in the public finance literature (see Harberger 1964), using second order approximations[56] which greatly simplifies the formulas. To apply these formulas, all we need to know is the size of price distortions in fuel markets, in other words, the difference between social costs of fuel use and private costs (in the model, these include road fuel taxes, renewables subsidies, and domestic environmental costs in fuel markets) any quantity changes in markets affected by these distortions (an output from the model), and any new source of distortions created by policies in directly affected markets.[57]

The net domestic welfare gains from a carbon tax in period t is computed using the formula:

$$\sum_{ji}\left(\Gamma_t^{ji} - \frac{\mu^{CO2i} \cdot \tau_t^{CO2}}{2}\right) \cdot \left(-\Delta F_t^{ji}\right) \tag{C1}$$

$$\Gamma_t^{ji} = VMORT_t \cdot m_t^{ji}, \text{ for } j \neq T \text{ and } ji \neq EREN; \tag{C2}$$
$$\Gamma_t^{Ti} = VMORT_t \cdot m_t^{Ti} + \left(\frac{\eta^{hTi}}{\eta^{hTi} + \eta^{UTi}}\right)\beta_t^{Ti} - \hat{\tau}_t^i; \qquad \Gamma_t^{EREN} = s_t^{EREN}$$

$$\Delta F_t^{ji} = F_t^{ji} - \hat{F}_t^{ji} \tag{C3}$$

where a ^ denotes the baseline value in a period with no carbon tax and Γ_t^{ji} is the price distortion in a fuel market.

In (C2), Γ_t^{ji} consists (for fossil fuels) of local air pollution costs, equal to premature mortalities per unit of fuel use times $VMORT_t$, the value per premature mortality. For road fuels, there is an additional environmental cost equal to the external costs of traffic congestion, accidents, and road damage expressed per unit of fuel use, β_t^{Ti}, and multiplied by the term in parentheses, which is the fraction of the change in fuel use in response to changes in fuel prices that comes from changes in vehicle km driven as opposed to the other fraction that comes from improvements in fuel economy (which essentially have no effect on congestion, accidents, or road damage).[58] For road fuels, the price distortion is also defined net of pre-existing road fuel taxes $\hat{\tau}_t^i$ which drive up private costs and partly internalize environmental costs. For the renewable general fuel, the price distortion is the per unit subsidy s_t^{EREN}.

In (C3), ΔF_t^{ji} is the change in fuel use, relative to its baseline level $\hat{F}_t^{ji}$.

According to equation (C1), the net welfare gain from the increase in tax in the market for a particular fossil fuel product in a particular sector consists of: (i) the reduction in fuel use times

[56] That is, assuming fuel demand curves are linear over the range of fuel changes induced by policies.

[57] Changes in quantities in markets with no distortions have no impacts on economic welfare.

[58] See Parry and others (2014), Ch. 5, for a detailed discussion.

the price distortion in that market less (ii) the 'Harberger triangle' equal to the reduction in fuel use times one-half of the tax increase, where the latter is the product of the fuel's CO_2 emissions factor and τ_t^{CO2}, the price on CO_2 emissions at time *t*. In addition, there is a small welfare loss from the increase in renewable generation, times the unit subsidy for renewables.

The above formula is also used to calculate the net welfare gain from the ETS, coal tax, and higher road fuel taxes. For the ETS no carbon charge applies to the transport sector or small fuel use in the other energy sector; for the coal tax the CO_2 charge applies only to coal use in the power and other energy sector; and for the road fuel tax scenario carbon charges apply only to these two fuels.

For the electricity tax, welfare gains are calculated from:

$$\frac{\tau_t^E \Delta Y_t^E}{2} + \sum_i \Gamma_t^{Ei} \cdot \left(-\Delta F_t^{Ei}\right) \tag{C4}$$

This expression is the Harberger triangle in the electricity market (a negative term equal to one half the tax rate times the change in electricity consumption), plus environmental benefits from reduced use of fossil fuels in power generation, plus a (small) gain from offsetting the distortion from the renewable subsidy.

Welfare gains for the renewable subsidy are calculated using:

$$\sum_i \Gamma_t^{Ei} \cdot \left(-\Delta F_t^{Ei}\right) - \left(\frac{s_t^{EREN} + \hat{s}_t^{EREN}}{2}\right) \cdot \Delta F_t^{EREN} \tag{C5}$$

This is the environmental benefits as use of fossil fuel falls in response to the greater subsidy, less a welfare loss trapezoid in the renewable generation market, with base equal to the increase in renewable generation and average height equal to the average of the pre-existing subsidy and the new subsidy.

Welfare gains from the policy to lower the CO_2/kWh rate for power generation are computed from:

$$\sum_i \left(\Gamma_t^{Ei} - \frac{\mu^{CO2i} \cdot \tau_t^{CO2implicit}}{2}\right) \cdot \left(-\Delta F_t^{Ei}\right) \tag{C6}$$

where $\tau_t^{CO2implicit}$ is the 'implicit charge' on CO_2 emissions from power generation, that is the incentive per ton to reduce emissions created by the policy. Welfare gains are somewhat smaller than for the case of an equivalently scaled direct tax on the carbon content of power generation fuels, because the latter policy has a greater impact on reducing electricity demand (because revenues raised by the tax are reflected in higher electricity prices) and hence reducing fossil fuel use.

Welfare gains for the energy efficiency policy for electricity-using capital are computed from:

$$\sum_i \Gamma_t^{Ei} \cdot \left(-\Delta F_t^{Ei}\right) - \left(\frac{\tau_t^{Eimplicit}}{2}\right) \cdot \frac{\Delta h_t^E}{\hat{h}_t^E} \cdot \hat{Y}_t^E \tag{C7}$$

Again, the first term is environmental benefits from the reduction in fossil fuel use (and from counteracting the renewables subsidy). The second expression is a welfare loss triangle with base equal to the reduction in electricity consumption from improved energy efficiency and height equal to the implicit charge on energy efficiency, $\tau_t^{Eimplicit}$, that is, the incentive at the margin created by the policy to increase energy efficiency.

Finally, welfare gains from the energy efficiency policies for gasoline vehicles and large users in the other energy sector are:

$$\Gamma_t^{TG} \cdot (-\Delta F_t^{TG}) - \left(\frac{\tau_t^{TGimplicit}}{2}\right) \cdot \left(1 - \frac{\Delta h_t^{TG}}{\hat{h}_t^{TG}}\right) \cdot \hat{F}_t^{TG} + \beta_t^{TG} \cdot \left\{F_t^{TG} + \frac{\Delta h_t^{TG}}{\hat{h}_t^{TG}} \cdot \hat{F}_t^{TG}\right\} \tag{C8}$$

$$\sum_i \Gamma_t^{Oi} \cdot \left(-\Delta F_t^{OLARGEi}\right) - \left(\frac{\tau_t^{OLARGEiimplicit}}{2}\right) \cdot \frac{\Delta h_t^{OLARGEi}}{\hat{h}_t^{OLARGEi}} \cdot \hat{F}_t^{OLARGEi} \tag{C9}$$

These formulas are essentially analogous to those for the energy efficiency policy for electricity with $\tau_t^{TGimplicit}$ the implicit incentive at the margin for improving the fuel economy of gasoline vehicles and $\tau_t^{OLARGEiimplicit}$ the implicit marginal incentive for large users in the other energy sector to reduce use of fuel i through higher efficiency. The notable exception in (C8) is the last term, which reflects the increase in km-related externalities as lower fuel costs per km slightly increase vehicle usage[59] (a similar term does not appear in (C7) or (C9) because there are no externalities analogous to road congestion and so on associated with use of products using electricity or other fuels in the other energy sector).

For all of the above formulas, where welfare gains are cumulated over the 2017-2030 period, they are converted into present values using a discount rate of 3 percent.

[59] See Fischer, Harrington, and Parry (2007) for further discussion.

Appendix D. Fully Efficient Pricing Policy

The fully efficient pricing policy is taken from Parry and others (2014), and updated. The policy has three components.

First is a carbon charge on fossil fuels equal to their CO_2 emissions factor times an estimate of the global damage from CO_2 emissions—the so-called 'social cost of carbon'.

Second is a charge for local air pollution costs, which primarily come from coal. This can be implemented downstream on emissions out of the smokestack or upfront on coal use with rebates provided for downstream coal users demonstrating (through continuous emission monitoring systems) that emissions released into the environment are less than embodied emissions in coal input. This pricing scheme both reduces coal use and air emission rates per unit of coal and is taken to be feasible for the power sector and large industrial firms but not for coal consumed by small users in the other energy sector (where abatement equipment is less practical). In the latter case, a local air pollution charge is still applied (upfront) to coal supply, but there is assumed to be no change in emission rates relative to the baseline.

Charges in line with local air pollution costs for natural gas and oil products are also imposed, with no effect on emission rates (an unimportant assumption given the small contribution of these fuels to air pollution deaths).

The third charge is applied to road fuels to fully reflect the external costs of congestion, accidents, and road damage, though quantitatively this component is far less important than the carbon and air pollution charges.

APPENDIX E. ADDITIONAL PARAMETERS FOR WELFARE CALCULATIONS AND FULLY EFFICIENT PRICING POLICY

Social cost of carbon. We rely on the widely cited study by the U.S. government for the social cost of carbon (US IAWG 2013, Table), RMB 390 ($60) for per ton of CO_2 for in 2030 (expressed in year 2015 RMB), while recognizing that the literature on this is much disputed (due in particular to disagreements over long-range discounting and the modelling of extreme climate risks).

Value per premature mortality. Parry and others (2014) use a value of RMB 7.35 ($1.13) million per premature mortality in China for year 2010 based on extrapolating empirical evidence from advanced countries under an assumption that the income elasticity for this valuation is 0.8. This figure is first increased by 15 percent to update it to year 2015 RMB based on the average increase in consumer prices between 2010 and 2015 (see IMF 2016). And the 2010 figure is updated to future periods based on future (real) per capita income relative to 2010 raised to the power 0.8.

Km-based externalities for road vehicles. Parry and others (2014) estimate congestion, accident, and road damage externalities for gasoline and diesel vehicles, β_t^{TG} and β_t^{TD}, at RMB 5.6 ($0.86) and RMB 3.6 ($0.56) respectively for year 2010. This figure is updated to future periods in the same way as for the value of mortality.

References

Allcott, Hunt, and Nathan Wozny, 2013. "Gasoline Prices, Fuel Economy, and the Energy Paradox." NBER Working Paper No. 18583, National Bureau of Economic Research, Cambridge, Massachusetts.

Anand, R., Coady, D., Mohommad, A., Thakoor A., Walsh, J., 2013. "The Fiscal and Welfare Impacts of Reforming Fuel Subsidies in India", IMF Working Paper, Washington DC.

Arze del Granado, J., Coady, D. and Gillingham, R., 2012. "The Unequal Benefits of Fuel Subsidies: A Review of Evidence for Developing Countries," World Development, 40(11), pp 2234-48.

Bernard, A.L., C. Fischer, and A.K. Fox, 2007. "Is There a Rationale for Output-based Rebating of Environmental Levies?" *Resource and Energy Economics* 29: 83–101.

Brauer, Michael, Markus Amann, Rick T. Burnett, Aaron Cohen, Frank Dentener, Majid Ezzati, Sarah B. Henderson, Michal Krzyzanowski, Randall V. Martin, Rita Van Dingenen, Aaron van Donkelaar, and George D. Thurston, 2012, "Exposure Assessment for Estimation of the Global Burden of Disease Attributable to Outdoor Air Pollution," *Environmental Science and Technology* 46, 652–60.

Burke, Paul J. and Hua Liao, 2015. "Is the Price Elasticity of Demand for Coal in China Increasing?" CCEP Working Paper 1506, Crawford School of Public Policy, Australian National University.

Calder, Jack, 2015. "Administration of a U.S. Carbon Tax." In *Implementing a U.S. Carbon Tax: Challenges and Debates*, edited by I. Parry, A. Morris, and R. Williams, New York: Routledge.

Cao, Jing, Mun S. Ho, and Dale W. Jorgenson, 2013. "The Economics of Environmental Policies in China." In C.P. Nielsen and M.S. Ho (eds.), *Clearer Skies over China: Reconciling Air Quality, Climate, and Economic Goals*, MIT Press, Cambridge, MA, pp. 329-373.

Charap, Joshua, Arthur Ribeiro da Silva and Pedro Rodriguez, 2013. "Energy Subsidies and Energy Consumption—A Cross Country Analysis." Working paper 13-112, International Monetary Fund, Washington, DC.

Coady, D., and Newhouse, D., 2006, "Evaluating the distribution of the real income effects of increases in petroleum product prices in Ghana", in A. Coudouel, A. Dani and S. Paternostro, eds., *Analyzing the Distributional Impacts of Reforms: Operational Experience in Implementing Poverty and Social Impact Analysis*, World Bank, Washington DC.

Dahl, Carol, A., 2012. Measuring Global Gasoline and Diesel Price and Income Elasticities." *Energy Policy* 41: 2-13.

De Mooij, Ruud, W. Raphael Lam, and Philippe Wingender, 2016. "Modernizing the Tax Regime," In *Modernizing China: Investing in "Soft" Infrastructure* edited by W. Raphael Lam, Markus Rodlauer and A. Schipke, International Monetary Fund, Washington, DC.

Dechezleprêtre Antoine and David Popp, 2016. "Fiscal and Regulatory Instruments for Clean Technology Development in the European Union." Paper presented at a conference *Energy Tax and Regulatory Policy in Europe: Reform Priorities and Research Needs*, Ifo Institute, Munich, November 2014.

Energy Information Administration (EIA), 2015. International Energy Statistics. US Department of Energy, Washington. www.eia.gov/cfapps/ipdbproject/iedindex3.cfm.

Farid, Mai, Michael Keen, Michael Papaioannou, Ian Parry, Catherine Pattillo, and Anna Ter-Martirosyan, 2016. "After Paris: Fiscal, Macroeconomic, and Financial Implications of Climate Change." Staff Discussion Note 16/01, International Monetary Fund, Washington, DC.

Fischer, Carolyn, Winston Harrgionton, and Ian W.H. Parry, 2007. "Should Corporate Average Fuel Economy (CAFE) Standards be Tightened?" *Energy Journal* 28: 1–29.

Fridley, David, Mark D. Levine, Hongyou Lu, and Cecilia Fino-Chen, 2014. Key China Energy Statistics 2014, Lawrence Berkeley National Laboratory.

GCEC, 2014. *China and the New Climate Economy*. Global Commission on the Economy and Climate. Tsinghua University, Beijing.

Gillingham, Kenneth, David Rapson, and Gernot Wagner, 2016. "The Rebound Effect and Energy Efficiency Policy." *Review of Environmental Economics and Policy* 10: 68-88.

Green, Fergus and Nicholas Stern, 2016. "China's Changing Economy: Implications for its Carbon Dioxide Emissions." Centre for Climate Change Economics and Policy, Working Paper 258.

Grubb, M., Sha, F., Spencer, T., Hughes, N., Zhang, Z., and Agnolucci, P., 2015. "A review of Chinese CO_2 Emission Projections to 2030: the Role of Economic Structure and Policy." *Climate Policy* 15(S1), S7–S39.

Harberger, Arnold C., 1964. "The Measurement of Waste". *American Economic Review* 54: 58-76.

Harrington, Winston, 2010. "Improving Fuel Economy in Heavy-Duty Vehicles." Discussion paper 12-02, Resources for the Future, Washington, DC.

Helfand, Gloria, and Ann Wolverton, 2011. "Evaluating the Consumer Response to Fuel Economy: A Review of the Literature." *International Review of Environmental and Resource Economics* 5: 103–46.

IEA, 2015. *World Energy Outlook*. International Energy Agency, Paris, France.

———, 2016. *World Energy Balances*. International Energy Agency, Paris, France.

International Monetary Fund (IMF), 2016. *World Economic Outlook*. International Monetary Fund, Washington, DC.

———, 2015. *People's Republic of China: Staff Report for the 2015 Article IV Consultation*. International Monetary Fund, Washington, DC.

Institute for Health Metrics and Evaluation (IHME), 2013. *Global Burden of Disease 2010*.

Jamil, Faisal and Eatzaz Ahmad 2011. "Income and price elasticities of electricity demand: Aggregate and sector-wise analyses." *Energy Policy* 39: 5,519-527.

Krupnick, Alan J., Ian W.H. Parry, Margaret Walls, Tony Knowles, and Kristin Hayes, 2010. *Toward a New National Energy Policy: Assessing the Options*. Washington DC, Resources for the Future and National Energy Policy Institute.

Lam, W. Raphael and Philippe Wingender, 2015. "China: How Can Revenue Reforms Contribute to Inclusive and Sustainable Growth?," IMF Working Paper 1566, Washington DC.

Löschel, Andreas and Oliver Schenker, 2016. "On the Coherence of Economic Instruments: Climate, Renewables and Energy Efficiency Policies." Paper presented at a conference *Energy Tax and Regulatory Policy in Europe: Reform Priorities and Research Needs*, Ifo Institute, Munich, November 2014.

Madlener, Reinhard, Ronald Bernstein and Miguel Ángel Alva González, 2011. *Econometric Estimation of Energy Demand Elasticities*. E.ON Energy Research Center, Series 3, Issue 8, Aachen University, Aachen, Germany.

Metcalf, Gilbert E. and David Weisbach, 2009. "The Design of a Carbon Tax." *Harvard Environmental Law Review* 3: 499-556.

Mischke, Peggy and Kenneth B. Karlsson, 2014. "Modelling Tools to Evaluate China's Future Energy System – A Review of the Chinese Perspective." *Energy* 69: 132–143.

Morris, Adele C., and Aparna Mathur, 2015. "The Distributional Burden of a Carbon Tax: Evidence and Implications for Policy," In *Implementing a U.S. Carbon Tax: Challenges and Debates*, edited by I. Parry, A. Morris, and R. Williams, New York: Routledge.

Myers, Erica, Karen L. Palmer, and Anthony Paul, 2009. "A Partial Adjustment Models of U.S. Electricity Demand by Region, Season and Sector." Discussion Paper 08-50, Resources for the Future, Washington, DC.

NDRC, 2014. *People's Republic of China Order No. 17*. National Development and Reform Commission.

National Research Council (NRC), 2009. *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* (Washington: National Research Council, National Academies).

Parry, Ian, 2004. "Are Emissions Permits Regressive?," Journal of Environmental Economics and Management, 47: 364-387.

———, and Kenneth A. Small, 2005. "Does Britain or The United States Have the Right Gasoline Tax?" *American Economic Review* 95: 1,276-1,289.

Parry, Ian W.H., David Evans, and Wallace E. Oates, 2014. "Are Energy Efficiency Standards Justified?" *Journal of Environmental Economics and Management* 67: 104–25.

Parry, Ian W.H., Dirk Heine, Shanjun Li, and Eliza Lis, 2014. *Getting Energy Prices Right: From Principle to Practice*. International Monetary Fund, Washington, DC.

REN 21, 2015. *Renewables 2015: Global Status Report*. Renewable Energy Policy Network for the 21st Century.

Sanstad, Alan H. and James E. McMahon, 2008. "Aspects of Consumers' and Firms' Energy Decision-Making: A Review and Recommendations for the National Energy Modeling System (NEMS)." Papers from the Workshop on Energy Market Decision-making for the New NEM. Energy Information Administration: Washington, DC.

Sterner, Thomas. 2007. "Fuel Taxes: An Important Instrument for Climate Policy." *Energy Policy* 35: 3,194–202.

Trüby, Johannes and Moritz Paulus. 2012. "Market Structure Scenarios in International Steam Coal Trade." The Energy Journal 33: 91-123.

UNEP, 2015. *The Chinese Automotive Fuel Economy Policy: February 2015 Update*. United Nations Environment Program.

United Nations Framework Convention on Climate Change (UNFCCC), 2015. INDCs as communicated by Parties, Bonn. www.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx.

United States Inter-Agency Working Group (US IAWG), 2013. "Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866." Washington.

World Bank and Development Research Center of the State Council. 2013. China 2030: Building a Modern, Harmonious, and Creative Society. Washington DC, World Bank

World Bank, 2016. World Development Indicators Database (Washington: World Bank). http://data.worldbank.org/indicator.

World Bank Group, 2015. *State and Trends of Carbon Pricing 2015*. Washington.

World Bank and State Environmental Protection Agency of China (WB/SEPAC), 2007. *Cost of Pollution in China: Economic Estimates of Physical Damages*, Washington DC, World Bank.

Xie, Y., J. Hu, J., and Zhang, C., 2014. "The China Family Panel Studies (CFPS): Design and Practice," Chinese Journal of Sociology (Shehui), 34, pp. 1–33.

Zhang, C., Xu, Q., Zhou, X., Zhang, X., and Xie, Y., 2014. "Are Poverty Rates Underestimated in China? New Evidence from Four Recent Surveys," China Economic Review, 31, 410-425.

Zhou, Shaojie, and Fei Teng, 2014. "Estimation of Urban Residential Electricity Demand in China Using Household Survey Data," *Energy Policy* 61: 394-402.

Zhou Ying, Jonathan I. Levy, John S. Evans, and James K. Hammitt, 2006 "The Influence of Geographic Location on Population Exposure to Emissions from Power Plants throughout China." Environment International 32: 365–373.