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Impacts of Carbon Pricing in Reducing the Carbon Intensity of China's GDP

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Abstract

In contributing to global climate change mitigation efforts as agreed in Paris in 2015, China has set a target of reducing the carbon dioxide intensity of gross domestic product by 60-65 percent in 2030 compared with 2005 levels. Using a dynamic computable general equilibrium model of China, this study analyzes the economic and greenhouse gas impacts of meeting those targets through carbon pricing. The study finds that the trajectory of carbon prices to achieve the target depends on several factors, including how the carbon price changes over time and how carbon revenue is recycled to the economy. The study finds that carbon pricing that starts at a lower rate and gradually rises until it achieves the intensity target would be more efficient than a carbon price that remains constant over time. Using carbon revenue to cut existing distortionary taxes reduces the impact on the growth of gross domestic product relative to lump-sum redistribution. Recycling carbon revenue through subsidies to renewables and other low-carbon energy sources also can meet the targets, but the impact on the growth of gross domestic product is larger than with the other policies considered.

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Impacts of Carbon Pricing in Reducing the Carbon Intensity of China's GDP[1]

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1 Introduction

In its Nationally Determined Contribution (NDC) coming out of the Paris Agreements reached at the 21st meeting of the Conference of Parties to the United Nations Framework Convention on Climate Change (UNFCCC), the Chinese government has set a goal to cut CO_2 emissions per unit of GDP by 60 to 65 percent by 2030, compared to 2005 levels. It also has reiterated previously announced goals that carbon emissions would peak, and that the share of non-fossil fuels would increase to 20% of total energy consumption, by 2030. Earlier in 2016 the government announced the 13th Five-year Plan, with the goals of reducing energy per unit GDP by 18% between 2015 and 2020 and to reduce CO_2 per unit GDP by 20%. The longer term targets imply that China would need additional low carbon infrastructure investments, including further deployment of renewable energy, as well as further improvements in energy efficiency.

This study addresses the following "what-if" question: what would be the economic consequences of China seeking to meet its NDC target with carbon pricing? In practice, China can be expected to use a range of policy instruments to that end. However, an examination of economic consequences using a hypothetical least-cost instrument, a dynamic carbon price, provides a useful context for evaluating more complicated policy portfolios. Moreover, an examination of carbon pricing is consistent with the expressed desire of the government to rely more on market mechanisms.

The analysis is carried out using a multi-sector growth model of China, including a household model component that allows us to discuss the impacts of policies on different demographic groups. While there exist a large number of studies analyzing impacts of a hypothetical carbon tax in China, studies analyzing the potential impacts of carbon pricing to meet China's NDC do not exist. To the knowledge of authors, this is the first analysis that examins implications of meeting China's NDC through a carbon pricing mechanism.

We first use the model to develop a base case up to 2030. The base case includes existing plans to expand the renewable energy and nuclear energy included in China's 12th and 13th Five year plans out to 2020. The base case does not include carbon pricing. The government has announced an intention to extend current experimental carbon trading programs to a national system beginning in 2017. However, no details of the level of cap and coverage of sources have been given, and so the planned national emission trading scheme is not included in the study. In the base case, the carbon emissions are rising continuously during the 2012-2030 period, though they peak around 2030 through various GHG mitigation measures already in the base case. The base case is then compared to scenarios with carbon pricing as well as a policy for additional investment in renewables for electricity generation. Carbon pricing is implemented in the model through surcharges on fossil fuel prices based on their carbon contents.

The study considers the following policy formulations. First, “lower” carbon pricing and “higher” carbon pricing trajectories are implemented to achieve, respectively, 60% or 65% reduction of carbon intensity of GDP from 2005 levels. For the 65% target, we compare a fixed carbon surcharge on fossil fuels over time to a trajectory where the surcharge starts at a low level but gradually rises.

As has been emphasized by many others in the literature, the method of recycling the revenues generated from carbon pricing is another important policy component, as it has an important impact on the net economic cost of such a pricing policy. We consider two approaches to recycle the carbon revenue to the economy– a lump sum transfer to households, and a cut in the VAT and capital income tax. In addition, the study considers a policy that subsidizes renewable energy with revenue generated through the carbon pricing.

We find that the carbon surcharge on fossil fuels aimed at achieving a 60% reduction in CO_2 intensity of GDP would rise from 1.6 yuan /ton of CO_2 in 2016 to 26 yuan/ton of CO_2 in 2030 (all units measured in 2010 yuan). This carbon price will reduce the absolute level of 2030 emissions by 3.3% with GDP only 0.11% lower than the base case, if carbon revenue is recycled to cut existing taxes. In this scenario, 2030 energy use falls by 2.6% and electricity use by 1.5%. With the carbon pricing policy to achieve a 65% reduction in CO_2 intensity of GDP, the carbon surcharge on fossil fuels rises to 157 yuan/ton of CO_2 in 2030, generating a 13% reduction in energy use, a 16% reduction in CO_2 and a 0.74% lower GDP, all relative to the base case..

If instead of cutting existing taxes, the carbon revenues are recycled by giving them to households as a lump sum rebate, then GDP is 1.2% lower than the base case in 2030, instead of 0.74%. In this case, the same carbon price slows aggregate output growth more, and hence also slows growth energy consumption and emissions more. This reinforces the lesson emphasized by many others – recycling revenues from carbon pricing by reducing existing tax wedges is a useful opportunity for softening adverse economic impacts.

The paper is organized as follows. Section 2 briefly highlights the CGE methodology developed for this study (detailed description of the model is presented in the Appendix A), followed by results of the model for the base case scenario in Section 3. Section 4 presents results of carbon pricing scenaruios to meet China's NDC, followed by sensitivity analysis in which the baseline is altered in Section 5. Section 6 concludes the paper.

2. The CGE model

The CGE model used for this study is a dynamic recursive growth model where the main agents are the household, producers, government and the rest of the world. Household savings, enterprise retained earnings and government-funded investments are the main sources of investment; unlike most developed economies the government role in China is much larger. Detailed description of the model is presented in Appendix A, here we summarize its key features.

One of the key features of this model that distinguishes it from large number of CGE models available for China for climate policy analysis is that it allows for heterogeneity among households, whereas most existing CGE models have a single representative household. In our model, households are distinguished by size, presence of children, age of head and region. The income elasticity is different for different consumption items and thus projects a different structure of consumption in the future when incomes rise. Such a function allows us to distinguish the impact of policies on different households via the consumption channel.[3] Labor is supplied inelastically by households.

The private household savings rate is set exogenously and total national private savings is made up of household savings and retained earnings of enterprises. These savings, together with allocations from the central plan, finance national investment. They also finance the government deficit and the current account surplus. Investment in period *t* increases the stock of capital that is used for production in future periods. The plan part of the capital stock is assumed immobile in any given period, while the market part responds to relative returns. Over time, plan capital is depreciated and the total stock becomes mobile across sectors.

The government imposes taxes on value added, sales and imports. On the expenditure side, it buys commodities, makes transfers to households, pays for plan investment, makes interest payments on the public debt and provides various subsidies. Expenditures on interest and

[3] See Equations A20-A24 for the household demand function in Appendix A.

transfers are exogenous, and the exogenous deficit target is met by making government spending on goods endogenous.

Finally, the rest of the world supplies imports and demands exports. Domestically produced goods are imperfect substitutes for imports. World relative prices and the current account balance are set exogenously in this one-country model, and an endogenous variable for terms of trade clears the current account equation. The world price of commodity *i* relative to *j* is assumed to be at base year ratios throughout the projection period with the exception of world oil prices, where projections from the U.S. Energy Information Administration 2013 *Annual Energy Outlook* are used (and treated as exogenous).

On the supply side, 33 industries are distinguished, each producing output that is given by a nested series of constant-returns-to-scale CES functions.[4] Primary factors include capital, labor and land. Pure TFP growth and biased technical change are allowed; in particular, energy input per unit output can decline faster than other input-output ratios.

Since the electricity sector is the main contributor of CO_2 emissions in China, in the version of the model used for this study, the electricity sector is disaggregated into one transmission subsector and 9 distinct generation sub-sectors – coal, gas, nuclear, hydro, other, wind, solar, coal-CCS and gas-CCS. The tier structure of electricity production is given in Figure 1. At the top node total output is the aggregate of Generation and Transmission, and Generation is in turn an aggregate of Baseload and Intermittent Renewables.[5] The Baseload aggregate is composed of the output from coal, gas, nuclear, hydro, miscellaneous other minor sources, and the potential technologies, coal with carbon storage and sequestration (CCS) and gas-CCS. The Intermittent Renewables are wind and solar. The elasticities of substitution among these generation sources are presented in Table A2 in Appendix A and also noted in Figure 3; we assume a high degree of substitution among the baseload sources, and we follow other studies in assuming an elasticity of one between Baseload and Renewables.

This structure reflects the reality that average generation costs are different and yet different generation sources co-exist; there are considerations beyond average costs that determine the share of various sources in a highly regulated sector. We should make a technical note regarding this formulation: the imperfect substitution of kWh's means that the quantity

[4] The production structure is given in Figure A1 and equations A4-A12 in Appendix A.
[5] This aggregation of Baseload and Renewables is similar to that in C-GEM (Qi et al. 2014).

index of output of generation source l (Q_{lt}^{EGEN} in Appendix A) is not identical to the kWh measure (Q_{lt}^{kWh}); the total generation output index (Q_t^{EG}) is not a simple sum ($\sum_l Q_{lt}^{kWh}$) but a CES index of the components that take into account the different prices.

The output from each generation source is also expressed as a nest of CES functions; for nuclear, hydro, wind and solar there is a "Resource" input that represents non-produced inputs such as suitable rivers, and land with wind and sun. In any given period, these resources are given by an upward sloping supply curve to represent the short-run costs of developing such regions. This is similar to the representation in Vennemo et al. (2013) and Sue Wing et al. (2014) as discussed in the Appendix A.

The electricity generation and distribution system in China is dominated by a few large enterprises and tightly regulated by the NDRC. The prices are set by the NDRC after negotiation among the generators, distribution monopolies and major users. The dispatch order (which generation units are used at any moment) is determined for the most part by a "fairness" principle and a loose aim to promote renewables; it is not set according to least-cost dispatch, and it does not reflect bid prices for electricity in a competitive wholesale generation market. For a carbon price to work in the electric power sector, there must thus be reforms that would allow price signals to matter – that the net cost of fossil fuels reflects the carbon price, and that dispatch is sensitive to the prices asked by the generators. Our policy simulation here is predicated on the assumption that such reforms will take place.

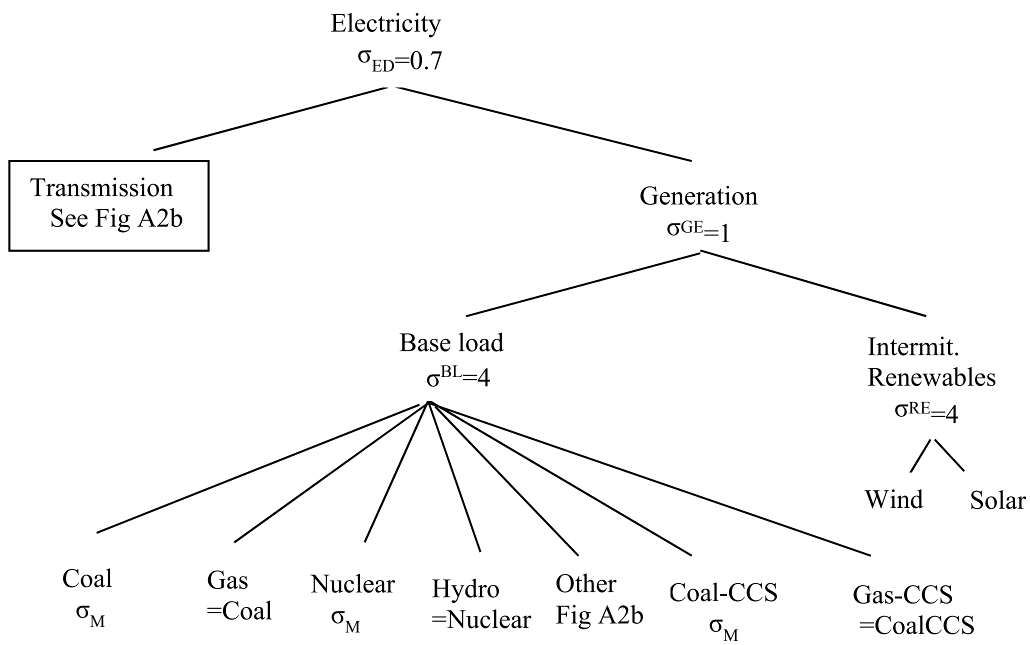
There are 33 markets for the commodities; that is, there are 33 endogenously determined prices that equate supply with demand for the domestic commodities identified in the model. The total supply consists of domestically produced goods and imported varieties; these are assumed to be imperfect substitutes. There are three markets for the factors of production – land, capital and labor – and three prices to clear them.

The base case simulation is determined by the projections of the exogenous variables and the initial stocks of debt, capital and labor force.[6] Given the initial stocks, we solve for the three factor prices and the 33 commodity prices that clear the markets in the first period. This gives us all the quantities for the first period, including investment that augments the next period stock.

[6] The projections of the exogenous projections are described in detail in Appendix A. The population projections come from UN Population Division's *World Population Prospects: 2012 Revision*, downloaded from their web site, http://esa.un.org/unpd/wpp/unpp/panel_population.htm .

The details of the construction of the base year data for the power sector and the base case projections of the various generation sources is given in Appendix B. We discuss the impact of using this electricity projection for the base case in section 5.

Figure 1. Structure of electricity sector



3. The Base Case Scenario

GDP growth in China between 1978 and 2007, the eve of the Global Financial Crisis, was 9.9% per year. With the stimulus to fight the effects of the Crisis in 2008 and 2009, the growth rate between 2007 and 2011 was maintained at a high 9.6%, however, with the end of the stimulus and the continuing weakness in the world economy, it decelerated to about 7.5% during 2012-14.[7] In the 13th Five-year plan announced in March 2016, the goal was to reduce the energy per unit GDP by 18% between 2015 and 2020, and reduce CO_2 per unit GDP by 20%.

[7] Cao and Ho (2014) discuss the sources of growth in China for the past 30 years – aggregate productivity and industry productivity performance – and discuss how these might inform projections of future growth. They relate this growth accounting of China to the literature about the middle-income trap and growth slowdowns.

The base case growth path is driven by the exogenous variables including population, labor force quality, capital quality growth, total factor productivity and saving rates. Our assumptions for the drivers are based on our reading of the historical record (Cao and Ho (2014) and are described in Section A.4 in the Model Appendix A. This base case is not designed to replicate precisely any particular projection; it is only intended to provide a point of comparison for the policy cases. The base case growth is summarized in Table 1 and Figure 2. Between 2010 and 2030 the population is projected to rise from 1,360 to 1,470 million, while the working age population falls from 938 to 883 million. With the assumed increase in average hours worked per person (including longer work lives) and labor quality, effective labor supply increase by 8% over these 20 years despite the fall in working population. Our model projects that GDP will grow with an average rate of 6.4% per year during 2015-20 and decelerates to 4.6% during 2020-30.[8] The 6.4% rate for the 2015-2020 period is very close to that assumed in 13th Five-year plan (6.5% for the 2016-2020 period). The consumption share of GDP rises from 35% in 2010 to 54% in 2030 due to falling trends in household saving rates. More precisely, growth decelerates due to lower TFP, lower savings rate, and falling working age population.

Primary energy use grows at 3.9% during 2015-20, implying a fall in energy intensity of 3.4% per year, close to the 13th FYP target of a 18% reduction in intensity. This is to be compared to the historical record given in Figure 2; the intensity index was quite volatile and averaged a decline of 4.1% per year during the 11th Five-year Plan (2006-10). During 2020-30 projected energy use decelerates more, but with the slowing GDP growth, the intensity falls at only 2.1% per year. There is a big change in the composition of energy sources; coal use only grows at 2.2% compared to oil at 4.3% and gas at 7.7% per year during 2015-20.

[8] GDP projection is endogenous to the model which is calculated based on several variables which are exogenous. They include population growth, share of working age population to total population, saving rates, dividend payout rates, government taxes and deficits, world prices for traded goods, current account deficits, rate of productivity growth, rate of improvement in capital and labor quality, The values of these variables are provided in Table A3 in Appendix A. Note that GDP projections vary from across the sources. For example, IMF (2014) projections were 6.9% for 2012-2020 and 5.3% for 2020-30. World Bank (2013) projections were 7.0% for 2016-2020 and 5.0% for 2026-30. Projections change across the sources and also overtime from the same source due to different assumptions.

Table 1. Base case projection

(All numbers in this table are model outputs except those specified at the bottom of the table)

Variable	2010	2015	2020	2030	2015-20 growth rate	2020-30 growth rate
Population (million) *	1,360	1,404	1,440	1,470	0.51%	0.21%
Effective labor supply (bil. 2010 yuan)	16,687	17,529	18,100	18,098	0.64%	0.00%
GDP (billion 2010 yuan)	40,145	58,956	80,465	126,235	6.4%	4.6%
Consumption/GDP*	0.35	0.44	0.50	0.55		
Energy use (million tons sce@)	3,249	4,005	4,839	5,958	3.9%	2.1%
Coal use (million tons)	3,122	3,666	4,083	4,610	2.2%	1.2%
Oil use (million tons)	441	537	662	835	4.3%	2.3%
Gas use (million cubic meters)	107,291	166,354	241,467	381,163	7.7%	4.7%
Electricity use (TWh)	4,206	5,554	6,886	8,951	4.4%	2.7%
CO_2 emissions (fossil fuel, million tons)	7,388	8,831	10,146	11,886	2.8%	1.6%
CO_2 emissions (total, million tons)	8,299	9,819	11,139	12,797	2.6%	1.4%
Carbon intensity (kg CO2/yuan)	0.184	0.150	0.126	0.094	-3.4%	-2.9%
GDP per capita (2010 yuan)	29522	42004	55884	85859		
GDP per capita; PPP US$2005	8228	11707	15575	23929		

* Exogenous variables
@ SCE refers to standard coal equivalent
** Model output but calibrated with growth rates from IEA (2014)

Figure 2. Projections of GDP, Energy and Emissions in the Base Case

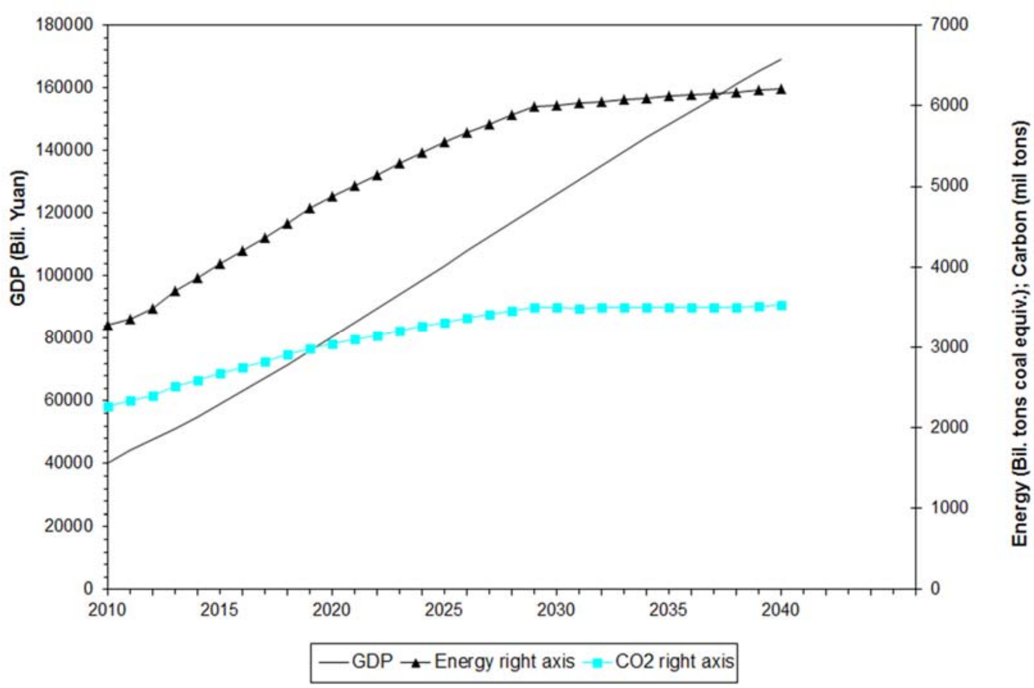
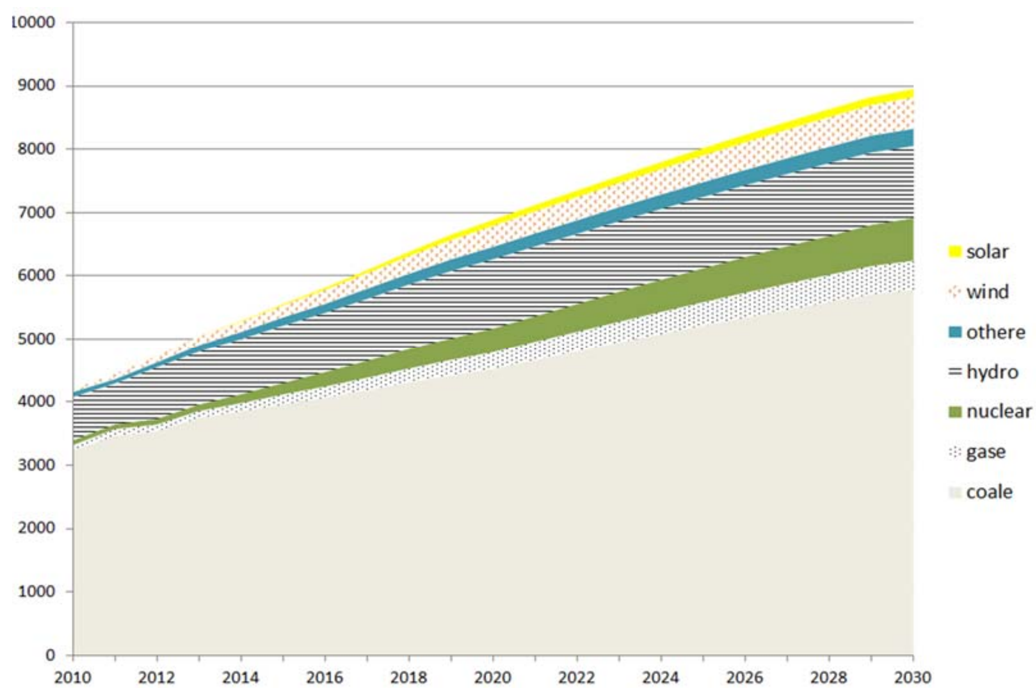


Table 2. Growth of electricity sector in base case

	2010	2015	2020	2025	2030	Annual growth rate 2015-20	2020-30
Total TWh	4206	5554	6886	8017	8951	4.4%	2.7%
	Percent share						
Coal	77.0	71.4	65.7	65.0	64.6	2.7%	2.5%
Gas	1.9	2.7	3.9	4.6	5.1	12.0%	5.5%
Nuclear	1.8	3.4	5.6	6.7	7.6	15.3%	5.8%
Hydro	16.3	16.2	15.7	14.0	12.7	3.7%	0.4%
Other	1.9	2.4	2.9	2.9	3.0	8.5%	3.1%
Wind	1.2	3.4	4.8	5.2	5.6	11.5%	4.2%
Solar	0.0	0.3	1.4	1.4	1.5	37.7%	3.2%
Prices relative to GDP deflator with P(coal,2010)=1							
Coal	1.00	0.93	0.89	0.89	0.89		
Gas	1.37	1.31	1.27	1.29	1.32		
Nuclear	1.00	0.93	0.90	0.90	0.90		
Hydro	0.74	0.69	0.66	0.67	0.68		
Other	1.39	1.33	1.29	1.32	1.34		
Wind	1.37	1.23	1.17	1.17	1.18		
Solar	2.77	2.51	2.33	2.35	2.38		
P_GDP:P_Labor	1.00	0.73	0.56	0.45	0.37		

Figure 3. Projections of electricity generation in the base case



Electricity use is projected to grow at 4.4% during 2015-20 and at 3.0% during 2020-30. The change in the structure of generation sources is given in Table 2 and graphed in Figure 3; we see that electricity use grows faster than coal due to the rise of renewables and nuclear energy – coal-fired electricity grows at 2.7% during 2015-20, nuclear at 12%, wind at 11%. Solar starts from a very tiny base but rises rapidly, at 40% per year. In the 2020-30 period, renewable growth decelerates sharply but is still faster than coal, with the exception of hydro growth which falls to 0.4% per year.

As a result of the shift towards cleaner fuels driven by the assumed improvements in energy efficiency and the endogenous changes in prices in the base case, CO_2 emissions, including those from cement manufacture, only grows at 2.6% per year during 2015-20. That is, the CO_2 intensity falls faster than energy intensity; by 2030 it is 58.7% lower than the 2005 level (compared to the NDC target of a 60-65% reduction). CO_2 emissions rise steadily from 8,300 million tons in 2010 to 12,800 million in 2030, thereafter we project a stabilization around 13 billion tons for at least the next 10 years. Coal use rises to 4.1 billion tons in 2020 and then plateaus at about 4.6 billion beginning in 2030.[9]

4. Simulations of Carbon Pricing Scenarios

In our base case the CO_2 intensity falls by 58.7% in 2030 relative to 2015. We consider carbon price trajectories that can reduce CO2 intensity by 60 or 65% by 2030, as in the NDC. To that end, we consider flat rates that apply for all years, and prices that start low and rise every year so as to achieve the same cumulative emission reductions. We also consider two alternative approaches for recycling the carbon revenue to the economy: (i) recycle the carbon revenue by cutting existing taxes and (ii) rebating it lump-sum to households.

These policy scenarios are defined in Table 3. In the R1CUT scenario, we find through trial-and-error that a carbon price starting at 1.6 yuan/ton of CO_2 in 2015,[10] and rising gradually to 26 yuan in 2030, hits the 60% reduction goal.[11] In this scenario, the carbon revenues collected

[9] Our energy projection is based on IEA (2014). In the "Current Policies" scenario of IEA, China's primary energy use is projected to grow at 2.9% during 2012-20 and 1.9% for 2020-30, and project coal use to grow at 2.1% (2012-20) and at 1.3% (2020-30).

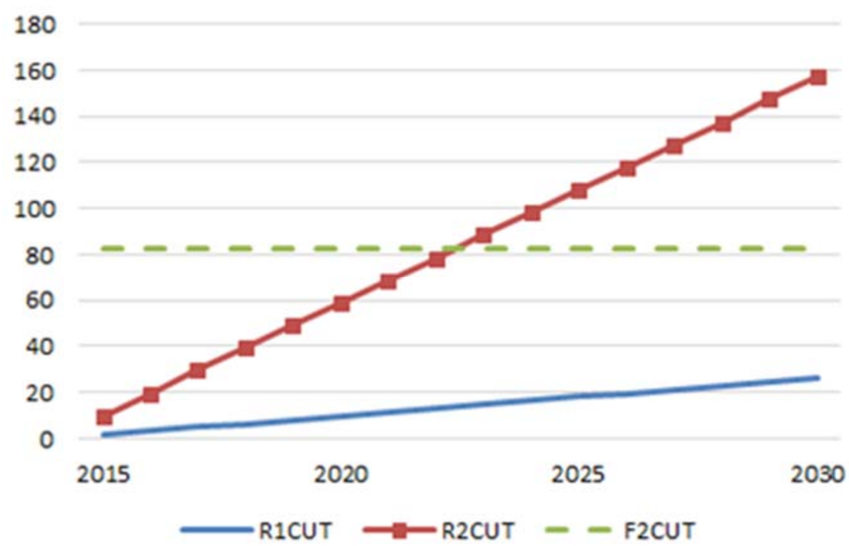
[10] All yuan units are measured in 2010 yuan, the base year of the model.

[11] We should digress here to clarify what is meant by a statement like "a carbon price of ¥10 per ton in each year of the projection." In an economy with no TFP growth and little capital accumulation, absolute (and thus relative) commodity prices will differ little from the base year. In this case there is little ambiguity about what ¥10 in each year means. With rapid growth in output and incomes per capita, the price of commodities relative to the price of labor is

are offset by cuts in the VAT and capital income tax. In the R2CUT scenario, through trial-and-error we find that a carbon price starting at ¥10/ton of CO_2 in 2015 and rising to ¥157 in 2030, hits the 65% reduction goal,. In the F2CUT scenario, we keep the carbon price flat at ¥82 level throughout the study horizon in order to achieve the same cumulative reductions in CO_2 emissions relative to the base case over the 2015-2030 period (-9.8%) as the rising carbon pricing policy R2CUT.[12]

To examine the effects of different revenue recycling options we have Policy R2lump which has a rising carbon price and the same cumulative CO_2 reductions as R2cut, but here the carbon revenues are returned lump sum to households instead of cutting VATs. The carbon price paths under various scenarios are illustrated in Figure 4. Finally, in the "rising renewable subsidies" (RRsub) scenario we introduce subsidies for renewable power in the electricity sector so that the share of wind, solar and hydro reaches those specified in the IEA (2014). These subsidies are financed by a fossil fuel tax in proportion to caron content of fuels and it rises over time as the renewable share rises.

Figure 4. Carbon price (Yuan/tCO_2)



falling rapidly, and relative prices are changing due to different capital-labor ratios (and possibly different industry TFP growth) . In our accounting system we measure things in terms of the GDP basket, and since relative prices change in our economy, "¥10 per ton" means a different basket of goods in each period. A flat ¥10/ton results in a changing ad valorem rate on the coal price.

[12] We also considered an analogous policy F1CUT for comparison with R1CUT, but the results were not particularly useful and so we omit it here.

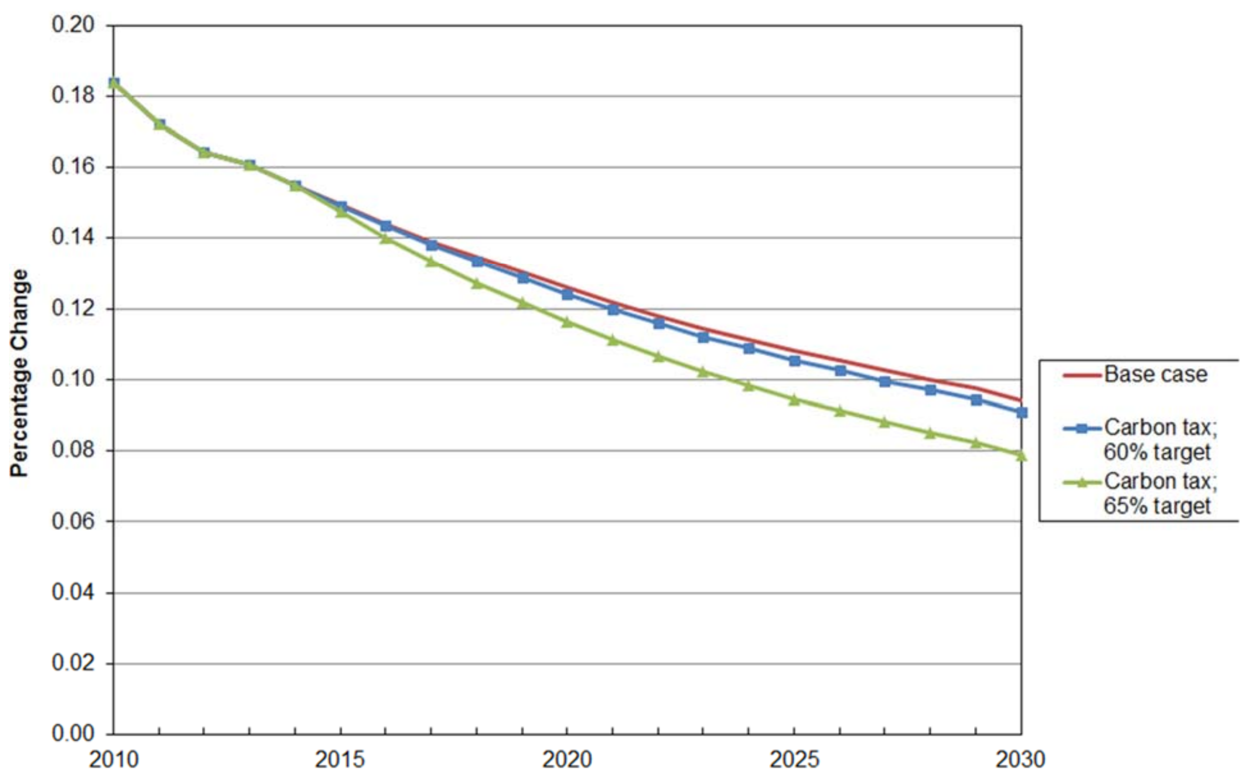
Table 3. Policy scenarios

Scenario definition	Scenario name	Target to be achieved under the scenario	Revenue recycling scheme	Carbon surcharge (per ton CO_2, yuan2015)		
				2015	2025	2030
Base case	B0	58.7% reduction of CO_2 intensity without carbon pricing				
Low carbon pricing with rising rate	R1CUT	60% reduction in CO_2 intensity by 2030	Cut VAT and capital tax	1.6	18	26
High carbon pricing with rising rate	R2CUT	65% reduction in CO_2 intensity by 2030	Cut VAT and capital tax	9.8	108	157
	R2LUMP	Same cumulative CO_2 reductions as R2cut	Lump sum rebate to households	9.3	102	149
High carbon pricing with flat rate	F2CUT	Same cumulative CO_2 reductions as R2cut	Cut VAT and capital tax	82	82	82
Rising renewable subsidies to reach IEA's New Policies scenario	RRSUB	Renewable subsidies financed by carbon revenue	Carbon tax to offset renewables costs	2.8	36	58

High versus low carbon prices

The NDC announced by the government set a goal for reducing the CO_2:GDP intensity in 2030 by 60-65% compared to 2005 levels. Here we compare the economic impacts of achieving the more stringent target, 65%, with the costs of reducing the intensity by only 60%, recalling that in the base case the reduction was 58.7%. The macroeconomic impacts of R2CUT versus R1CUT are given in Table 4. We present the results for the first year of the carbon pricing, 2015, and the final year. The impact of CO_2 intensity over time is plotted in Figure 5 while the impact on GDP, energy use and CO_2 emissions for the high carbon price case are plotted in Figure 6. The impact on prices and output of each of the 33 industries in 2030 are plotted in Figures 7 and 8.

Figure 5. CO_2 intensity in R1CUT and R2CUT scenarios



We first describe the impact of the lower carbon price case (R1). The initial impact on GDP and energy use in 2015 of the small carbon price is correspondingly small, about 0.2% reduction in energy use. By 2030, when the carbon price reached 26¥/ton CO_2, energy use has fallen 2.6%, and CO_2 emissions has fallen 3.3%. The carbon price has discouraged the use of fossil fuels, and raised the price of electricity, leading to a rise in the prices of energy intensive goods relative to the base case as shown in Figure 7 for 2030. Coal price at the mine-mouth rises by 6.2% while crude oil price rises by 1.2% inclusive of the tax, leading to a 1.4% rise in electricity prices.

Table 4. The effects of achieving higher reductions with higher carbon price case

(R1CUT vs R2CUT; rising carbon prices with offsetting cuts in VAT)

	2015			2030		
	Base case	R1CUT: Low C price	R2CUT: High C price	Base case	R1CUT: Low C price	R2CUT: High C price
Variable	values	% change from base		values	% change from base	
GDP (billion yuan 2010)	58,956	-0.004	-0.027	126,235	-0.11	-0.74
Consumption (bil yuan 2010)	25,290	-0.003	-0.017	67,264	-0.11	-0.71
Investment (bil yuan 2010)	25,374	-0.007	-0.045	43,747	-0.13	-0.86
Government consumption (bil yuan 2010)	6,973	0.000	0.000	12,785	0.00	0.00
Energy use (million tons of sce)	4,005	-0.21	-1.21	5,958	-2.6	-13.1
Coal use (million tons)	3,666	-0.29	-1.71	4,610	-4.1	-20.0
Oil use (million tons)	537	-0.04	-0.27	835	-0.7	-4.0
Gas use (billion cubic meters)	166,354	-0.09	-0.53	381,163	-1.8	-9.4
Electricity (billion kWh)	5,554	-0.11	-0.65	8,951	-1.5	-7.9
CO2 emissions (inc cement; mil tons)	9,819	-0.23	-1.33	12,797	-3.3	-16.0
Cumulative CO2 (2015-2030)				166,675	-1.9	-9.8
Carbon price yuan/ton CO2		¥1.6	¥9.8		¥26.2	¥157.1
Carbon price as a share of total revenue		0.11%	0.66%		1.1%	5.8%
Electricity generation	values	% change		values	% change	
Coal	3967	-0.18	-1.04	5782	-2.7	-14.2
Gas	152	0.02	0.11	459	-0.3	-2.2
Nuclear	190	0.06	0.35	678	1.0	5.4
Hydro	902	0.06	0.35	1132	0.9	5.2
Other	133	0.11	0.67	271	1.6	8.5
Wind	191	0.002	0.01	498	0.01	0.12
Solar	19	0.004	0.02	130	0.04	0.25

Figure 6. Impacts of carbon pricing to achieve 65% reduction in CO_2 intensity (Scenario R2CUT)

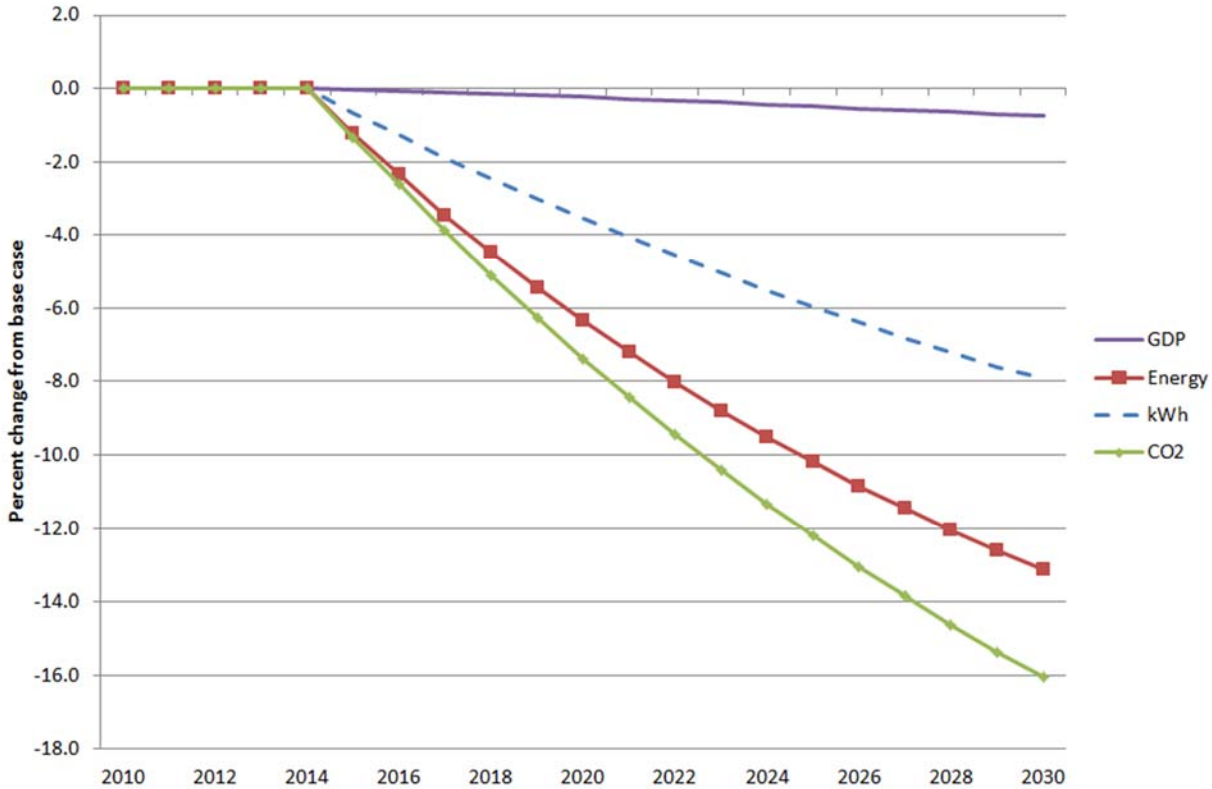
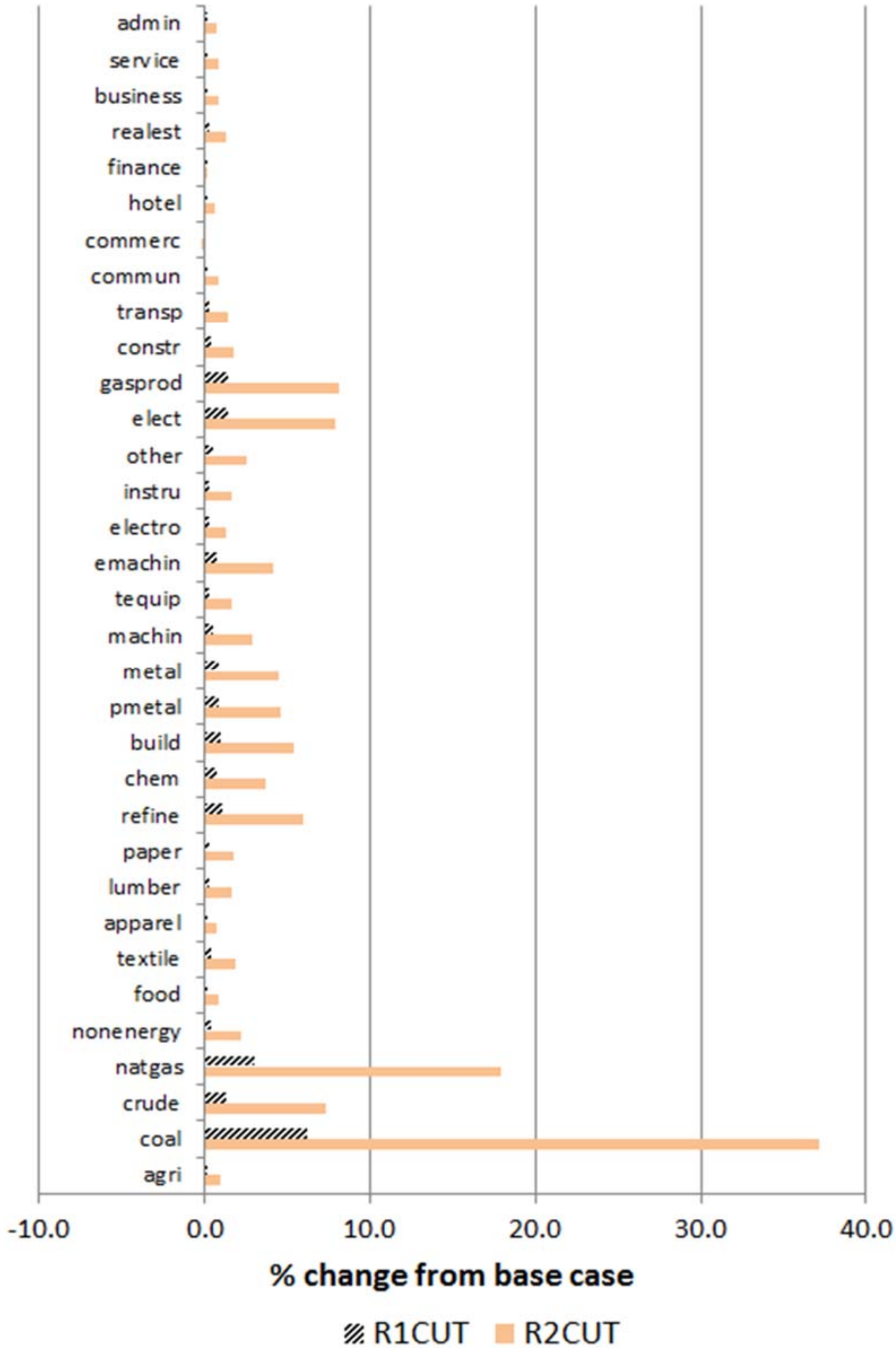


Figure 7. Impacts of carbon pricing on commodity prices in 2030

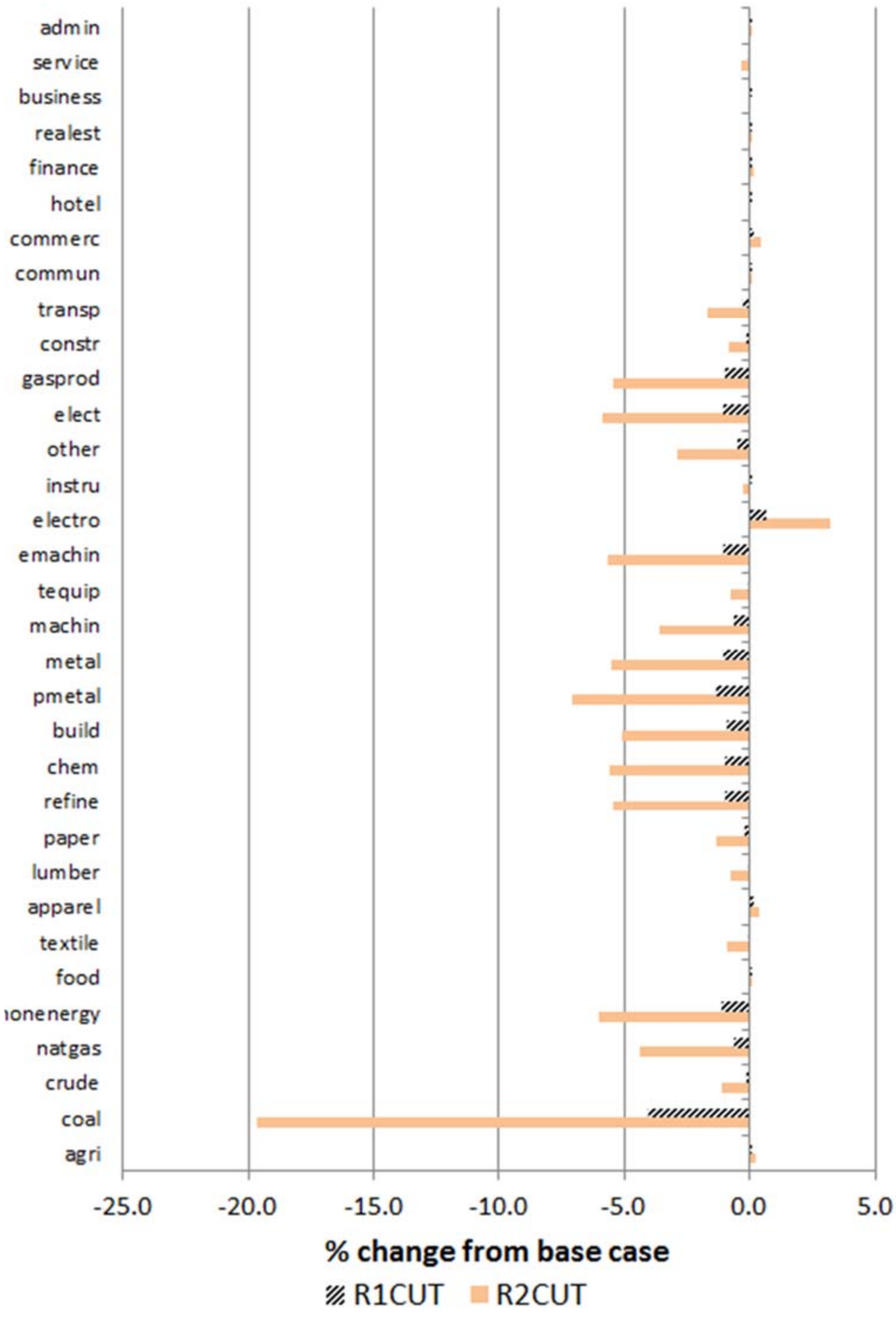


These changes in relative prices, and the reduction in capital stocks, lead a fall in industry output relative to the base case, as shown in Figure 8. By 2030, the consumption of coal falls in relative terms by 4.1%, oil by 0.7% and electricity by 1.5% (Table 4). The output of energy intensive goods, including primary metals and cement (building materials sector), fall more than the output of consumer goods and services industries. These price distortions reduce GDP, leading to lower investment every year. By 2030 GDP is lower y 0.11%, aggregate consumption is lower by 0.11%, investment by 0.13%, and total energy by 2.6%. As a result of these reductions, CO_2 emissions fall by 3.3% in 2030 in Policy R1CUT.

The composition of electricity generation change at the same time that total electricity output falls by 1.5%; coal generation falls by 2.7% in 2030 while nuclear and hydro rise by about 1% (bottom section of Table 4). The price of intermittent renewables (wind and solar) are essentially unchanged and their output remains unchanged leading to a rise in their share contribution.

When we raise taxes much higher in the R2CUT scenario, the effects are amplified. The tax by 2030 is 157¥/ton, and the price of coal rises by 37% instead of 6%.The impact of lower investment and capital stocks due to these price shocks is a 0.23% reduction in 2020 GDP, and a 0.74% reduction in 2030 (compared to the 0.11% cut in GDP under the low tax policy). The tax on CO_2 raises revenues equal to 5.8 percent of total revenues and enables a corresponding cut in the VAT and capital taxes. The lower GDP and higher energy prices lead to a 13% reduction in energy use compared to 2.6% under policy R1. Carbon emissions are 16% lower in order to reach the 65% intensity target. Within the electricity group, coal generation falls by 14% while nuclear and hydro rises by more than 5%. This is due to the rise in coal price leading to a rise in the relative price, P(coal electricity)/P(hydro), of 5.6%. Solar power output rises by only 0.3% given that we assumed that the elasticity between intermittent renewables and baseload is only 1, that is, most of the substitution is from coal to nuclear and hydro and not to intermittent sources.

Figure 8. Impacts of carbon pricing on sectoral outputs in 2030



Flat versus rising carbon prices

In this comparison we illustrate the benefits of phasing in a carbon price gradually rather than imposing a flat rate over time. We compare two paths of carbon prices that deliver the same cumulative carbon emission reduction by 2030 – R2CUT versus F2CUT (carbon prices are plotted in Figure 4). The comparison of impacts is shown in Table 5 for the first and final years. Note that the reduction in cumulative CO_2 emissions over 2015-30 is the same, 9.8%, and that the first year the tax is 82¥/ton in F2CUT compared to 9.8¥ in the rising tax case.

With the higher tax rate in the first year of F2CUT, the larger distortion lead to a 0.26% fall in GDP relative to base case, compared to 0.03% in R2CUT. There is a bigger impact on investment that cumulates to a 0.56% reduction in the 2030 capital stock relative to base case, compared to a 0.51% relative reduction in the rising tax scenario.

The other variables such as energy consumption, electricity composition and CO_2 emissions follow the same pattern – much bigger changes in year 1 and a more modest change in 2030, but cumulative losses that are bigger. The cumulative reduction in CO_2 is the same but the reduction relative to base case in year 2030 is only 9.5% in the flat tax case compared to 16% in the rising tax case. In that year the changes relative to base case in coal generated electricity are -8.2% versus -14.2%, and in hydro they are +2.7% versus +5.2%.

To summarize, the flat tax path that delivers the same cumulative CO_2 reduction as the rising tax trajectory imposes greater GDP losses. A richer model that takes explicit account of adjustment costs would generate even bigger differences between a gradually rising tax and a flat tax profile.

Options for recycling carbon tax revenue

To give an illustration of the importance of how recycling carbon tax revenues is done, we compare the previous R2cut scenario where we cut existing VAT and capital income tax to a case where the revenues are given back to households as a lump sum transfer. The results for this R2LUMP case are shown in Table 6 for 2030 together with R2cut. These two paths of rising carbon tax rates are set so that the cumulative change in CO_2 emissions over 2015-2030 are the same -9.8%. It turns out that the relatively weaker economic performance in the lump-sum case generates lower emissions, and so the same cumulative reduction requires a lower carbon price than in R2CUT. This difference means that the change in carbon intensity in 2030 is not exactly equal to the 65.0% reduction in the R2cut case, but very close.

Table 5. The effects of flat versus rising carbon taxes (F2cut vs. R2cut)
(High tax cases, revenue recycled by cutting VAT and TK)

	2015			2030		
	Base case	F2CUT: Flat C Tax	R2CUT: High C Tax	Base case	F2CUT: Flat C Tax	R2CUT: High C Tax
Variable	values	% change from base		values	% change from base	
GDP (billion yuan 2010)	58,956	-0.26	-0.027	126,235	-0.61	-0.74
Cumulative GDP (not discounted)					-0.50	-0.42
Consumption (bil yuan 2010)	25,290	-0.17	-0.017	67,264	-0.54	-0.71
Investment (bil yuan 2010)	25,374	-0.41	-0.045	43,747	-0.64	-0.86
Capital stock (bil yuan 2010)	138,851	0.00	0.00	386,091	-0.56	-0.51
Energy use (million tons of sce)	4,005	-8.9	-1.21	5,958	-7.8	-13.1
Coal use (million tons)	3,666	-12.4	-1.71	4,610	-11.9	-20.0
Oil use (million tons)	537	-2.2	-0.27	835	-2.4	-4.0
Gas use (billion cubic meters)	166,354	-4.3	-0.53	381,163	-5.4	-9.4
Electricity (billion kWh)	5,554	-5.0	-0.65	8,951	-4.6	-7.9
CO_2 emissions (inc cement; mil tons)	9,819	-9.8	-1.33	12,797	-9.5	-16.0
Cumulative CO_2 (2015-2030)				184,840	-9.8	-9.8
Carbon tax yuan/ton CO_2		¥82.5	¥9.8		¥82.5	¥157
Carbon tax as a share of total revenue		5.0%	0.66%		3.3%	5.8%
Electricity generation	values	% change from base		values	% change from base	
Coal	3967	-7.96	-1.04	5782	-8.2	-14.2
Gas	152	0.41	0.11	459	-1.1	-2.2
Nuclear	190	2.78	0.35	678	2.9	5.4
Hydro	902	2.78	0.35	1132	2.7	5.2
Other	133	5.22	0.67	271	4.6	8.5
Wind	191	0.09	0.01	498	-0.1	0.12
Solar	19	0.17	0.02	130	0.1	0.25

The carbon tax rate in 2030 is ¥149 in the R2lump case but slightly higher at ¥157 in the tax cut case. The lack of an offsetting cut means that the VAT's in the lump sum case remain high and generate greater distortions. The net effect for many goods is a higher price in R2lump; for example, the price of primary metals rise by 5.7% versus 4.6% in R2CUT, for food manufacturing it is 2.1% versus 0.9%, and for construction it is 2.9% versus 1.8%. These greater price distortions contribute to a smaller GDP. The cut in capital taxes in R2CUT also allows enterprises to retain more earnings and invest more, and thus the capital stock by 2030 falls relative to base case by only 0.51% compared to a 1.3% reduction in R2lump. As a result of this lower capital stock and higher value-added tax rates in the lump sum case, GDP in 2030 is 1.2% below base case, compared to only 0.74% lower in the tax cut case.

With lower aggregate output and lower carbon taxes prices in the lump sum case, the reduction in energy consumption is very similar, 13.2% versus 13.1%. The changes in CO_2 emissions are corresponding similar, -16%, and thus the fall in CO2:GDP intensity relative to base case is slightly smaller in the R2lump case. Hydro generation is +4.7% in R2lump versus +5.2% in R2CUT. The change in intermittent renewables is different; in the lump-sum case the reduction in total energy demand leads to a 0.22% relative fall in wind power, while it rose by 0.12% in the tax cut case.

In sum, we have similar reductions in emissions at the cost of somewhat greater reduction in GDP growth (relative to base case) with the lump-sum transfer case than the tax-cut case. The slower GDP growth is compounded over time. Note that our gains in efficiency by reducing existing value-added taxes and capital taxes are calculated for a recursive model; in a dynamic model with foresight the impact of cuts in capital taxation would be even bigger, that is, the slowdown in GDP with the tax cuts would be even more modest than we have calculated.

Table 6. The impact of different methods of recycling carbon revenues
(R2CUT vs. R2LUMP, cases with high and rising carbon tax)

	2030		
	Base case	R2CUT: Cut in VAT, TK	R2LUMP: Lump sum transfer
Variable	values	% change from base	
GDP (billion yuan 2010)	126,235	-0.74	-1.17
Consumption (bil yuan 2010)	67,264	-0.71	-0.77
Investment (bil yuan 2010)	43,747	-0.86	-2.13
Capital stock (bil yuan 2010)	386,091	-0.51	-1.28
Energy use (million tons of sce)	5,958	-13.1	-13.2
Coal use (million tons)	4,610	-20.0	-19.9
Oil use (million tons)	835	-4.0	-4.5
Gas use (billion cubic meters)	381,163	-9.4	-9.4
Electricity (billion kWh)	8,951	-7.9	-8.1
CO2 emissions (inc cement; mil tons)	12,797	-16.0	-16.1
Cumulative CO2 (2015-2030)	184,840	-9.8	-9.8
Carbon tax yuan/ton CO2		¥157	¥149
Carbon tax as a share of total revenue		5.8%	5.5%
Electricity generation	values	% change from base	
Coal	5782	-14.2	-14.3
Gas	459	-2.2	-2.4
Nuclear	678	5.4	4.9
Hydro	1132	5.2	4.7
Other	271	8.5	7.8
Wind	498	0.12	-0.22
Solar	130	0.25	0.00

Subsidies for renewables and other low-carbon sources of electricity

In the policy RRsub we subsidize the cost of nuclear, hydro, wind, and solar using the revenues from a fossil fuel tax in proportion to their carbon contents. The subsidies are chosen so that the share of each of these sources in generation is equal to the projection by IEA (2014) under their "New Policies Scenario (NPS)". We focus on the kilowatt-hours generated rather than the capacity of the various sources which are also projected separately in IEA (2014).

Table 7 gives the shares of electricity generation (by kWh) projected in IEA (2014) under their two scenarios – "Current Policies" and "New Policies" for two selected years. We first compute the change in shares for each year of the projection period between the two policies, e.g. under NPS the coal share in 2030 falls by 8.8 percentage points, and the wind share rises by 2.2 points. Although our base case shares not identical with the IEA's Current Policies projections in each year, they are set to be very close. We set the annual renewable targets in our policy scenarios as our base case shares plus the differences between the IEA scenarios, as illustrated in Table 7 for 2020 and 2030. In the RRsub policy we set subsidies separately for nuclear, hydro, wind, solar and other to hit the higher shares under the New Policies Scenario.

The results of using the carbon tax to subsidize renewables and other low-carbon energy sources are given in Table 8, together with those from R1cut and R2cut for comparison. In RRsub, the subsidies for renewables start at low rates but become quite substantial in the later years as given in the last column of Table 7. The share for wind has to rise from 5.7% in the base case to 7.9%, which requires a subsidy of 48%, while the share of hydro has to rise from 12.8% to 14.7%. As noted in Section 2, these renewables require natural resource inputs that have upward sloping supply curves and thus require higher returns to meet higher resource demands.

Table 7. Renewables target from IEA (2014) "New Policies Scenario" and subsidies in the model.

	2020			2030			
	Current Policies	New Policies	Differ-ence	Current Policies	New Policies	Differ-ence	RRsub subsidy (%)
	% contribution			% contribution			
Coal	65.4	61.9	-3.6	64.1	55.3	-8.8	
Nuclear	5.8	6.3	0.5	7.6	9.2	1.6	18.9
Hydro	15.6	17.1	1.4	12.8	14.7	1.9	13.2
Wind	4.8	5.6	0.8	5.7	7.9	2.2	48.3
Solar	1.4	1.8	0.4	1.5	2.5	1.0	46.7
Gas, other	7.0	7.4	0.5	8.3	10.4	2.1	
Total	100	100	0	100	100	0	

The value of output of the electricity sector was ¥3240 billion in 2010, with a value added of 810 billion equaling 2.1% of GDP. These high subsidies thus require a sizable carbon tax to finance them. By 2030 the CO_2 tax needed is ¥58/ton, which is in between the ¥26 carbon price in R1cut and ¥157 in R2cut. These subsidies result in a 2.2% fall in the price of electricity compared to the base case and thus the 1.9% reduction in the consumption of electricity is only slightly bigger than the 1.5% reduction in the R1cut scenario with its much lower carbon price. That is, the carbon prices that raised the price of electricity in R1cut encouraged conservation and generated a 3.3% cut in total CO_2 emissions at a modest cost of reducing GDP by 0.11% in 2030. In this Renewable subsidy scenario, the subsidies discourage electricity saving and mutes the total CO_2 impact of generating less coal electricity.

Total CO_2 emissions in 2030 fall by 7.9% relative to base case, given the 58 yuan carbon price. The cumulative 2015-2030 relative cut in emissions of 2.1% is only slightly bigger than the 1.9% cut in R1cut, with the 26 yuan carbon price. The large carbon price and distortions of the electricity price generate a relative GDP loss of 0.53% in 2030 compared to only 0.11% loss in R1cut. The GDP loss in R2cut is bigger at 0.74% but that achieved a cumulative CO_2 reduction of 9.8% compared to 2.1% for RRsub. That is, the ambitious renewable targets require large distortions in the later years, which generate CO_2 reductions as a byproduct of a greater slowdown in GDP growth.

With the subsidies, coal generation in 2030 falls to 58.4% of total kWh compared to 64.6% in the base case and 63.8% in R1CUT, and hydro rises to a 14.5% share compared to 13.0% in R1CUT. These changes result in a larger reduction coal use in 2030, 10% versus 4.1% in R1cut, and CO_2 emissions fall by 7.9% compared with 3.3% in R1CUT.

5. Sensitivity Analysis on Non-Fossil Fuels Growth Assumptions

In the base case the projection of resource inputs and capital inputs into the electricity generation functions is set according to the projections under the "Current Policies" scenario (CPS) for China in IEA (2014). As shown in Table 2, this scenario assumes a rapid growth of nuclear, wind and solar generation. The rapid expansion of relatively expensive generation resources (i.e., nuclear, wind, solar) implies higher subsidies and ultimately higher costs to the society.

Table 8. Subsidies to renewables financed by carbon taxes (scenario RRsub).

	2015			2030			
	Base case	RRsub	R1CUT	Base case	RRsub	R1CUT	R2CUT
Variable	values	% change from base		values	% change from base		
GDP (billion ¥2010)	58,956	-0.018	-0.004	126,235	-0.53	-0.11	-0.74
Consumption (bil ¥2010)	25,290	-0.014	-0.003	67,264	-0.45	-0.11	-0.71
Investment (bil ¥2010)	25,374	-0.020	-0.007	43,747	-0.61	-0.13	-0.86
Government consumption (bil ¥)	6,973	-0.023	0.00	12,785	-0.40	0.00	0.00
Fossil energy use (mil tons of sce)	4,005	-0.41	-0.21	5,958	-5.8	-2.6	-13.1
Coal use (million tons)	3,666	-0.63	-0.29	4,610	-10.1	-4.1	-20.0
Oil use (million tons)	537	-0.03	-0.04	835	-1.1	-0.7	-4.0
Gas use (billion cubic meters)	166,354	-0.29	-0.09	381,163	-6.0	-1.8	-9.4
Electricity (billion kWh)	5,554	-0.09	-0.11	8,951	-1.9	-1.5	-7.9
Electricity price		-0.18	0.10		-2.2	1.4	7.9
CO2 emissions (mil tons)	9,819	-0.48	-0.23	12,797	-7.9	-3.3	-16.0
Cumulative CO2 (2015-2030)				184,840	-2.1	-1.9	-9.8
Carbon tax yuan/ton CO2		¥2.8	¥1.6		¥58	¥26	¥157
Electricity generation	share of total generation			share of total generation			
Coal	0.714	0.709	0.714	0.646	0.584	0.638	0.602
Gas	0.027	0.027	0.027	0.051	0.046	0.052	0.054
Nuclear	0.034	0.035	0.034	0.076	0.092	0.078	0.087
Hydro	0.162	0.166	0.163	0.127	0.145	0.130	0.145
Other	0.024	0.024	0.024	0.030	0.038	0.031	0.036
Wind	0.034	0.035	0.034	0.056	0.075	0.057	0.061
Solar	0.003	0.004	0.003	0.015	0.020	0.015	0.016

In order to get an idea of the economic impacts of this push away from coal and towards non-fossil fuels in the IEA Current Policies Scenario, we conducted an alternative set of simulations with a "no coal reduction" (NCR) scenario and a "CPS targets" scenario. In the NCR case we allow the coal share to fall from the first year 2010 to 2016 as in the base case, but then maintain close to that share out to 2030. The share of hydro in the base case is falling due to the projected difficulty in finding more hydro resources, and we maintain this in NCR. Note that even with the falling share the absolute production of hydro power is rising over time. The remainder of the electricity demand is met by the other sources (gas, nuclear, wind, solar, others) that rise modestly in their share contribution to offset the falling hydro contribution.

In the CPS case, we do not change the resource and capital supplies exogenously as in the base case, but let them remain at the NCR paths and use a system of taxes and subsidies to hit the higher targets for renewables and nuclear. We impose taxes on coal and subsidies for the rest in order to attract more resources and capital into the non-fossils and discourage coal generation. We require that the tax revenue exactly equal the subsidies so that there is no net (new) transfer to the government.

The comparison of these two scenarios is given in Table 9. In the NCR case, total coal consumption in 2020 is 4,147 million tons compared to 4,083 in the base case. The coal power is cheaper and thus the electricity demand in NCR is slightly higher, 6,949 billion kWh in 2020 compared to 6,886 in the base case. The impact of achieving the CPS targets via taxes and subsidies is substantial even in 2020; coal use is 3.5% lower than in NCR leading to a 2.1% reduction in total energy consumption. The price of average electricity is 1.3% higher leading to a 2.7% reduction in 2020.

By 2030 the impact is magnified by the cumulative GDP losses and reduction in capital stock. Coal use in 2030 is 5.5% lower in the CPS case while total energy consumption in 3.5% lower. Aggregate GDP is 0.29% lower due to these distortions with reductions in both consumption and investment. The generation mix shifts from 70.6% coal and 4.9% nuclear to 65.3% coal and 7.6% nuclear. The wind contribution rises from 4.7% to 5.7%.

While our specifications of the cost functions for the renewables and nuclear are simple, it allows a representation of the costs of finding suitable sites for such generation methods, and also possibly higher costs of transmission. The simulated costs are comparable to the renewable subsidies case shown in Table 8 given that the same cost function elasticities are used. There the cost of reducing CO_2 emissions by 7.9% in 2030 is a 0.53% relative cut in GDP, here the 4.0% reduction in CO_2 reduces GDP relative to base case by 0.29%.

Table 9. Comparing "no coal reduction (NCR)" with IEA "Current Policies" scenarios

	2020		2030	
	NCR	CPS vs NCR	Base case	CPS vs NCR
Variable	values	% change	values	% change
GDP (billion ¥2010)	80,494	-0.10	126,235	-0.29
Consumption (bil ¥2010)	38,784	-0.13	67,264	-0.35
Investment (bil ¥2010)	31,532	-0.07	43,747	-0.25
Government consumption (bil ¥2010)	8,958	-0.14	12,785	-0.27
Fossil energy use (million tons of sce)	4,915	-2.1	6,113	-3.5
Coal use (million tons)	4,147	-3.5	4,794	-5.5
Oil use (million tons)	663	0.12	836	-0.16
Gas use (billion cubic meters)	239,647	2.1	361,272	-1.5
Electricity (billion kWh)	6,949	-2.7	9,102	-4.3
Electricity price		1.3		3.4
CO2 emissions (inc cement; mil tons)	11,236	-2.3	13,073	-4.0
Cumulative CO2 (2015-2030)			187,684	-2.8
Electricity generation	share of total generation		share of total generation	
Coal	0.678	0.657	0.706	0.653
Gas	0.037	0.037	0.040	0.039
Nuclear	0.047	0.058	0.049	0.076
Hydro	0.157	0.156	0.127	0.128
Other	0.025	0.030	0.022	0.031
Wind	0.046	0.048	0.047	0.057
Solar	0.010	0.014	0.009	0.015

6. Conclusion

As part of the Paris Agreement, China has set for itself targets for reducing energy intensity by 60-65% in 2030 compared to 2005 levels. This study examines the economic consequences if the targets were met through a carbon pricing mechanism, where all fossil fuels are taxed in proportion to their carbon contents. The study uses a recursive dynamic computable general equilibrium model of the Chinese economy for the purpose this analysis.

The study finds that the carbon pricing policy would lead to a such a 65% reduction in intensity at a modest cumulative cost to GDP, which would be 0.7% lower than the base case by 2030, when revenues generated from the carbon pricing are recycled to the economy to cut existing value-added taxes. The goal of reducing the intensity by 60% is projected to cut GDP by only 0.1% relative to the base case by 2030. The carbon price not only reduces energy demand but also causes a shift away from more energy intensive industries to less energy intensive ones; it also causes a larger-scale deployment of renewable energy in electricity and heat generation.

A policy focused on promoting renewables in electricity generation using subsidies financed by a fossil fuel tax in proportion to their carbon contents would achieve the carbon reduction at a somewhat greater relative loss in GDP growth than a carbon pricing case. Putting more of the burden of adjustment on the power sector, when there are costs to a rapid ramp-up of hydro, nuclear, wind and solar power, results in a greater distortion of the price of electricity and a more difficult adjustment. A more careful study of the costs of resources going into these renewables is needed, including land, and suitable rivers.

As noted, this study does not attempt to model China's actual plan to achieve its NDC, which includes both market and non-market measures. Instead, it focuses on the cost of achieving the NDC through a market mechanism, carbon pricing. Comparison of the economic consequences of the carbon pricing mechanism considered here with that of government's actual plan of implementing the NDC is a natural extension of this study. Moreover, this study focuses only on CO_2 emissions from fossil fuel combustion, and does not include other GHG emissions from fossil fuel combustion and also GHG emissions from industrial processes and land use change. This is a limitation of the study to be addressed in future work.

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Appendix A: Economic-Environmental Model of China

In this appendix we describe the model for China in some detail, beginning with the modeling of each of the main economic agents. Then in section A.2 we describe the data and parameters underlying the model. A previous version of this model of the Chinese economy is used in Nielsen and Ho (2013) and here we describe the updates to it. This is a multi-sector model of economic growth where the main drivers of growth are population, total factor productivity growth and changes in the quality of labor and capital. It has a dynamic recursive structure, i.e. where investment is determined by fixed savings rate as in the Solow model. Consumption demand is driven by a translog household model that distinguishes demand by different demographic groups. The electricity sector is composed of 7 different generation technologies.

A.1 Structure of the Model

We discuss the five main actors in the economy in turn – producers, households, capital owners, government and foreigners. The electricity sector is described in greater detail explaining how the different generation technologies are allocated. For easy reference Table A1 lists variables which are referred to with some frequency. In general, a bar above a symbol indicates that it is a plan parameter or variable while a tilde indicates a market variable. Symbols without markings are total quantities or average prices. To reduce unnecessary notation, we include the time subscript, *t*, only when necessary to note the time dependence.

A.1.1. Production

Each of the 33 industries is assumed to produce its output using a constant returns to scale technology. Except for electricity, for each sector *j* the output at time t, QI_{jt}, is expressed as:

(A1) $$QI_j = f(KD_j, LD_j, TD_j, A_{1j}, \ldots, A_{nj}, t) \quad ,$$

where KD_j, LD_j, TD_j, and A_{ij} are capital, labor, land, and intermediate inputs, respectively.[13] In sectors for which both plan and market allocation exists, output is made up of two components,

[13] QI_j denotes the quantity of industry *j*'s output. This is to distinguish it from, QC_j, the quantity of commodity *j*. Each industry may produce more than one commodity and each commodity may be produced by more than one industry. In the language of the input output tables, we make use of both the Use and Make (or Supply) matrices.

the plan quota output ($\overline{QI}_j$) and the output sold on the market ($\widetilde{QI}_j$). The plan quota output is sold at the state-set price ($\overline{PI}_j$) while the output in excess of the quota is sold at the market price ($\widetilde{PI}_j$). The *PI* and *QI* names are chosen to reflect that these are domestic *industry* variables, as opposed to commodities (*PC*) or total supply (*PS*), the sum of domestic output and imports.

A more detailed discussion of how this plan-market formulation is different from standard market economy models is given in Garbaccio, Ho, and Jorgenson (1999). In summary, if the constraints are not binding, then the "two-tier plan/market" economy operates at the margin as a market economy with lump sum transfers between agents. The capital stock in each industry consist of two parts – the fixed capital, $\overline{K}_j$, that is inherited from the initial period, and the market portion, $\widetilde{KD}_j$, that is rented at the market rate. The before-tax return to the owners of fixed capital in sector *j* is:

(A2) $$profit_j = \overline{PI}_j\, \overline{QI}_j + \widetilde{PI}_j\, \widetilde{QI}_j - \widetilde{P}_j^{KD}\, \widetilde{KD}_j - PL_j LD_j - PT_j TD_j - \sum_i \overline{PS}_i\, \overline{A}_{ij} - \sum_i \widetilde{PS}_i\, \widetilde{A}_{ij} \quad .$$

For each industry, given the capital stock $\overline{K}_j$ and prices, the first order conditions from maximizing equation A2, subject to equation A1, determine the market and total input demands.

We represent the production structure with the cost dual, expressing the output price as a function of input prices and an index of technology. The 3 primary factors and 33 intermediate inputs for each industry are determined by a nested series of constant elasticity of substitution (CES) functions taken from the GTAP model (version 7). The nest structure is given in Figure A1 and applies to all industries except electricity which is treated separately below.

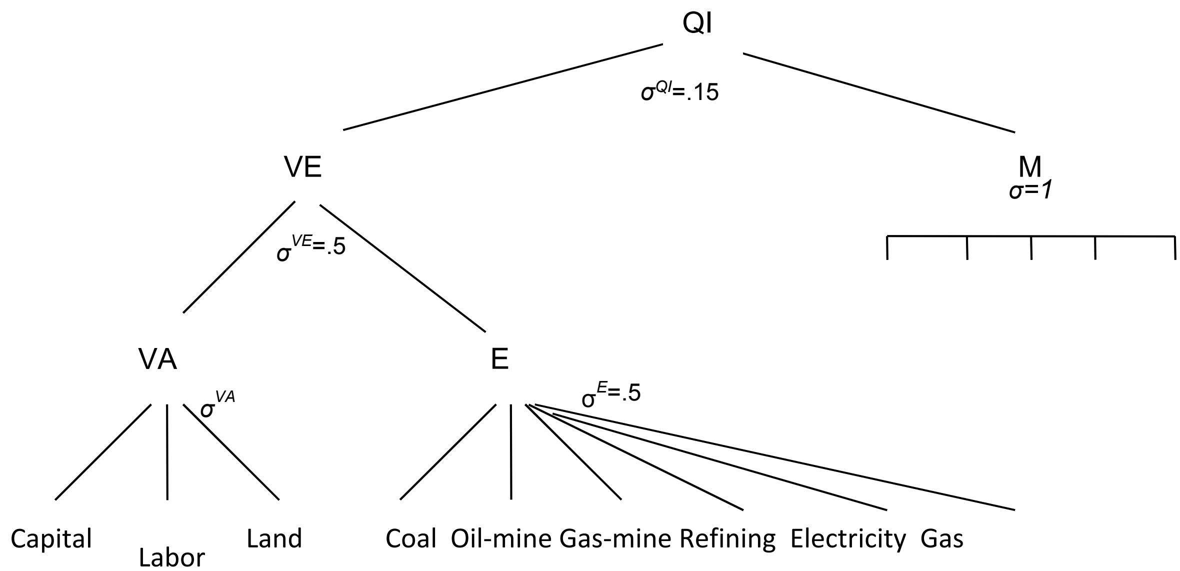


Figure A1. Production structure for each industry except electricity.

At the top tier, output is a function of the primary factor-energy basket (VE) and the non-energy intermediate input basket (M), $QI_{jt} = f(VE_{jt}, M_{jt}, t)$. The VE basket is an aggregate of value added (VA) and the energy basket (E). Value added is a function of the 3 primary factors – capital (K), labor (L) and land (T). The energy aggregate is a CES function of coal, oil mining, gas mining, petroleum refining & coal products, electricity and gas commodities. The materials aggregate (M) is a Cobb-Douglas function of the 27 non-energy commodities.

For the top tier, the value equation and cost function are, respectively:

(A3) $$PI_{jt}QI_{jt} = P_{jt}^{VE}VE_{jt} + PM_{jt}M_{jt}$$

(A4) $$PI_{jt} = \frac{\kappa_{jt}^{QI}}{g_{jt}}\left[\alpha_{Mjt}^{\sigma_{jt}^{QI}} PM_{jt}^{\left(1-\sigma_{jt}^{QI}\right)} + \left(1 - \alpha_{Mjt}\right)^{\sigma_{jt}^{QI}} P_{jt}^{VE\left(1-\sigma_{jt}^{QI}\right)}\right]^{\frac{1}{1-\sigma_{jt}^{QI}}}$$

where α_{Mj} is the weight for all non-energy inputs into industry *j*, and $1/\sigma_{jt}^{QI}$ is the elasticity of substitution between the two inputs. g_{jt} is the index of the level of technology where a rising value indicates positive TFP growth and falling output prices. We assume that the change follows an exponential function: $\dot{g}_j(t) = A_j \exp(-\mu_j t)$. This implies technical change that is rapid initially, but gradually declines toward zero.

The primal function corresponding to the above dual cost is:

$$\text{(A4b)}\quad QI_{jt} = \frac{g_{jt}}{\kappa_{jt}^{QI}} \left[\alpha_{Mjt} M_{jt}^{\frac{\sigma_{jt}^{QI}-1}{\sigma_{jt}^{QI}}} + \left(1 - \alpha_{Mjt}\right) VE_{jt}^{\frac{\sigma_{jt}^{QI}-1}{\sigma_{jt}^{QI}}} \right]^{\frac{\sigma_{jt}^{QI}}{\sigma_{jt}^{QI}-1}}$$

The input demands derived from the CES cost function are:

$$\text{(A5)}\quad VE_{jt} = \left(\frac{\kappa_{jt}^{QI}}{g_{jt}} \right)^{1-\sigma_{jt}^{QI}} \left[\left(1 - \alpha_{Mjt}\right) \frac{PI_{jt}}{P_{jt}^{VE}} \right]^{\sigma_{jt}^{QI}} QI_{jt}$$

$$M_{jt} = \left(\frac{\kappa_{jt}^{QI}}{g_{jt}} \right)^{1-\sigma_{jt}^{QI}} \left[\alpha_{Mjt} \frac{PI_{jt}}{PM_{jt}} \right]^{\sigma_{jt}^{QI}} QI_{jt}$$

The weights for the CES functions are explained in Rutherford (2003) and Klump, McAdam and Willman (2011); these are calibrated using the base year values:

$$\text{(A5b)}\quad \alpha_{Mj0} = \frac{PM_{j0} M_{j0}^{1/\sigma_{jt}^{QI}}}{P_{j0}^{VE} VE_{j0}^{1/\sigma_{jt}^{QI}} + PM_{j0} M_{j0}^{1/\sigma_{jt}^{QI}}};$$

$$\text{(A5c)}\quad \frac{g_{j0}}{\kappa_{j0}^{QI}} = QI_{j0} / \left[\alpha_{Mj0} M_{j0}^{\frac{\sigma_{jt}^{QI}-1}{\sigma_{jt}^{QI}}} + \left(1 - \alpha_{Mj0}\right) VE_{j0}^{\frac{\sigma_{jt}^{QI}-1}{\sigma_{jt}^{QI}}} \right]^{\frac{\sigma_{jt}^{QI}}{\sigma_{jt}^{QI}-1}}$$

The corresponding value, price and input demand equations for the primary factor-energy basket (VE) and the value-added basket (VA) are:

$$\text{(A6)}\quad \begin{aligned} P_{jt}^{VE} VE_{jt} &= P_{jt}^{VA} VA_{jt} + PE_{jt} E_{jt} \\ P_{jt}^{VA} VA_{jt} &= P_{jt}^{KD} KD_{jt} + PL_{jt} LD_{jt} + PT_{jt} TD_{jt} \end{aligned}$$

$$\text{(A7)}\quad P_{jt}^{VE} = \frac{1}{\kappa_{jt}^{VE}} \left[\alpha_{Ejt}^{\sigma_{jt}^{VE}} PE_{jt}^{\left(1-\sigma_{jt}^{VE}\right)} + \left(1 - \alpha_{Ejt}\right)^{\sigma_{jt}^{VE}} P_{jt}^{VA\left(1-\sigma_{jt}^{VE}\right)} \right]^{\frac{1}{1-\sigma_{jt}^{VE}}}$$

$$\text{(A8)}\quad P_{jt}^{VA} = \frac{1}{\kappa_{jt}^{VA}} \left[\alpha_{Kjt}^{\sigma_{jt}^{VA}} P_{jt}^{KD\left(1-\sigma_{jt}^{VA}\right)} + \alpha_{Ljt}^{\sigma_{jt}^{VA}} PL_{jt}^{\left(1-\sigma_{jt}^{VA}\right)} + \left(1 - \alpha_{Ljt} - \alpha_{Ljt}\right)^{\sigma_{jt}^{VA}} PT_{jt}^{\left(1-\sigma_{jt}^{VA}\right)} \right]^{\frac{1}{1-\sigma_{jt}^{VA}}}$$

(A9) $$VA_{jt} = \left(\frac{1}{\kappa_{jt}^{VE}}\right)^{1-\sigma_{jt}^{VE}} \left[\left(1-\alpha_{Ejt}\right)\frac{P_{jt}^{VE}}{P_{jt}^{VA}}\right]^{\sigma_{jt}^{VE}} VE_{jt}$$

$$E_{jt} = \left(\frac{1}{\kappa_{jt}^{VE}}\right)^{1-\sigma_{jt}^{VE}} \left[\alpha_{Ejt}\frac{P_{jt}^{VE}}{PE_{jt}}\right]^{\sigma_{jt}^{VE}} VE_{jt}$$

(A10) $$KD_{jt} = \left(\frac{1}{\kappa_{jt}^{VA}}\right)^{1-\sigma_{jt}^{VA}} \left[\alpha_{Kjt}\frac{P_{jt}^{VA}}{P_{jt}^{KD}}\right]^{\sigma_{jt}^{VA}} VA_{jt} \qquad TD_{jt} = \left(\frac{1}{\kappa_{jt}^{VA}}\right)^{1-\sigma_{jt}^{VA}} \left[\alpha_{Tjt}\frac{P_{jt}^{VA}}{PT_{jt}}\right]^{\sigma_{jt}^{VA}} VA_{jt}$$

$$LD_{jt} = \left(\frac{1}{\kappa_{jt}^{VA}}\right)^{1-\sigma_{jt}^{VA}} \left[\alpha_{Ljt}\frac{P_{jt}^{VA}}{PL_{jt}}\right]^{\sigma_{jt}^{VA}} VA_{jt}$$

The parameters of the value-added-energy and value-added nodes are calibrated to base year values in the following way:

$$\alpha_{Ej0} = \frac{PE_{j0}E_{j0}^{1/\sigma_{jt}^{VE}}}{P_{j0}^{VA}VA_{j0}^{1/\sigma_{jt}^{VE}} + PE_{j0}E_{j0}^{1/\sigma_{jt}^{VE}}}; \quad \kappa_{j0}^{VE} = VE_{j0} / [\alpha_{Ej0}E_{j0}^{\frac{\sigma_{jt}^{VE}-1}{\sigma_{jt}^{VE}}} + \left(1-\alpha_{Ej0}\right)VA_{j0}^{\frac{\sigma_{jt}^{VE}-1}{\sigma_{jt}^{VE}}}]^{\frac{\sigma_{jt}^{VE}}{\sigma_{jt}^{VE}-1}}$$

$$\alpha_{Kj0} = \frac{P_{j0}^{KD}KD_{j0}^{1/\sigma_{jt}^{VA}}}{P_{j0}^{KD}KD_{j0}^{1/\sigma_{jt}^{VA}} + P_{j0}^{LD}LD_{j0}^{1/\sigma_{jt}^{VA}} + P_{j0}^{TD}TD_{j0}^{1/\sigma_{jt}^{VA}}}; \; \alpha_{Lj0} = \ldots; \; \alpha_{Tj0} = \ldots$$

$$\kappa_{j0}^{VA} = VA_{j0} / [\alpha_{Kj0}KD_{j0}^{\frac{\sigma_{jt}^{VA}-1}{\sigma_{jt}^{VA}}} + \alpha_{Lj0}LD_{j0}^{\frac{\sigma_{jt}^{VA}-1}{\sigma_{jt}^{VA}}} + \left(1-\alpha_{Kj0}-\alpha_{Lj0}\right)TD_{j0}^{\frac{\sigma_{jt}^{VA}-1}{\sigma_{jt}^{VA}}}]^{\frac{\sigma_{jt}^{VA}}{\sigma_{jt}^{VA}-1}}$$

Note that the cost functions for the sub-aggregates do not have an index of technology like the top tier; however, the share coefficients – $\alpha_{Ejt}, \alpha_{Kjt}$, etc. – are allowed to change over time to reflect biases in technical change.

The energy basket equations give the demands for the 6 types of energy:

(A11) $$PE_{jt}E_{jt} = \sum_{k \in IE} PS_{kt}A_{kjt}$$

$$PE_{jt} = \frac{1}{\kappa_{jt}^{E}}\left[\sum_{k \in IE}\alpha_{kjt}^{E\sigma_{jt}^{E}} PS_{kt}^{\left(1-\sigma_{jt}^{E}\right)}\right]^{\frac{1}{1-\sigma_{jt}^{E}}} \qquad \text{IE=\{coal, oil, gasmine, refine, elect, gas\}}$$

$$A_{kjt} = \left(\frac{1}{\kappa_{jt}^{E}}\right)^{1-\sigma_{jt}^{E}} \left[\alpha_{kjt}^{E}\frac{PE_{jt}}{PS_{kt}}\right]^{\sigma_{jt}^{E}} E_{jt} \qquad k \in IE$$

$$\alpha_{kj0}^{E} = \frac{PS_{k0} A_{kj0}^{1/\sigma_{jt}^{E}}}{\sum_{i \in IE} PS_{i0} A_{ij0}^{1/\sigma_{jt}^{E}}}; \quad \kappa_{j0}^{E} = E_{j0} / [\sum_{k \in IE} \alpha_{kj0}^{E} A_{kj0}^{\frac{\sigma_{jt}^{E}-1}{\sigma_{jt}^{E}}}]^{\frac{\sigma_{jt}^{E}}{\sigma_{jt}^{E}-1}}$$

The non-energy basket is a Cobb-Douglas function and the corresponding equations are:

(A12) $\ln PM_{jt} = \sum_{k \in NE} \alpha_{kjt}^{M} \ln PS_{kt}$ NE={agri, … , services, admin}

$$PM_{jt} M_{jt} = \sum_{k \in NE} PS_{kt} A_{kjt}$$

$$A_{kjt} = \alpha_{kjt}^{M} \frac{PM_{jt} M_{jt}}{PS_{kt}} \quad k \in NE$$

We set the energy share α_{Ej} to fall gradually over the next 40 years while the labor coefficient, α_{Lj}, rises correspondingly. The composition of the aggregate energy input E_j (i.e. the α_{kj}^{E} coefficients) are also allowed to change over time.

The price to buyers of industry output includes the indirect tax on output, the externality ad-valorem tax, the externality unit tax:

(A13) $PI_i^t = (1 + t_i^t + t_i^{xv}) PI_i + t_i^{xu}$

A carbon tax on coal, e.g., is represented by t_{coal}^{xu}.

Industries versus Commodities

The model distinguishes industries from commodities as in the official Use and Make input-output tables. Each industry may make a few commodities and each commodity may be made by a few industries; e.g. the Refining industry produces Refining commodity and Chemical commodity, and the Chemical commodity comes from Refining, Chemical, Primary Metal and other industries. The quantity of domestic commodity is denoted *QC* and its price *PC*; the sum of column *i* in the Make matrix gives the value of commodity *i*, and the sum of row *j* is the industry output value. The relation between commodity and industry output and prices are written as:

(A14) $VQC_i = PC_i QC_i = \sum_j m_{ji}^{r} PI_i^t QI_i$

$$\ln PC_i = \sum_j m_{ji}^c \ln PI_i^t$$

where m_{ji}^r is the row share and m_{ji}^c is the column share.

A.1.2. The electricity sector

In version 17 of the China Model we disaggregate the electricity sector into different generation technologies unlike the previous versions that represent the output of electricity using the common production function (A.4b) above. The production and input structure of this sector is illustrated in Figure A2; this consists of a nested structure of CES functions. At the top tier, electricity output is an aggregate of Transmission & Distribution and Electricity Generation. The price of electricity output (sector 22) is a function of the price of transmission $P_{j=22,t}^{tt,TD}$ and the price of generation $P_{j=22,t}^{EG}$:

$$\text{(A.15)}\quad PI_{jt}^{tt} = \frac{\kappa_{jt}^{QI}}{g_{jt}} \left[\alpha_{EGjt}^{\sigma_t^{ED}} P_{jt}^{EG(1-\sigma_t^{ED})} + \left(1-\alpha_{EGjt}\right)^{\sigma_t^{ED}} P_{jt}^{tt,TD(1-\sigma_t^{ED})} \right]^{\frac{1}{1-\sigma_t^{ED}}}$$

j=22(elec)

The superscript *tt* denotes that this is a price inclusive of indirect business taxes that are levied at the level of the generating sectors and transmission. This is explained in (A21b) below. The quantity and value equations are:

$$\text{(A.16)}\quad Q_t^{EG} = \left(\frac{\kappa_{jt}^{QI}}{g_{jt}}\right)^{1-\sigma_t^{ED}} \left[\alpha_{EGjt} \frac{PI_{jt}}{P_{jt}^{EG}}\right]^{\sigma_t^{ED}} QI_{jt}$$

$$Q_t^{TD} = \left(\frac{\kappa_{jt}^{QI}}{g_{jt}}\right)^{1-\sigma_t^{ED}} \left[\left(1-\alpha_{EGjt}\right) \frac{PI_{jt}^{tt}}{P_{jt}^{tt,TD}}\right]^{\sigma_t^{ED}} QI_{jt}$$

$$PI_{j=elec,t}^{tt} QI_{j=elec,t} = P_t^{EG} Q_t^{EG} + P_t^{tt,TD} Q_t^{TD}$$

At the Generation node we assume that this consists of Base load sources and Renewables (intermittent) in a way similar to the C-GEM model (Qi et al 2014). The price of Electricity Generation is thus a function of the price of Base load Electricity (P_{Et}^{BL}) and price of Renewable Electricity (P_{Et}^{RE}):

$$P_t^{EG} = \frac{1}{\kappa_t^{EG}} \left[\alpha_{BLt}^{\sigma_t^{EG}} P_{Et}^{BL(1-\sigma_t^{EG})} + \left(1 - \alpha_{BLt}\right)^{\sigma_t^{EG}} P_{Et}^{RE(1-s_t^{EG})} \right]^{\frac{1}{1-\sigma_t^{EG}}} \quad \text{(A.17)}$$

When σ_t^{EG}=1, this simplifies to: $P_t^{EG} = \frac{1}{\kappa_t^{EG}} P_{Et}^{BL\alpha_{BLt}} P_{Et}^{RE(1-\alpha_{BLt})}$

Figure A2. Structure of electricity sector

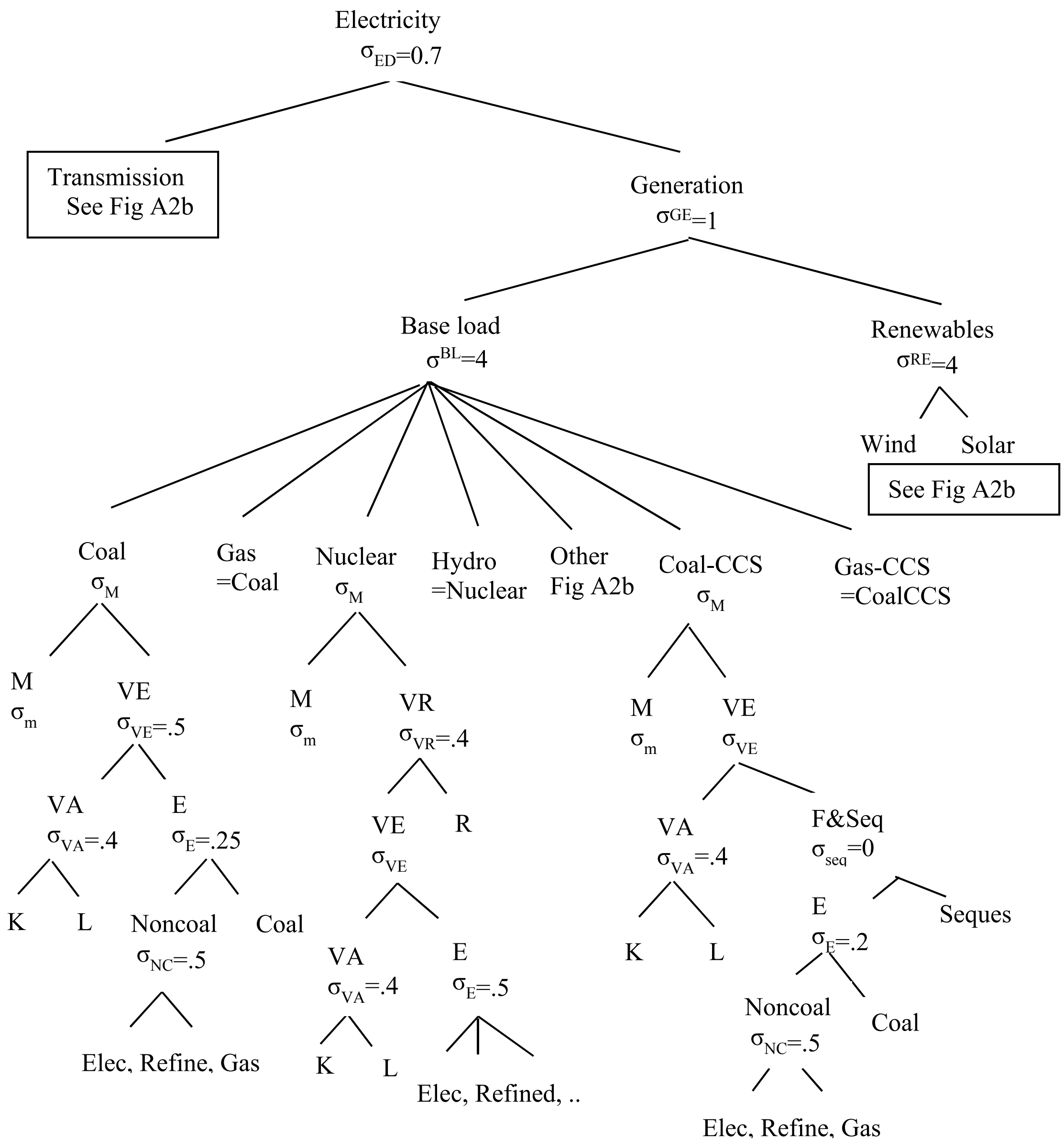
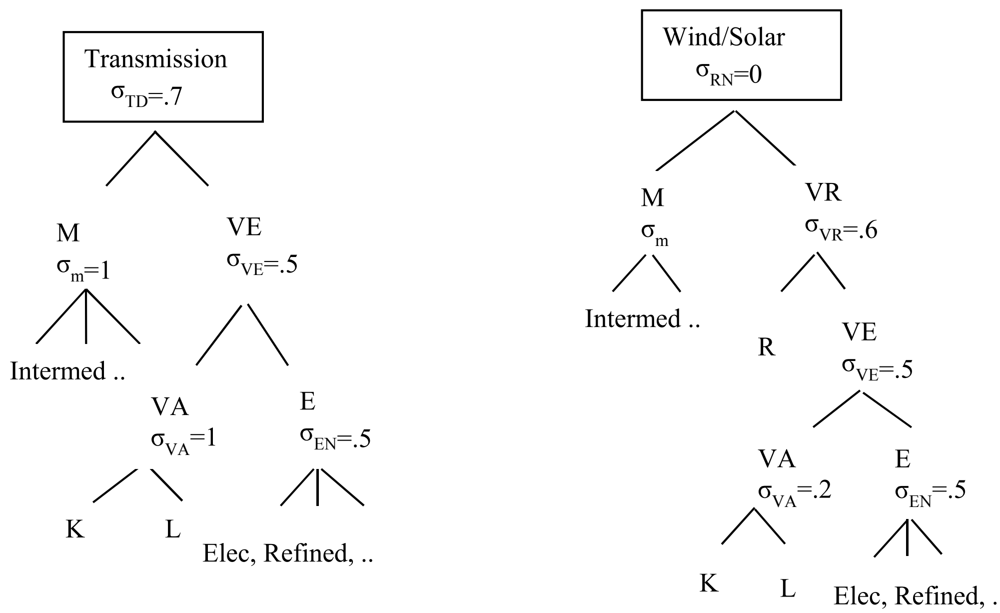

Electricity
σED=0.7
Transmission
See Fig A2b
Generation
σGE=1
Base load
σBL=4
Renewables
σRE=4
Wind
Solar
See Fig A2b
Coal
σM
Gas
=Coal
Nuclear
σM
Hydro
=Nuclear
Other
Fig A2b
Coal-CCS
σM
Gas-CCS
=CoalCCS
M
σm
VE
σVE=.5
VA
σVA=.4
E
σE=.25
K
L
Noncoal
σNC=.5
Coal
Elec, Refine, Gas
M
σm
VR
σVR=.4
VE
σVE
R
VA
σVA=.4
E
σE=.5
K
L
Elec, Refined, ..
M
σm
VE
σVE
VA
σVA=.4
F&Seq
σseq=0
K
L
E
σE=.2
Seques
Noncoal
σNC=.5
Coal
Elec, Refine, Gas

Figure A2. Structure of electricity sector

(b) Transmission and Renewables structure



The quantities of Base load output and Renewable output are:

(A.18) $$Q_{Et}^{BL} = \left(\frac{1}{\kappa_t^{EG}}\right)^{1-\sigma_t^{EG}} \left[\alpha_{BLt} \frac{P_t^{EG}}{P_{Et}^{BL}}\right]^{\sigma_t^{EG}} Q_t^{EG}$$

$$Q_{Et}^{RE} = \left(\frac{1}{\kappa_t^{EG}}\right)^{1-\sigma_t^{EG}} \left[(1-\alpha_{BLt}) \frac{P_t^{EG}}{P_{Et}^{RE}}\right]^{\sigma_t^{EG}} Q_t^{EG}$$

$$P_t^{EG} Q_t^{EG} = P_{Et}^{BL} Q_{Et}^{BL} + P_{Et}^{RE} Q_{Et}^{RE}$$

Renewables here consist only of Wind and Solar which are intermittent sources and requires either parallel storage capacities, or conventional backup. We thus assume that such electricity is imperfectly substitutable with base load sources and specify an elasticity of substitution, σ^{GE}, in a way similar to Qi et al. (2014) for our main parameter value of 1.0.[14] All other sources of electricity contribute to the Base load aggregate with a high elasticity of substitution, σ^{BL}=4.[15] In the base year, these sources include conventional coal, gas, hydro, nuclear and a minor "other" (oil, biomass, geothermal, etc.) In the future years we allow the options of coal with CCS and gas with CCS. The price of Base load electricity is thus a function of the component prices $P_{coal,t}^{tt,EGEN}$, $P_{gas,t}^{tt,EGEN}$, $P_{nuclear,t}^{tt,EGEN}$, $P_{hydro,t}^{tt,EGEN}$, $P_{other,t}^{tt,EGEN}$, $P_{coalCCS,t}^{tt,EGEN}$, $P_{gasCCS,t}^{tt,EGEN}$:

(A.19) $$P_{Et}^{BL} = \frac{1}{\kappa_t^{BL}} \left[\sum_{l \in BL} \alpha_{lt}^{BL\sigma^{BL}} P_{lt}^{tt,EGEN(1-\sigma^{BL})}\right]^{\frac{1}{1-\sigma^{BL}}}$$

l=coal, gas, nuclear, hydro, other, coal-ccs, gas-ccs

The price variables have a *tt* superscript to denote that they are inclusive of (net) output taxes and subsidies. The value equation and quantities of the various Base load technologies are:

(A.20) $$P_{Et}^{BL} Q_{Et}^{BL} = \sum_{l \in BL} P_{lt}^{tt,EGEN} Q_{lt}^{EGEN}$$

[14] In the Phoenix model (Sue Wing et al 2011), the elasticity of substitution between "peak load" (which includes wind and solar) and "base load" sources is also 1.

$$Q_{lt}^{EGEN} = \left(\frac{1}{\kappa_t^{BL}}\right)^{1-\sigma^{BL}} \left[\alpha_{bt}^{BL} \frac{P_{Et}^{BL}}{P_{lt}^{tt,EGEN}}\right]^{\sigma^{BL}} Q_{Et}^{BL}$$

For the intermittent renewable aggregate we only identify two types in this model: wind and solar (the others are part of the miscellaneous "other" in the base load tier). We assume that wind and solar are close, but not perfect, substitutes with an elasticity σ^{RE} =4. This is the elasticity chosen in Sue Wing et al. (2011, p 31). The equations for the renewable tier are:

(A.21) $$P_{Et}^{RE} = \frac{1}{\kappa_t^{RE}}\left[\alpha_{wind,t}^{RE\sigma^{RE}} P_{wind,t}^{EGEN(1\text{-}s^{RE})} + \left(1 - \alpha_{wind,t}^{RE}\right)^{\sigma^{RE}} P_{solar,t}^{EGEN(1-\sigma^{RE})}\right]^{\frac{1}{1-\sigma^{RE}}}$$

$$Q_{wind,t}^{EGEN} = \left(\frac{1}{\kappa_t^{RE}}\right)^{1-\sigma_t^{RE}} \left[\alpha_{wind,t}^{RE} \frac{P_t^{RE}}{P_{wind,t}^{RE}}\right]^{\sigma_t^{RE}} Q_{Et}^{RE}$$

$$Q_{solar,t}^{EGEN} = \left(\frac{1}{\kappa_t^{RE}}\right)^{1-\sigma_t^{RE}} \left[(1-\alpha_{wind,t}^{RE}) \frac{P_t^{RE}}{P_{solar,t}^{RE}}\right]^{\sigma_t^{RE}} Q_{Et}^{RE}$$

$$P_{Et}^{RE} Q_{Et}^{RE} = P_{wind,t}^{tt,EGEN}\ Q_{wind,t}^{EGEN} + P_{solar,t}^{tt,EGEN}\ Q_{solar,t}^{EGEN}$$

The price to the purchasers of such electricity is $P_{l,t}^{tt,EGEN}$ which includes the net output tax, $tt_{l,t}^{EL}$ and externality tax, $tt_{l,t}^{ELxu}$. The prices to the producers are net of this tax:

(A21b) $$P_{l,t}^{tt,EGEN} = (1+tt_{l,t}^{EL})P_{l,t}^{EGEN} + tt_{l,t}^{ELxu}$$

The input demand structure for coal generation is given in Figure A2; at the top tier coal power is produced by a low elasticity CES function of value-added-energy (VE) and non-energy intermediates (M).[16] Productivity growth in this sector is represented by the g_{ct}^{BL} term in the price function (A22). The VE bundle is a CES function of value-added (VA) and energy (E) with σ^{VE} =0.5, while the VA node has an elasticity σ^{VA} of 1.0 between capital and labor. The Energy aggregate is a function of coal and non-coal energy which is a small item that includes electricity and refined petroleum products (lubricants and vehicle fuels) as described in the data appendix. We set the elasticity between them to a low value (σ^{E}

[15] Our specification of base load and renewables follows EPPA-4, which assumes perfect substitution among the base load sources. We have, however, chosen to use an elasticity of 4 as used in the Phoenix model; in a similar setup, Vennemo et al (2014) use an elasticity of 20.
[16] In Qi et al. (2014) this is set to be a Leontief function, here we use the low general elasticity between materials and value-added-energy in GTAP of 0.15.

=0.2). The non-coal quantity is an aggregate of only electricity and refined oil since the other energy inputs (oil mining, gas) are zero.

The input structure for gas generation is similar to the one for coal for the top tiers for output price, price of VE, price of VA and price of M. The equations for the top tiers, in terms of the producer prices, are:

$$P_{c,t}^{EGEN} = \frac{\kappa_{ct}^{BL}}{g_{ct}^{BL}} \left[\alpha_{M,t}^{BLc\,\sigma_{BL,c}^{M}} PM_{c,t}^{BL(1-\sigma_{BL,c}^{M})} + \left(1 - \alpha_{M,t}^{BLc}\right)^{\sigma_{BL,c}^{M}} P_{BLc,t}^{VE(1-\sigma_{BL,c}^{M})} \right]^{\frac{1}{1-\sigma_{BL,c}^{M}}} \tag{A.22}$$

$$P_{c,t}^{EGEN} Q_{c,t}^{EGEN} = PM_{c,t}^{BL} M_{c,t}^{BL} + P_{BL,c,t}^{VE} VE_{c,t}^{BL}; \qquad \text{c=coal, coal\_ccs, gas, gas\_ccs}$$

$$VE_{c,t}^{BL} = \left(\frac{\kappa_{ct}^{BL}}{g_{ct}^{BL}}\right)^{1-\sigma_{BLc}^{M}} \left[\left(1-\alpha_{Mt}^{BLc}\right)\frac{P_{ct}^{BL}}{P_{BL,ct}^{VE}}\right]^{\sigma_{BLc}^{M}} Q_{ct}^{EGEN}$$

$$M_{c,t}^{BL} = \left(\frac{\kappa_{ct}^{BL}}{g_{ct}^{BL}}\right)^{1-\sigma_{BLc}^{M}} \left[\alpha_{Mt}^{BLc}\frac{P_{ct}^{BL}}{PM_{ct}^{BL}}\right]^{\sigma_{BLc}^{M}} Q_{ct}^{EGEN}$$

$$\ln PM_{c,t}^{BL} = \sum_{k\in NE} \alpha_{kMt}^{BLc} \ln PS_{kt} \tag{A.23}$$

; c=coal, coal_ccs, gas, gas_ccs

$$A_{k,c,t}^{BL} = \alpha_{kMt}^{BLc} PM_{c,t}^{BL} M_{c,t}^{BL} / PS_{kt}$$

$$P_{BL,c,t}^{VE} = \frac{1}{\kappa_{BLc,t}^{VE}} \left[\alpha_{Et}^{BLc\,\sigma_{BLc}^{VE}} PE_{c,t}^{BL(1-\sigma_{BLc}^{VE})} + (1-\alpha_{Et}^{BLc})^{\sigma_{BLc}^{VE}} P_{BLc,t}^{VA(1-\sigma_{BLc}^{VE})} \right]^{\frac{1}{1-\sigma_{BLc}^{VE}}} \tag{A.24}$$

$$P_{BLc,t}^{VE} VE_{BLc,t} = P_{BLc,t}^{VA} VA_{BLc,t} + PE_{BLc,t} E_{BLc,t}$$

$$VA_{c,t}^{BL} = \left(\frac{1}{\kappa_{ct}^{VE}}\right)^{1-\sigma_{BLc}^{VE}} \left[\left(1-\alpha_{Et}^{BLc}\right)\frac{P_{BL,ct}^{VE}}{P_{BL,ct}^{VA}}\right]^{\sigma_{BLc}^{VE}} VE_{ct}^{BL}$$

$$E_{c,t}^{BL}=\left(\frac{1}{\kappa_{ct}^{VE}}\right)^{1-\sigma_{BLc}^{VE}}\left[\alpha_{Et}^{BLc}\,\frac{P_{BL,ct}^{VE}}{PE_{ct}^{BL}}\right]^{\sigma_{BLc}^{VE}}VE_{ct}^{BL}$$

(A.25)
$$P_{BLc,t}^{VA}=\frac{1}{\kappa_{BLc,t}^{VA}}\left[\alpha_{Kt}^{BLc\,\sigma_{BLc}^{VA}}P_{BLc,t}^{KD(1-\sigma_{BLc}^{VA})}+(1-\alpha_{Kt}^{BLc})^{\sigma_{BLc}^{VA}}PL_{BLc,t}^{(1-\sigma_{BLc}^{VA})}\right]^{\frac{1}{1-\sigma_{BLc}^{VA}}}$$

$$P_{BLc,t}^{VA}VA_{c,t}^{BL}=P_{BLc,t}^{KD}KD_{c,t}^{BL}+PL_{c,t}^{BL}LD_{c,t}^{BL}$$

$$KD_{ct}^{BL}=\left(\frac{1}{\kappa_{BLct}^{VA}}\right)^{1-\sigma_{BLc}^{VA}}\left[\alpha_{Kt}^{BLc}\,\frac{P_{BLct}^{VA}}{P_{BLct}^{KD}}\right]^{\sigma_{jt}^{VA}}VA_{ct}^{BL}$$

$$LD_{ct}^{BL}=\left(\frac{1}{\kappa_{BLct}^{VA}}\right)^{1-\sigma_{BLc}^{VA}}\left[(1-\alpha_{Kt}^{BLc})\frac{P_{BLct}^{VA}}{PL_{BLct}}\right]^{\sigma_{jt}^{VA}}VA_{ct}^{BL}$$

For the energy tier, the equations for coal and noncoal (NC) inputs in sector *c* are:

(A.26)
$$PE_{c,t}^{BL}=\frac{1}{\kappa_{BLc,t}^{Ecoal}}\left[\alpha_{Ect}^{BLcoal\,\sigma_{BLc}^{Ecoal}}PS_{coal,t}^{(1-\sigma_{BLc}^{Ecoal})}+(1-\alpha_{Ect}^{BLcoal})^{\sigma_{BLc}^{Ecoal}}P_{BLc,t}^{NC(1-\sigma_{BLc}^{Ecoal})}\right]^{\frac{1}{1-\sigma_{BLc}^{Ecoal}}}$$

$$PE_{c,t}^{BL}E_{c,t}^{BL}=PS_{coal,t}A_{coal,c,t}^{BL}+P_{BLc,t}^{NC}Q_{BLc,t}^{NC}\qquad \text{c=\{coal,coal\_ccs\}}$$

$$A_{coal,c,t}^{BL}=\left(\frac{1}{\kappa_{BLct}^{Ecoal}}\right)^{1-\sigma_{BLc}^{Ecoal}}\left[\alpha_{Ect}^{BLcoal}\,\frac{PE_{ct}^{BL}}{PS_{coal,t}}\right]^{\sigma_{BLc}^{Ecoal}}E_{ct}^{BL}$$

$$Q_{BL,c,t}^{NC}=\left(\frac{1}{\kappa_{BLct}^{Ecoal}}\right)^{1-\sigma_{BLc}^{Ecoal}}\left[(1-\alpha_{Ect}^{BLcoal})\frac{PE_{ct}^{BL}}{P_{BLc,t}^{NC}}\right]^{\sigma_{jt}^{VA}}E_{ct}^{BL}$$

(A.27)
$$P_{BLc,t}^{NC}=\frac{1}{\kappa_{BLc,t}^{NC}}\left[\sum_{k\in NC}\alpha_{k,BLc,t}^{NC\,\sigma_{BLc,t}^{NC}}PS_{kt}^{\left(1-\sigma_{BLc,t}^{NC}\right)}\right]^{\frac{1}{1-\sigma_{BLc,t}^{NC}}}$$

NC={oil, gasmine, refine, elect, gas}

$$P_{BLc,t}^{NC}Q_{BLc,t}^{NC}=\sum_{k\in NC}PS_{kt}A_{k,c,t}^{BL}$$

$$A_{kc,t}^{BL}=\left(\frac{1}{\kappa_{BLct}^{NC}}\right)^{1-\sigma_{BLc}^{NC}}\left[\alpha_{k,BLct}^{NC}\,\frac{P_{BLct}^{NC}}{PS_{k,t}}\right]^{\sigma_{BLc}^{NC}}Q_{BL,ct}^{NC}$$

The elasticities of substitution are summarized in Table A2. The top tier is Leontief between Materials and the VE bundle ($\sigma_{BL,c}^{M}=0$). The substitution between energy and value added ($\sigma_{BL,c}^{VE}$) is set at 0.5, the value used in the GTAP model.[17] Labor input is a very small share in the electricity sector and we set $\sigma_{BL,c}^{VA}=1$ following EPPA and Qi et al. (2014). This model explicitly recognizes the small amount of energy used besides the main fuel source unlike the other models mentioned so far; in the case of coal, the non-coal inputs include refined petroleum, electricity and gas. The substitution between the main fuel and the small non-coal energy bundle is set at 0.25, this is similar in spirit to the value of energy-capital substitution used in Phoenix for electricity generation. The substitution among the components of non-coal energy is set at 0.5, the general elasticity for energy inputs in GTAP and EPPA.

The input structure for gas-fired power plants is similar to that for coal, except that in the bottom tier for energy, gas inputs (GS) are aggregated with non-gas (NG; electricity and refined petroleum). The value equations for the gas and gas_ccs nodes are:

$$\text{(A.28)}\quad P_{g,t}^{EGEN}Q_{g,t}^{EGEN}=PM_{g,t}^{BL}M_{g,t}^{BL}+P_{BLg,t}^{VE}VE_{g,t}^{BL} \qquad g=\text{gas, gas\_ccs}$$

$$PM_{g,t}^{BL}M_{g,t}^{BL}=\sum_{k\in NE}PS_{kt}A_{k,g,t}^{BL}$$

$$P_{BLgas,t}^{VE}VE_{BLgas,t}=P_{BLgas,t}^{VA}VA_{gas,t}^{BL}+PE_{BLgas,t}E_{BLgas,t}$$

$$P_{BLgas,t}^{VA}VA_{BLgas,t}=P_{BLgas,t}^{KD}KD_{BLgas,t}+PL_{BLgas,t}LD_{BLgas,t}$$

$$PE_{BLg,t}E_{g,t}^{BL}=P_{BLg,t}^{GS}Q_{BLg,t}^{GS}+P_{BLg,t}^{NG}Q_{BLg,t}^{NG}$$

$$P_{BLgas,t}^{GS}Q_{BLgas,t}^{GS}=PS_{natgas,t}A_{natgas,BLgas,t}^{BL}+PS_{gasprod,t}A_{gasprod,BLgas,t}^{BL}$$

$$P_{BLg,t}^{NG}Q_{BLg,t}^{NG}=\sum_{k\in NG}PS_{kt}A_{k,BLg,t}^{BL} \qquad \text{set NG=\{coal, oil, refine, elect\}}$$

The price functions of the energy aggregate, the gas aggregate and the non-gas aggregate are:

$$\text{(A29a)}\quad PE_{g,t}^{BL}=\frac{1}{\kappa_{BLg,t}^{Egas}}\left[\alpha_{Egt}^{BLgas\,\sigma_{BLg}^{Egas}}P_{BLg,t}^{GS(1-\sigma_{BLg}^{Egas})}+(1-\alpha_{Egt}^{BLgas})^{\sigma_{BLg}^{Egas}}P_{BLg,t}^{NG(1-\sigma_{BLg}^{Egas})}\right]^{\frac{1}{1-\sigma_{BLg}^{Egas}}}$$

$$Q_{BL,g,t}^{GS}=\left(\frac{1}{\kappa_{BLgt}^{Egas}}\right)^{1-\sigma_{BLg}^{Egas}}\left[\alpha_{Egt}^{BLgas}\frac{PE_{gt}^{BL}}{P_{BLgt}^{GS}}\right]^{\sigma_{BLg}^{Egas}}E_{gt}^{BL} \qquad g=\text{gas,gas\_ccs}$$

$$Q_{BL,g,t}^{NG}=\left(\frac{1}{\kappa_{BLgt}^{Egas}}\right)^{1-\sigma_{BLg}^{E}}\left[(1-\alpha_{Egt}^{BLgas})\frac{PE_{gt}^{BL}}{P_{BLgt}^{NG}}\right]^{\sigma_{BLg}^{E}}E_{gt}^{BL}$$

$$\text{(A29b)}\quad P_{BLg,t}^{GS}=\frac{1}{\kappa_{BLg,t}^{GS}}\left[\alpha_{natgas,g,t}^{GSgas\,\sigma_{BLg}^{GS}}PS_{natgas,t}^{(1-\sigma_{BLg}^{GS})}+(1-\alpha_{natgas,g,t}^{GSgas})^{\sigma_{BLg}^{GS}}PS_{gasprod,t}^{(1-\sigma_{BLg}^{GS})}\right]^{\frac{1}{1-\sigma_{BLg}^{GS}}}$$

[17] The EPPA (Paltsev et al, Table 3) model uses an elasticity of 0.4-0.5; Qi et al. (2014) uses 0.1 and Phoenix (Sue Wing, Fig 2) uses 0.25.

$$A^{BL}_{natgas,g,t} = \left(\frac{1}{\kappa^{GS}_{BLgt}}\right)^{1-\sigma^{GS}_{BLg}} \left[\alpha^{GSgas}_{natgas,gt} \frac{P^{GS}_{BL,gt}}{PS_{natgas,t}}\right]^{\sigma^{Ecoal}_{BLc}} Q^{GS}_{BL,gt}$$

$$A^{BL}_{gasprod,g,t} = \left(\frac{1}{\kappa^{GS}_{BLgt}}\right)^{1-\sigma^{GS}_{BLg}} \left[(1-\alpha^{GSgas}_{natgas,gt}) \frac{P^{GS}_{BL,gt}}{PS_{gasprod,t}}\right]^{\sigma^{Ecoal}_{BLc}} Q^{GS}_{BL,gt}$$

(A29c) $$P^{NG}_{BLg,t} = \frac{1}{\kappa^{NG}_{BLg,t}} \left[\sum_{k \in NG} \alpha^{NG\sigma^{NG}_{BLg,t}}_{k,BLg,t} PS_{kt}^{\left(1-\sigma^{NG}_{BLg,t}\right)}\right]^{\frac{1}{1-\sigma^{NG}_{BLg,t}}}$$

$$A^{BL}_{k,g,t} = \left(\frac{1}{\kappa^{NG}_{BL,gt}}\right)^{1-\sigma^{NG}_{BLg}} \left[\alpha^{NG}_{k,BLg,t} \frac{P^{NG}_{BLct}}{PS_{kt}}\right]^{\sigma^{NG}_{BLg}} Q^{NG}_{BL,gt}$$

The values of the substitution elasticities follow that of coal and are given in Table A2.

We also project fossil fuel technologies that will be cost competitive in the future with a high carbon price: coal integrated gasification with carbon capture (IGCC) and natural gas with carbon capture (NGCC). The IGCC tier structure is given in Figure A2; the NGCC structure is identical. It is the same as the coal tier structure except that the energy node is replaced by a "fuel and sequestration" node. This structure follows Sue Wing et al. (2011, p33) where the fuel and sequestration technology in combined in a Leontief function, and the sequestration input is a fixed factor resource with an upward sloping supply curve.

The equations for $P^{BL}_{c=coalccs,t}$ are the same as (A.22), and (A.23) for $PM^{BL}_{c=coalccs,t}$, (A.25) for $P^{VA}_{BL,c=coalccs}$, (A.26) for $PE^{BL}_{c=coalccs}$, and (A.27) for $P^{NC}_{BL,c=coalccs}$. The price for the fuel-sequestration sub-aggregate is given, in general, by:

(A26b) $$P^{ESEQ}_{coalccs,t} = \frac{1}{\kappa^{ESEQ}_{coalccs,t}} \left[\alpha^{coalccs\ \sigma^{eseq}_{coalccs}}_{Et} PE^{(1-\sigma^{eseq}_{coalccs})}_{coalccs,t} + (1-\alpha^{coalccs}_{Et})^{\sigma^{eseq}_{coalccs}} P^{SEQ(1-\sigma^{eseq}_{coalccs})}_{coalccs,t}\right]^{\frac{1}{1-\sigma^{eseq}_{coalccs}}}$$

$$P^{ESEQ}_{coalccs,t} Q^{ESEQ}_{coalccs,t} = PE_{coalccs,t} E_{coalccs,t} + P^{SEQ}_{coalccs,t} Q^{SEQ}_{coalccs,t}$$

In the case of a Leontief function with $\sigma^{eseq}_{coalccs} = 0$, the equation is simply:

(A26c) $$P^{ESEQ}_{coalccs,t} = \left[\alpha^{E,seq}_{coalccs} PE_{coalccs,t} + \alpha^{seq}_{coalccs} P^{SEQ}_{coalccs,t}\right]$$

$$E_{coalccs,t} = \alpha^{E,seq}_{coalccs} Q^{ESEQ}_{coalccs,t}; \qquad Q^{SEQ}_{coalccs,t} = \alpha^{seq}_{coalccs} Q^{ESEQ}_{coalccs,t}$$

where we may normalize the units of the fuel-sequestration bundle to be the same as the fuel units, $\alpha_{coalccs}^{E,seq}=1$ and the sequestration coefficient $\alpha_{coalccs}^{seq}$ reflects to addition cost for this technology, per unit fuel.

The price of VE in the ccs sectors is then an aggregate of the $P_{coalccs,t}^{VA}$ and $P_{ccs,t}^{ESEQ}$:

(A26d) $$P_{BL,c,t}^{VE}=\frac{1}{\kappa_{BLc,t}^{VE}}\left[\alpha_{EESt}^{BLc\,\sigma_{BLc}^{VE}}P_{c,t}^{ESEQ(1\text{-}\sigma_{BLc}^{VE})}+(1-\alpha_{EESt}^{BLc})^{\sigma_{BLc}^{VE}}P_{BLc,t}^{VA(1-\sigma_{BLc}^{VE})}\right]^{\frac{1}{1-\sigma_{BLc}^{VE}}}$$

c=coal_ccs, gas_ccs

$$Q_{c,t}^{ESEQ}=\left(\frac{1}{\kappa_{BLc,t}^{VE}}\right)^{1-\sigma_{BLc}^{VE}}\left[\alpha_{EES,t}^{BLc}\frac{P_{BL,c,t}^{VE}}{P_{c,t}^{ESEQ}}\right]^{\sigma_{BLc}^{VE}}VE_{c,t}^{BL}\qquad \text{c=coal\_ccs, gas\_ccs}$$

The sequestration resource supply is given by:

(A.26e) $$R_{coalccs,t}^{SEQ}=R_{coalccs,\mathrm{t}}^{SEQ0}\left(\frac{P_{coalccs,t}^{SEQ}}{P_{coalccs,0}^{SEQ}}\right)^{\sigma_{coalseq}^{R}}$$

A parallel set of equations hold for NGCC with the price of fuel-sequestration in NGCC given by:

(A.28c) $$P_{gasccs,t}^{ESEQ}=\left[\alpha_{gasccs}^{E,seq}PE_{gasccs,t}+\alpha_{gasccs}^{seq}P_{gasccs,t}^{SEQ}\right]$$

$$E_{gasccs,t}=\alpha_{gasccs}^{E,seq}Q_{gasccs,t}^{ESEQ};\qquad Q_{gasccs,t}^{ESEQ}=\alpha_{gasccs}^{seq}Q_{gasccs,t}^{ESEQ}$$

(A.28d) $$R_{gasccs,t}^{SEQ}=R_{gasccs,t}^{SEQ0}\left(\frac{P_{gasccs,t}^{SEQ}}{P_{gasccs,0}^{SEQ}}\right)^{\sigma_{gasseq}^{R}}$$

The modeling of nuclear power supply is always treated specially in the models cited given its unusual nature. While there is no obvious constraint like the availability of rivers for hydro power, it is recognized that actual construction of nuclear plants has been difficult with substantial opposition by those worried about safety. Vennemo et al. (2014) uses an upward sloping supply function due to "the political suitability of different locations." Sue Wing et al. (2014) also use a "fixed factor" in their specification of nuclear power, but justify it by saying that a "supply curve is used to parameterize the mining and milling of resources to produce the fuel rods." EPPA-4 also has a fixed factor in nuclear generation but interprets it as a stock of knowledge that builds over time with cumulative output.

We follow the logic of Vennemo at al., and the Phoenix model, and require a non-reproducible resource input for nuclear power. In the second tier (see Figure A2), the VR bundle is an aggregate of resource (R^{NUCL}) and value-added-energy (VE) with an elasticity of σ^{VR} =0.4, following the EPPA-4 value (Phoenix uses a top elasticity of 0.5). We follow Vennemo et al. in using a nuclear resource supply elasticity of 2.5.

The specification of the hydro power production function is another complicated matter. Rivers suitable for hydro power is an obvious input, and one might think of the stock of such water resources and the cost of using the marginal river. If the next unused water source requires a more costly structure (or implementation costs including relocation of people) than existing dams, then one may represent this as a production function with a lower TFP factor, or as a paying more for a fixed quantity of effective water resource R. For simplicity we have chosen the latter approach and set up the hydro function like that of nuclear, with a rising supply curve for the water resource input, R^{HYDR}. In the same spirit, our wind and solar output functions follow those of nuclear and hydro with specific Resource inputs. This is illustrated in Figure A2(b). The parameterization of the resource input shares follows that given in EPPA 4 (Paltsev et al. 2005 Table 11); the resource share for wind and solar is set at 0.05 and we assume the resource share for hydro is also 0.05 of total gross output.

The cost functions for the renewables – nuclear, hydro, wind, solar and "other" – are the same The following equations are for the sub-aggregates – output price $P_{b,t}^{EGEN}$, intermediate input price $PM_{b,t}^{BL}$, value-added-resource price $P_{BLb,t}^{VR}$, value-added-energy price $P_{BLb,t}^{VE}$, the energy price $PE_{b,t}^{BL}$:

$$P_{b,t}^{EGEN} = \frac{\kappa_{bt}^{B}}{g_{bt}^{B}} \left[\alpha_{M,t}^{Bb\,\sigma_{BL,b}^{M}} PM_{b,t}^{B(1-\sigma_{B,b}^{M})} + \left(1-\alpha_{M,t}^{Bb}\right)^{\sigma_{B,b}^{M}} P_{Bb,t}^{VR(1-\sigma_{B,b}^{M})} \right]^{\frac{1}{1-\sigma_{B,b}^{M}}} \tag{A.30}$$

$$P_{b,t}^{EGEN} Q_{b,t}^{EGEN} = PM_{b,t}^{B} M_{b,t}^{B} + P_{Bb,t}^{VR} VR_{b,t}^{B} \qquad b=\{\text{nucl, hydro,other,wind,solar}\}$$

$$M_{\mathrm{b},t}^{B} = \left(\frac{\kappa_{bt}^{B}}{g_{bt}^{B}}\right)^{1-\sigma_{Bb}^{M}} \left[\alpha_{Mt}^{Bb} \frac{P_{bt}^{EGEN}}{PM_{bt}^{B}}\right]^{\sigma_{Bb}^{M}} Q_{bt}^{EGEN}$$

$$VR_{bt}^{B} = \left(\frac{\kappa_{bt}^{B}}{g_{bt}^{B}}\right)^{1-\sigma_{Bb}^{M}} \left[(1-\alpha_{Mt}^{Bb}) \frac{P_{bt}^{EGEN}}{P_{B,bt}^{VR}}\right]^{\sigma_{Bb}^{M}} Q_{bt}^{EGEN}$$

$$\ln PM_{b,t}^{B} = \sum_{k\in NE} \alpha_{kMt}^{Bb} \ln PS_{kt} \tag{A.31}$$

$$PM_{b,t}^{B} M_{b,t}^{B} = \sum_{k\in NE} PS_{kt} A_{k,b,t}^{B}\,; \qquad A_{k,b,t}^{B} = \alpha_{kMt}^{Bb} PM_{b,t}^{B} M_{b,t}^{B} / PS_{kt}$$

$$P^{VR}_{Bb,t} = \frac{1}{\kappa^{VR}_{Bb,t}} \left[\alpha^{Bb\,\sigma^{VR}_{Bb}}_{Rt} PR^{(1-\sigma^{VR}_{Bb})}_{Bb,t} + (1-\alpha^{Bb}_{Rt})^{\sigma^{VR}_{Bb}} P^{VE(1-\sigma^{VR}_{Bb})}_{Bb,t} \right]^{\frac{1}{1-\sigma^{VR}_{Bb}}}$$

(A.32)

$$P^{VR}_{Bb,t} VR^{B}_{b,t} = P^{VE}_{Bb,t} VE^{B}_{b,t} + PR_{Bb,t} R^{B}_{b,t}$$

$$R^{B}_{bt} = \left(\frac{1}{\kappa^{B}_{bt}} \right)^{1-\sigma^{VR}_{Bb}} \left[\alpha^{Bb}_{Rt} \frac{P^{VR}_{bt}}{PR_{B,bt}} \right]^{\sigma^{VR}_{Bb}} VR^{B}_{bt}$$

$$VE^{B}_{bt} = \left(\frac{1}{\kappa^{B}_{bt}} \right)^{1-\sigma^{VR}_{Bb}} \left[(1-\alpha^{Bb}_{Rt}) \frac{P^{VR}_{bt}}{P^{VE}_{B,bt}} \right]^{\sigma^{VR}_{Bb}} VR^{B}_{bt}$$

$$P^{VE}_{Bb,t} = \frac{1}{\kappa^{VE}_{Bb,t}} \left[\alpha^{Bb\,\sigma^{VE}_{Bb}}_{Et} PE^{(1-\sigma^{VE}_{Bb})}_{Bb,t} + (1-\alpha^{Bb}_{Et})^{\sigma^{VE}_{Bb}} P^{VA(1-\sigma^{VE}_{Bb})}_{Bb,t} \right]^{\frac{1}{1-\sigma^{VE}_{Bb}}}$$

(A.33)

$$P^{VE}_{Bb,t} VE_{Bb,t} = P^{VA}_{Bb,t} VA_{Bb,t} + PE_{Bb,t} E_{Bb,t}$$

$$E^{B}_{bt} = \left(\frac{1}{\kappa^{VE}_{bt}} \right)^{1-\sigma^{VE}_{Bb}} \left[\alpha^{Bb}_{Et} \frac{P^{VE}_{bt}}{PE_{B,bt}} \right]^{\sigma^{VE}_{Bb}} VE^{B}_{bt}$$

$$VA^{B}_{bt} = \left(\frac{1}{\kappa^{VE}_{bt}} \right)^{1-\sigma^{VE}_{Bb}} \left[(1-\alpha^{Bb}_{Et}) \frac{P^{VE}_{bt}}{P^{VA}_{B,bt}} \right]^{\sigma^{VE}_{Bb}} VE^{B}_{bt}$$

$$P^{VA}_{Bb,t} = \frac{1}{\kappa^{VA}_{Bb,t}} \left[\alpha^{Bb\,\sigma^{VA}_{Bb}}_{Kt} P^{KD(1-\sigma^{VA}_{Bb})}_{Bb,t} + (1-\alpha^{Bb}_{Kt})^{\sigma^{VA}_{Bb}} PL^{(1-\sigma^{VA}_{Bb})}_{Bb,t} \right]^{\frac{1}{1-\sigma^{VA}_{Bb}}}$$

(A.34)

$$P^{VA}_{Bb,t} VA_{Bb,t} = P^{KD}_{Bb,t} KD_{Bb,t} + PL_{Bb,t} LD_{Bb,t}$$

$$KD_{Bbt} = \left(\frac{1}{\kappa^{VA}_{bt}} \right)^{1-\sigma^{VA}_{Bb}} \left[\alpha^{Bb}_{Kt} \frac{P^{VA}_{bt}}{P^{KD}_{B,bt}} \right]^{\sigma^{VA}_{Bb}} VA^{B}_{bt}$$

$$LD_{Bbt} = \left(\frac{1}{\kappa^{VA}_{bt}} \right)^{1-\sigma^{VA}_{Bb}} \left[\alpha^{Bb}_{Lt} \frac{P^{VA}_{bt}}{PL_{B,bt}} \right]^{\sigma^{VA}_{Bb}} VA^{B}_{bt}$$

(A.35) $$PE_{Bb,t} = \frac{1}{\kappa^{E}_{Bbt}} \left[\sum_{k \in IE} \alpha^{EB\sigma^{E}_{Bb,t}}_{kb,t} PS^{\left(1-\sigma^{E}_{Bb,t}\right)}_{kt} \right]^{\frac{1}{1-\sigma^{E}_{Bb,t}}}$$ IE={coal,oil,natgas, refine, elect, gas}

$$PE_{Bb,t} E_{Bb,t} = \sum_{k \in IE} PS_{kt} A^{B}_{k,b,t};$$

$$A^{B}_{k,b,t} = \left(\frac{1}{\kappa^{E}_{Bbt}} \right)^{1-\sigma^{E}_{Bb}} \left[\alpha^{EB}_{kbt} \frac{PE_{bt}}{PS_{kt}} \right]^{\sigma^{E}_{Bb}} E^{B}_{bt}$$

In Vennemo et al. (2014) the wind resource grows in a logistic manner, while in Phoenix the supply curve is a constant elasticity one. EPPA-4 introduces a "Fixed Factor" for wind and solar and interprets it as knowledge that grows with cumulated output, and sets an elasticity between the Fixed Factor and value-added (σ_{BLb}^{VR}) at 0.6. Paltsev et al. (2005) states that the "Choice of the substitution elasticity creates an implicit supply elasticity of wind in terms of the share of electricity supplied by the technology."

We interpret of the resource variable for hydro, wind and solar as a limited supply of sites suitable for such technologies, and set the Nuclear, Hydro, Wind and SolarPV resources to grow in the base case at the rates projected in IEA (2014). In any period *t*, in the policy case, the supply curve for Wind or SolarPV resources is given by:

(A.36) $R_t^r = \bar{R}_t^r PR_{rt}^{\varepsilon_r^R}$ r=NUCL, HYDR, WIND, SOLR

where $\bar{R}_t^r$ is the projected base case resource availability. This means that opening an additional river, or wind farm, or solar farm, will require paying a price for the resource that is higher than the base case price. We follow Vennemo et al. (2014) in using an elasticity of 2.5, which means that this price is only slightly higher than base case resource price. It may be reasonable to not assume an identical function for all possible values of the base case resources availability, that is, when there is a high utilization of these water or wind sites, the marginal cost might increase substantially. That is, imposing a lower elasticity in the future years when there is a high penetration of such renewable sources.

The final element of the electricity sector is transmission and distribution. There is little data on this; even the 500-sector IO table for the U.S. has just one sector for total electric utilities. In the data appendix we describe how the data for Electric Utilities is separated into two sets for Generation and Transmission. The resulting input vector for Transmission includes almost all 33 commodities identified in the model. The tier structure for it is given in Figure A2(b) and is similar to the general structure for all other regular sectors given in Figure A1. The equations for the top tier of the Transmission sector, in terms of the producer price, are:

(A37)
$$P_t^{TD} = \frac{\kappa_t^{TD}}{g_t^{TD}} \left[\alpha_{M,t}^{TD\,\sigma_{TD}^M} PM_t^{TD(1-\sigma_{TD}^M)} + \left(1-\alpha_{M,t}^{TD}\right)^{\sigma_{TD}^M} P_{TD,t}^{VE(1-\sigma_{TD}^M)} \right]^{\frac{1}{1-\sigma_{TD}^M}}$$

$$P_t^{TD} Q_t^{TD} = P_{TD,t}^{VE} VE_t^{TD} + PM_t^{TD} M_t^{TD}$$

$$VE_t^{TD} = \left(\frac{\kappa_t^{TD}}{g_t^{TD}}\right)^{1-\sigma_{TD}^M} \left[\left(1-\alpha_{Mt}^{TD}\right)\frac{P_t^{TD}}{P_{TD,t}^{VE}}\right]^{\sigma_{TD}^M} Q_t^{TD}$$

$$M_t^{TD} = \left(\frac{\kappa_t^{TD}}{g_t^{TD}} \right)^{1-\sigma_{TD}^M} \left[\alpha_{Mt}^{TD} \frac{P_t^{TD}}{PM_t^{BL}} \right]^{\sigma_{TD}^M} Q_t^{TD}$$

$$P_t^{tt,TD} = (1+tt_{TD}^{EL})P_t^{TD}$$

The equations for the lower tiers are:

(A38) $\ln PM_{TDt} = \sum_{k \in NE} \alpha_{kMt}^{TD} \ln PS_{kt}$

$$P_{TD,t}^{VE} = \frac{1}{\kappa_{TD,t}^{VE}} \left[(1-\alpha_{VAt}^{TD})^{\sigma_{TD}^{VE}} PE_{TD,t}^{(1-\sigma_{TD}^{VE})} + \alpha_{VAt}^{TD\,\sigma_{TD}^{VE}} P_{TD,t}^{VA(1-\sigma_{TD}^{VE})} \right]^{\frac{1}{1-\sigma_{TD}^{VE}}}$$

$$P_{TD,t}^{VA} = \frac{1}{\kappa_{TD,t}^{VA}} \left[\alpha_{Kt}^{TD\sigma_{TD}^{VA}} P_{TD,t}^{KD(1-\sigma_{TD}^{VA})} + (1-\alpha_{Kt}^{TD})^{\sigma_{TD}^{VA}} PL_{TD,t}^{(1-\sigma_{TD}^{VA})} \right]^{\frac{1}{1-\sigma_{TD}^{VA}}}$$

$$PE_{TD,t} = \frac{1}{\kappa_{TDt}^{E}} \left[\sum_{k \in IE} \alpha_{k,TD,t}^{E\sigma_{TD,t}^{E}} PS_{kt}^{\left(1-\sigma_{TDb}^{E}\right)} \right]^{\frac{1}{1-\sigma_{TD}^{E}}} \qquad \text{IE=\{coal,oil,natgas, refine, elect, gas\}}$$

$$P_{TD,t}^{VE} VE_{TD,t} = P_{TD,t}^{VA} VA_{TD,t} + PE_{TD,t} E_{TD,t}$$

$$PM_{TD,t} M_{TD,t} = \sum_{k \in NE} PS_{kt} A_{k,TD,t}$$

$$PE_{TD,t} E_{TD,t} = \sum_{k \in IE} PS_{kt} A_{k,TD,t}$$

$$P_{TD,t}^{VA} VA_{TD,t} = P_{TD,t}^{KD} KD_{TD,t} + PL_{TD,t} LD_{TD,t}$$

The elasticity of substitution between materials and VE (σ_{TD}^{QI}) is set at 0.7, and $\sigma_{TD}^{VA} = 1.0$ following Sue Wing (2011, p 30).

Note on aggregation and units of measurement

Equation (A17) is the cost dual of the quantity function that expresses the index of total generation output (Q_t^{EG}) as a CES function of baseload output (Q_{Et}^{BL}) and intermittent renewables (Q_{Et}^{RE}). Baseload output is, in turn, a CES aggregate of the output coal, gas, nuclear, wind and others, { $Q_{l,t}^{EGEN}$ }, that is, Q_{Et}^{BL} is not a simple linear sum of the $Q_{l,t}^{EGEN}$'s. We must thus be careful and distinguish between the output of kWh of each generation source *l*, and the aggregate indices. $Q_{l,t}^{EGEN}$ is the output measured in billions of Y2010, and the kWh is given by a conversion coefficient:

(A39) $$Q_{l,t}^{kWh} = \psi_l^{EL} Q_{l,t}^{EGEN}$$

The total output in kWh is the simple sum: $Q_{TOT,t}^{kWh} = \sum_l Q_{l,t}^{kWh}$ which grows at a (slightly) different rate from the output index Q_t^{EG}.

One may express the output index as a product of a quality index and the total kWh:

(A40) $$Q_t^{EG} = \psi_t^{EL} Q_{TOT,t}^{kWh}$$

The quality, or composition, index ψ_l^{EL} represents the impact of changes in shares of components that have different relative prices. For example, the price per kWh of coal is much lower than that of solar and if the share of solar kWh rises, then the quality index rises. This is analogous to the relation between effective labor input, quality of labor and hours worked; the index of labor input is the product of labor quality and total hours, and a rising labor quality indicates that hours from more highly paid workers is rising as a share of total hours worked by all workers. One may think that the term "quality" of electricity may be misleading since kilowatt hours as perfectly homogenous and substitutable, it however, represents an economically meaningful distinction between kWh and value of kWh. The electrons that are identical from the user point of view are distinguished by the method of production – clean versus polluting, steady versus intermittent, near versus far. The ψ_l^{EL} index represents changes in the costs of production as the composition of methods change; Q_t^{EG} is an index of the (marketed) economic resources that went into producing $Q_{TOT,t}^{kWh}$ kWh of electricity. The non-marketed resources such as clean air, or clean water, are accounted for separately.

A.1.3. Households

Private consumption in this model is driven by an aggregate demand function that is derived by aggregating over different household types. Each household derives utility from the consumption of commodities, is assumed to supply labor inelastically, and owns a share of the capital stock. It also receives income transfers from the government and foreigners, and receives interest on its holdings of public debt. Aggregate private income is the sum over all households, and this income, after taxes and the payment of various non-tax fees (*FEE*), is written as:

(A45) $Y^{p} = \sum_{k} y_{k}^{p}$

$$Y^{p} = YL + DIV + G\_I + G\_transfer + R\_transfer - FEE - T^{LUMP}$$

YL denotes aggregate labor income from supplying LS units of effective labor, less income taxes:

(A46) $YL = (1 - t^{L}) PL\, LS$.

The relationship between labor demand and supply is given in equation A63 below. Aggregate supply *LS* is a function of the working age population, average annual hours, and an index of labor quality:

(A47) $LS_{t} = POP_{t}^{w}\, hr_{t}\, q_{t}^{L}$.

DIV denotes dividends from the households' share of capital income and is explained below in A75. *G_I* and *G_transfer* represent interest and transfers from the government, and *R_transfer* is transfers from the rest-of-the-world. T^{LUMP} is the lump sum tax that is used in policy simulations.

Household income is allocated between consumption (VCC_{t}) and savings. In this model we use a simple Solow growth model formulation with an exogenous savings rate (s_{t}) to determine private savings (S_{t}^{p}):

(A48) $S_{t}^{p} = s_{t} Y_{t}^{p} = Y_{t}^{p} - VCC_{t}$.

Total consumption expenditures are allocated to the 33 commodities identified in the model. We do this with a demand function estimated over household consumption survey data. This consumption data is at purchaser's prices and follows the expenditure classification; these have to be linked later to the IO classifications and the factory-gate prices of the IO system. We arrange the demand system in a tier structure shown in Table 1. At the top tier total expenditures is allocated to Food, Consumer Goods, Housing and Services. In the sub-tiers these four bundles are allocated to 27 items.

Table 1. Tier structure of household consumption

		Name	Components in Consumer Expenditures
1	C	Consumption	Food, Consumer goods, Services, Housing $CC = CC(FD, CG, SV, HS)$
2	FD	Food	Food & tobacco, Dining out $C^{FD} = C^{FD}(\mathrm{C1, C2})$
3	CG	Consumer goods	Clothing, Residential goods, Recreational & misc. goods, Vehicles & parts $C^{CG} = C^{CG}(\mathrm{CL,RG,RM,C14})$
4	SV	Services	Communication, Education, Recreational svc, Health, Other services, Imputations, Transportation $C^{SV} = C^{SV}(\mathrm{C19,C22,C23,C24,C26,C27,TR})$
5	HS	Housing	Rental & housing services, Utilities-Energy $C^{HS} = C^{HS}(\mathrm{C5}, EN)$
6	CL	Clothing	Clothes-shoes, Clothing services $C^{CL} = C^{CL}(\mathrm{C3, C4})$
7	RG	Residential goods	Furniture, Appliances, Interior Decorations, HH daily-use articles $C^{RG} = C^{RG}(\mathrm{C10, C11,C12,C13})$
8	RM	Recreational & Misc. goods	Communications equip, Recreational articles, Books, Other goods $C^{RM} = C^{RM}(\mathrm{C18, C20,C21,C25})$
9	EN	Energy (dom)	Water, Electricity, Coal, Gas $C^{EN} = C^{EN}(\mathrm{C6,C7,C8,C9})$
10	TR	Transportation	Gasoline, Vehicle svcs, Transportation fees $C^{TR} = C^{TR}(\mathrm{C15,C16,C17})$

Household *k*'s indirect utility function over the four aggregates in the top tier, $V(p,M_k)$, is of a form that allows for exact aggregation:

$$\text{(A50)} \quad \ln V_k = \alpha_0 + \ln(\frac{p_k}{M_k})'\alpha_p + \frac{1}{2}\ln(\frac{p_k}{M_k})'B\ln(\frac{p_k}{M_k}) + \ln(\frac{p_k}{M_k})'B_{pA}A_k \quad ,$$

where M_k is the expenditures of household k, and $p = (p^k_{FD}, p^k_{CG}, p^k_{HS}, p^k_{SV})'$ is the price vector of the 4 bundles. Each household type has its own distinct utility function and A_k is a vector of demographic dummy variables to indicate the size of the household, the presence of children, the age of the head, and the region. The budget constraint for household k is:

$$\text{(A51)} \quad M_k = \sum_i p_i^k c_i^k = p_{FD}^k c_{FD}^k + p_{CG}^k c_{CG}^k + p_{HS}^k c_{HS}^k + p_{SV}^k c_{SV}^k$$

Let $w_i^k = p_i^k c_i^k / M_k$ denote the share of expenditure allocated to bundle i. Applying Roy's Identity we get the demand share vector:

$$\text{(A52)} \quad w^k = \frac{1}{D(p_k)}(\alpha_p + B \ln \frac{p_k}{M_k} + B_{pA} A_k) = \frac{1}{D(p_k)}(\alpha_p + B \ln p_k - Bi \ln M_k + B_{pA} A_k)$$

where $D(p_k) = -1 + i' B_{pp} \ln p_k$ and $w^k = (w_{FD}^k, w_{CG}^k, w_{HS}^k, w_{SV}^k)'$.

The aggregate demand is obtained by summing over all household types. Let n_k be the number of households of type k; the aggregate share vector is then:

$$\text{(A53)} \quad \begin{aligned} w_t &= \frac{\sum_k n_{kt} M_{kt} w_t^k}{\sum_k n_{kt} M_{kt}} = \frac{\sum_k n_{kt} M_{kt} w_t^k}{M_t} \\ &= \frac{1}{D(p_t)}[\alpha_p + B \ln p_t - Bi \frac{\sum n_{kt} M_{kt} \ln M_{kt}}{M_t} + B_{pA} \frac{\sum n_{kt} M_{kt} A_k}{M_t}]. \end{aligned}$$

The above equations (A52) and (A53) are estimated simultaneously, with (A52) estimated over one year of cross-sectional consumer expenditure data, and (A53) estimated using time series national prices and aggregate consumption expenditures.

To use the estimated equation (A53) in the model that include projections into the future we make some modifications. Firstly, the consumer survey data does not include some items that are in the National Accounts such as imputed rentals for owner-occupied housing and FISIM. We make some adjustments to the α_p's to scale the shares to match the consumption in the Input-Output table for our base year 2010. We project the distribution and demographic terms to account for the aging impact and thus re-write the share demand system as:

$$\text{(A54)} \quad w_t = \frac{1}{D(p_t)}[\alpha_p + B \ln p_t - Bi(\sum n_{kt} \frac{M_{k0}}{M_0} \ln \frac{M_{k0}}{M_0} + \ln M_{kt}) + B_{pA} \sum n_{kt} \frac{M_{k0}}{M_0} A_k]$$

$$w_t = \frac{1}{D(p_t)}[\alpha_p + B \ln p_t - Bi(\xi_t^{dd} + \ln M_{kt}) + B_{pA} \xi_t^L]$$

Next, the aggregate expenditures on the 4 bundles are allocated to the 27 commodities according to the tier structure in Table 1. This is done with a linear logarithmic function that allows the shares to change over time. For example, for the Transportation bundle, the value of expenditures (vc_{TR}), the price index (p_{TR}^{CE}) and implied quantity is:

$$(A55)\quad vc_{TR} = p_{TR}^{CE} c_{TR} = p_{15}^{CE} C_{15} + p_{16}^{CE} C_{16} + p_{16}^{CE} C_{17}$$

$$\ln p_{TR,t}^{CE} = \alpha_{18,t} \ln p_{18,t}^{CE} + \alpha_{19,t} \ln p_{19,t}^{CE} + \alpha_{20,t} \ln p_{20,t}^{CE}; \quad \alpha_{18,t} + \alpha_{19,t} + \alpha_{20,t} = 1$$

$$c_{TR,t} = vc_{TR,t} / p_{TR,t}^{CE}$$

The demand for gasoline, item 15, is then:

$$(A56)\quad C_{15,t} = \alpha_{15,t} vc_{TR} / p_{15}^{CE}$$

The consumption items listed in Table 1 are those used in the consumption survey and must be linked to the factory gate values in the Input-Output Accounts. For example, Food & tobacco in the Consumption accounts consist of commodities from Agriculture, Food Manufacturing, Trade (Commerce) and Transportation in the IO categories. The CE superscript denotes that these are prices for the consumption expenditure items. Table 2 gives the bridge that links these two accounts in the benchmark year 2010 for urban consumption. Column *i* of the bridge $\mathbf{H}^u$ gives the shares to allocate consumption item *i* to the 33 IO commodities. A similar table is constructed for rural consumption. Let be $VC_t^{u,CE}$ the vector of consumption values for the urban sector, then the vector of consumption in IO terms is given by:

$$(A57)\quad VC_t^{u,IO} = \mathbf{H}^u VC_t^{u,CE}$$

The prices of the consumption commodities are linked to the prices of the IO commodities via the same share matrix:

$$(A58)\quad p_t^{u,CE} = \mathbf{H}^{u\prime} P_t^{C,IO}; \qquad p_t^{r,CE} = \mathbf{H}^{r\prime} P_t^{C,IO}$$

The total value of consumption of commodity *i* is the sum of the urban and rural components:

$$(A59)\quad VC_{it}^{IO} = VC_{it}^{u,IO} + VC_{it}^{r,IO} = p_{it}^{C,IO} C_{it}$$

The value of national consumption in equation (A48) is the sum over all the commodities:

$$(A60)\quad \begin{aligned} VCC_t &= \sum\nolimits_i VC_{it}^{IO} \\ &= p_{FD,t} C_{FD,t} + p_{CG,t} C_{CG,t} + C_{HS,t} p_{HS,t} + p_{SV,t} C_{SV,t} \\ &= \sum\nolimits_i VC_{it}^{CE} \end{aligned}$$

Table 2. Bridge to link Consumption Expenditures (urban) to Input-Output accounts

		Food, Tobacco	Dining Out	Clothes		Applian-ces	Health-care	
		1	2	3	…	11	24	…
Agri	1	0.141	0.280	0.000		0.000	0.000	
Coal	2	0.000	0.000	0.000		0.000	0.000	
Crude	3	0.000	0.000	0.000		0.000	0.000	
natgas	4	0.000	0.000	0.000		0.000	0.000	
nonenergy	5	0.000	0.000	0.000		0.000	0.000	
Food	6	0.781	0.100	0.000		0.000	0.000	
textile	7	0.000	0.000	0.030		0.000	0.000	
apparel	8	0.000	0.000	0.776		0.000	0.000	
lumber	9	0.000	0.000	0.000		0.000	0.000	
paper	10	0.000	0.000	0.000		0.000	0.000	
Refine	11	0.000	0.000	0.000		0.000	0.000	
Chem	12	0.002	0.000	0.000		0.011	0.130	
Build	13	0.000	0.000	0.000		0.000	0.000	
pmetal	14	0.000	0.000	0.000		0.001	0.000	
metal	15	0.000	0.000	0.000		0.000	0.000	
machin	16	0.000	0.000	0.000		0.020	0.000	
tequip	17	0.000	0.000	0.000		0.030	0.000	
emachin	18	0.000	0.000	0.000		0.638	0.088	
electro	19	0.000	0.000	0.000		0.162	0.000	
Instru	20	0.000	0.000	0.000		0.000	0.000	
Other	21	0.000	0.000	0.006		0.010	0.074	
Elect	22	0.000	0.000	0.000		0.000	0.000	
gasprod	23	0.000	0.000	0.000		0.000	0.000	
constr	24	0.000	0.000	0.000		0.000	0.000	
transp	25	0.006	0.000	0.026		0.023	0.000	
commun	26	0.000	0.000	0.000		0.000	0.000	
commerc	27	0.069	0.000	0.156		0.106	0.083	
Hotel	28	0.000	0.620	0.000		0.000	0.000	
finance	29	0.000	0.000	0.000		0.000	0.079	
realest	30	0.000	0.000	0.000		0.000	0.000	
business	31	0.000	0.000	0.000		0.000	0.000	
service	32	0.000	0.000	0.006		0.000	0.546	
admin	33	0.000	0.000	0.000		0.000	0.000	
Sum of share		1.000	1.000	1.000		1.000	1.000	

A.1.4. Government and Taxes

In the model, the government has two major roles. First, it sets plan prices and output quotas and allocates investment funds. Second, it imposes taxes, purchases commodities, and redistributes resources. Public revenue comes from direct taxes on capital, labor, value-added taxes, indirect taxes on output, tariffs on imports, the externality tax, and other non-tax receipts:

$$\text{(A61)}\quad Rev = \sum_j t^k (P_j^{KD} KD_j - D_j) + t^L PL.LS + t^V \sum_j (P_j^{KD} KD_j + PL_j LD_j + PT_j TD_j)$$
$$+\sum_j t_j^t PI_j QI_j + R\_EXT + \sum_i t_i^r PM_i^* M_i + \sum_i t_i^c (QI_i - X_i + M_i) + FEE + T^{LUMP}$$

where D_j is the depreciation allowance and X_i and M_i are the exports and imports of good *i*.

Externality taxes, such as those on SO_2 or CO_2, may be on the value of output, or on the quantities. We allow for both, the total revenue from the externality tax on output is:

$$\text{(A62)}\quad R\_EXT_t = \sum_j t_{jt}^x PI_{jt} QI_{jt}$$

In one application of the model described in Ho and Nielsen (2007, Chapter 10), the externality tax rate is set proportional to the marginal air pollution damages (MD^O) from output *j*:

$$\text{(A63)}\quad t_{jt}^x = \lambda MD_{jt-1}^O$$

When we consider a tax on fossil fuels based on the carbon content, the externality tax per unit of fuel *j* is:

$$\text{(A64)}\quad t_j^x = tx^u c_j \quad ,$$

where c_j is the carbon content per unit of fuel of type *j*.

The nontax payments to the government are set as a fixed share of household income:

$$\text{(A65)}\quad FEE_t = \gamma^{NHH} Y_t^p$$

Total government expenditure is the sum of commodity purchases and other payments:

$$\text{(A66)}\quad Expend = VGG + G\_INV + \sum s_i^e PI_i X_i + G\_I + G\_IR + G\_transfer$$

Government purchases of specific commodities are allocated as shares of the total value of government expenditures, *VGG*. For good *i*:

(A67) $PS_i G_i = \alpha_i^G VGG$.

We construct a price index for government purchases as $\log PGG = \sum_i \alpha_i^G \log PS_i$. The real quantity of government purchases is then:

(A68) $GG = \dfrac{VGG}{PGG}$.

Transfers are set equal to a fixed rate of the population multiplied by the wage rate:

(A69) $G\_transfer = \gamma^{tr} PL_t POP_t$

The difference between revenue and expenditure is the deficit, ΔG, which is covered by increases in the public debt, both domestic (B) and foreign (B^{G*}):

(A70) $\Delta G_t = Expend_t - Rev_t$,

(A71) $B_t + B_t^{G*} = B_{t-1} + B_{t-1}^{G*} + \Delta G_t$.

The deficit and interest payments are set exogenously and equation A70 is satisfied by making the level of total nominal government expenditure on goods, VGG, endogenous in the base case. In simulating policy cases we would often set the real government expenditures in the policy case equal to those in the base case. In this counterfactual we would use some endogenous tax variable to meet equation A70.

A.1.5. Capital, Investment, and the Financial System

We model the structure of investment in a fairly simple manner. In the Chinese economy, some state-owned enterprises receive investment funds directly from the state budget and are allocated credit on favorable terms through the state-owned banking system. Non-state enterprises get a negligible share of state investment funds and must borrow at competitive interest rates. There is also a small but growing stock market that provides an alternative channel for private savings. We abstract from these features and define the capital stock in each sector *j* as the sum of two parts, which we call plan and market capital:

(A72) $K_{jt} = \overline{K}_{jt} + \widetilde{K}_{jt}$.

The plan portion evolves with plan investment and depreciation:

(A73) $\overline{K}_{jt} = (1-\delta)\overline{K}_{jt-1} + \psi_t^I \overline{I}_{jt}$, t = 1, 2, …, T .

The rate of depreciation is δ , and ψ_t^I is an aggregation that converts the investment units to capital stock units.[18] In this formulation, $\overline{K}_{j0}$ is the capital stock in sector *j* at the beginning of the simulation. This portion is assumed to be immobile across sectors. Over time, with depreciation and limited government investment, it will decline in importance. Each sector may also rent capital from the total stock of market capital, $\tilde{K}_t$:

(A74) $\tilde{K}_t = \sum_j \tilde{K}_{jt}$, where $\tilde{K}_{ji} > 0$.

The allocation of market capital to individual sectors, $\tilde{K}_{jt}$, is based on sectoral rates of return. As in equation A2, the rental price of market capital by sector is $\tilde{P}_j^{KD}$. The supply of $\tilde{K}_{jt}$, subject to equation A72, is written as a translog function of all of the market capital rental prices, $\tilde{K}_{jt} = K_j(\tilde{P}_1^{KD}, \dots, \tilde{P}_n^{KD})$:

(A74b) $$\frac{\tilde{K}_{jt}}{\tilde{K}_t} = \alpha_j^{KS} + \sum_i \beta_{ij}^{KS} \ln \tilde{P}_i^{KD}$$

To simplify the modeling of the capital supply in the electricity sector, we first allocate $\tilde{K}_{elect,t}$ according to (A74b) and then allocate that to the various generation subsectors, using a similar function of the rental rates in the various electricity subsectors:

$$\tilde{K}_{elect,t} = \tilde{K}_{transm,t} + \tilde{K}_{coal,t} + \dots \tilde{K}_{solar,t}; \qquad K_{elect,t} = K_{transm,t} + K_{coal,t} + \dots K_{solar,t}$$

$$\tilde{P}_{elect,t}^{KD} K_{elect,t} = \sum_e \tilde{P}_{e,t}^{KD} K_{e,t} \qquad \text{e=transm, coal, … solar}$$

In three sectors, agriculture, crude petroleum and gas mining, "land" is a factor of production. We have assumed that agricultural land and oil fields are supplied inelastically, abstracting from the complex property rights issues regarding land in China. After taxes, income derived from plan capital, market capital, and land is either kept as retained earnings by the enterprises, distributed as dividends, or paid to foreign owners:

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[18] Both K and I are aggregates of many asset types, ranging from computer equipment to structures. The composition of total investment and total capital stock are different and an aggregation coefficient is needed to reconcile the historical series.

(A75) $\sum_j profits_j + \sum_j \widetilde{P}_j^{KD} \widetilde{K}_j + \sum_j PT_j T_j = tax(k) + RE + DIV + r(B^*)$,

where $tax(k)$ is total tax on capital and value added (the first two terms on the right hand side of equation A2).[19]

As discussed below, total investment in the model is determined by savings. This total, *VII*, is then distributed to the individual investment goods sectors through fixed shares, α_{it}^I:

(A76) $PS_{it} I_{it} = \alpha_{it}^I VII_t$.

A portion of sectoral investment, $\bar{I}_t$, is allocated directly by the government, while the remainder, $\widetilde{I}_t$, is allocated through other channels.[20] The total, I_t, can be written as:

(A77) $I_t = \widetilde{I}_t + \bar{I}_t = I_{1t}^{\alpha_1^I} I_{2t}^{\alpha_1^I} ... I_{nt}^{\alpha_n^I}$.

As in equation A73 for the plan capital stock, the market capital stock, $\widetilde{K}_{jt}$, evolves with new market investment:

(A78) $\tilde{K}_{jt} = (1-\delta)\tilde{K}_{jt-1} + \psi_t^I \tilde{I}_{jt}$.

Non-reproducible assets

In addition to the capital stock, the households own the non-reproducible assets – land, renewable resources and sequestration resources. The supply of land (or mining resources) is simply assumed fixed for each type (agriculture, coal mining, oil mining):

(A79) $T_{jt} = T_{j0}$

The supply curves for nuclear and hydro resources are assumed to be upward sloping curves.

(A80) $RS_{b,t}^B = \left(\frac{PR_{b,t}^B}{PR_{b0}^B} \right)^{\sigma_b^R}$

[19] In China, a substantial part of the "dividends" are actually income due to agricultural land.

[20] It should be noted that the industries in the Chinese accounts include many sectors that would be considered public goods in other countries. Examples include local transit, education, and health.

A.1.6. The Foreign Sector

Trade flows are modeled using the method followed in most single-country models. Imports are considered to be imperfect substitutes for domestic commodities and exports face a downward sloping demand curve. We write the total domestic supply of commodity *i* as a CES function of the domestic (DC_i) and imported good (M_i):

$$\text{(A81)} \quad DS_i \;=\; A_0\left[\alpha^d DC_i^{\rho} \;+\; \alpha^m M_i^{\rho}\right]^{\frac{1}{\rho}} \quad ,$$

where *DC* is the quantity of domestically produced goods that are sold domestically. The elasticity is $\sigma = 1/(1-\rho)$. The cost dual corresponding to the above primal function is:

$$\text{(A82)} \quad PS_i \;=\; \frac{1}{A_0}\left[\alpha^{d\sigma} PD_i^{1-\sigma} \;+\; \alpha^{m\sigma} M_i^{1-\sigma}\right]^{\frac{1}{1-\sigma}}$$

and the value of total domestic supply is:

$$PS_i DS_i \;=\; PD_i DC_i + PM_i M_i$$

The purchaser's price for domestic goods, PD_i, is related to the commodity supply price PC_i and is discussed in the export section below. PS_i is the price of the basket of commodity *i* to domestic purchasers. The price of imports to buyers is the foreign price plus tariffs (less export subsidies), multiplied by a world relative price, *e*:

$$\text{(A83)} \quad PM_i = e(1+t_i^r)PM_i^* + t_i^{ru} \quad .$$

From (A82) we may derive the demand for imports as:

$$\text{(A.84)} \quad \frac{PM_i M_i}{PS_i DS_i} \;=\; \frac{\alpha^{m1/1-\rho} M_i^{\rho/\rho-1}}{\alpha^{d1/1-\rho} DC_i^{\rho/\rho-1} + \alpha^{m1/1-\rho} M_i^{\rho/\rho-1}} = \frac{\alpha^{m\sigma} PM_i^{1-\sigma}}{\alpha^{d\sigma} PD_i^{1-\sigma} + \alpha^{m\sigma} PM_i^{1-\sigma}}$$

Domestically produced commodities (QC) are allocated to the domestic market and exports according to a constant elasticity of transformation (CET) function:

$$\text{(A85)} \quad QC_{it} = \kappa_{it}^x \left[\alpha_{it}^x X_{it}^{\frac{\sigma_i^e - 1}{\sigma_i^e}} + \left(1 - \alpha_{it}^x\right) DC_{it}^{\frac{\sigma_i^e - 1}{\sigma_i^e}}\right]^{\frac{\sigma_i^e}{\sigma_i^e - 1}}$$

The ratio of exports to domestically sold goods depends on the domestic price (PD) relative to world prices adjusted for export subsidies (s_{it}^e):

(A85b) $X_{it} = DC_{it}\left[\frac{1-\alpha_{it}^{x}}{\alpha_{it}^{x}}\frac{PD_{it}}{PX_{it}}\right]^{\sigma_{t,r}^{e}}$; $PX_{it} = e_t(1+s_{it}^{e})PE_{it}^{*}$

The value identity is:

(A86) $PC_{it}QC_{it} = PD_{it}DC_{it} + PX_{it}X_{it}$

The weights and constant terms are set using base year values:

$$\alpha_{it}^{x} = \frac{PD_{i0}X_{i0}^{-1/\sigma_{t,r}^{e}}}{PD_{i0}X_{i0}^{-1/\sigma_{t,r}^{e}} + PX_{i0}DC_{i0}^{-1/\sigma_{t,r}^{e}}};\kappa_{i}^{x} = QC_{i0}\Bigg/\left[\alpha_{i0}^{e}X_{i0}^{\frac{\sigma_{t,r}^{e}-1}{\sigma_{t,r}^{e}}} + \left(1-\alpha_{i0}^{e}\right)DC_{i0}^{\frac{\sigma_{t,r}^{e}-1}{\sigma_{t,r}^{e}}}\right]^{\frac{\sigma_{t,r}^{e}}{\sigma_{t,r}^{e}-1}}$$

The share parameters α_{it}^{x} are projected exogenously to take into account the rising role of exports during 1980-2010 and a falling role in the future. The price *PC* is given in equation (A14) above, and is also an implicit dual function of (A85), PC=f(PX,PD).

The current account balance is equal to exports minus imports (valued at world prices before tariffs), less net factor payments, plus transfers:

(A87)
$$\begin{aligned} CA &= \sum_i \frac{PX_iX_i}{(1+s_i^e)} - \sum_i ePM_i^*M_i - r(B^*) - G\_IR + R\_transfer \\ &= VX - VM - r(B^*) - G\_IR + R\_transfer \end{aligned} ,$$

Like the government deficits, the current account balances are set exogenously and accumulate into stocks of net foreign debt, both private (B_t^*) and public (B_t^{G*}):

(A88) $B_t^* + B_t^{G*} = B_{t-1}^* + B_{t-1}^{G*} - CA_t$.

A.1.7. Markets

The economy is in equilibrium in period *t* when the market prices clear the markets for the 33 commodities and the three factors. The supply of domestically produced commodity *i* must satisfy the total of intermediate and final demands:

(A89) $DS_i = \sum_j A_{ij} + C_i + I_i + G_i \quad , \quad i = 1, 2, \ldots, 33.$

For the labor market, we assume that labor is perfectly mobile across sectors so there is one average market wage which balances supply and demand. As is standard in models of this type, we reconcile this wage with the observed spread of sectoral wages using wage distribution coefficients, ψ_{jt}^{L}. Each industry pays $PL_{jt} = \psi_{jt}^{L} PL_t / (1 - t_j^V)$ for a unit of labor. The labor market equilibrium is then given as:

(A90) $$\sum_j \psi_{jt}^{L} LD_{jt} = LS_t \quad .$$

For the non-plan portion of the capital market, adjustments in the market price of capital, $\tilde{P}_j^{KD}$, clears the market in sector *j*:

(A91) $$KD_{jt} = \psi_{jt}^{K} K_{jt} \quad ,$$

where ψ_{jt}^{K} converts the units of capital stock into the units used in the production function. The rental price PT_j adjusts to clear the market for "land":

(A92) $$TD_j = T_j \quad , \quad \text{where} \quad j = \text{“agriculture”, “crude petroleum”, "gas mining"}.$$

In this model without foresight, investment equals savings. There is no market where the supply of savings is equated to the demand for investment. The sum of savings by households, businesses (as retained earnings), and the government is equal to the total value of investment plus the budget deficit and net foreign investment:

(A93) $$S^p + RE + G\_INV = VII + \Delta G + CA \quad .$$

The budget deficit and current account balance are fixed exogenously in each period. The world relative price (*e*) adjusts to hold the current account balance at its exogenously determined level.

The model is a constant returns-to-scale model and is homogenous in prices, that is, doubling all prices leaves the economy unchanged. We are free to choose a price normalization.

A.1.8 Welfare Other accounting identities

The household welfare function (A50) is chosen to allow aggregation over different households. The aggregation issues are discussed in Jorgenson et al. (2013, Chapter 3); equation (A54) gives the aggregate demand function for the four consumption bundles. Jorgenson et al. expresses social welfare as a function that takes into account the different compositions of households (different size and number of children), using the concept of household equivalents. The welfare function depends on the average level of consumption as well as inequality of consumption (efficiency and equity). Here we compute only the average levels to give the efficiency measure which is given by:

(A94) $$\ln \overline{V} = \frac{\sum_k m_0(p, A_k) \ln V_k}{\sum_k m_0(p, A_k)}$$

V_k is the household utility in (A50), and $m_0(p, A_k)$ is the household equivalent to the reference household which is aged 18-34, male, elementary school, two members and in the East. The equivalence scale is explained in Jorgenson and Slesnick (1987) and is given by:

(A94b) $$\ln m_0(p, A_k) = \frac{1}{D(p)}[\ln p' B_{pA} A_k]$$

The money measure of welfare is given by a social expenditure function (Jorgenson and Slesnick 1987, eq. 5.15):

(A95) $$\ln M(p, W) = \frac{1}{D(p)}[\ln p' \alpha_p + \frac{1}{2}\ln p' B \ln p - W] + \ln \sum_k m_0(p, A_k)$$

The money measure of the change in welfare due to a policy (from W^0 to W^1) is a function of the policy case measured at base case prices (p^0):

(A96) $$\Delta M = M(p^0, W^1) - M(p^0, W^0)$$

Gross domestic product in nominal terms is the sum of consumption, investment, government spending, plus net exports:

(A97) $$VGDP = VCC + VII + VGG + VX - VM$$

To construct real, constant yuan, GDP we need to first define real consumption, investment, etc. These are expressed as the divisia aggregate of the 33 commodities that make up each component, for example, real personal consumption expenditures is:

(A98) $$CC^{div} = divisia(C_i; PS_i^C)$$

$$\mathrm{d}\Delta \ln \frac{CC_t^{div}}{CC_{t-1}^{div}} = \sum_i \tfrac{1}{2}(v_{it}^c + v_{i,t-1}^c)\Delta \ln \frac{C_{it}}{C_{i,t-1}}; \qquad v_{it}^c = \frac{PS_{it} C_{it}}{VCC_t}$$

Real GDP is then a divisia index of these components:

(A99) $rGDP = divisia(CC^{div}, II^{div}, GG^{div}, X^{div}; PCC, ...) - M^{div}$

A.1.9 Energy, emissions and environmental accounting

To account for atmospheric environmental damages we consider a range of criteria pollutants: particulate matter (PM_{25} and PM_{10}), sulphur dioxide, nitrogen oxides, VOCs, ammonia. We also account for greenhouse gas emissions, in particular carbon dioxide. The PM concentration is due to primary PM emissions as well as secondary particles such as sulfates and nitrates which are formed from sulfur dioxide and NOx respectively. The emissions inventory is described in *Clearer Skies*, Chapters 4-6. To illustrate the calculations we describe here a simplified account of energy flows and primary PM, SO_2 and NOx emissions.

We begin by describing the energy variables. Very often a simple indicator of total primary energy production and consumption is produced by summing the energy equivalents of the fossil fuels and primary electricity and heat. This may not be a very useful indicator given that a joule of energy from burning coal is very different in the ease of use from a joule from gasoline or a joule of electricity; a difference that is reflected in the prices per joule. Nevertheless, for comparison with well-known series we compute the standard coal equivalent (sce) of these primary sources of energy.

First, recall that we distinguish between industry output (*QI*) and commodity output (*QC*). QC_{ft} is the constant yuan quantity of commodity produced (billions of 2010 yuan). QP^f, the total quantity of coal, crude, and gas *produced* (whether combusted or not) in year *t* is given by the commodity output (*QC*) multiplied by the fuel conversion coefficient, ξ^f_{mean}:

(A101) $QP^f_t = \xi^f_{mean} QC_{f,t}$ f=coal, crude oil, gas mining, electricity

where ξ^f_{mean} is the quantity of the commodity output (in million tons, million m^3, or billion kWh) per billion yuan of commodity output. For example, the quantity of raw coal produced in million tons is given by $QP^{rawcoal}_t = \xi^{coal}_{mean} QC_{coal,t}$. Since electricity is only a part of the "Electricity, Steam & Hot water" sector, the quantity of electricity produced (in billion kWh) is:

$$QP^{elect}_t = \xi^{elect}_{mean} \alpha^{el\_only}_{elect} QC_{elect,t}$$

where a^{el_only} is the electricity share of the "Electricity, Steam, & Hot water" sector's commodity output.

We compute energy consumption in two ways. The first way simply uses the total output of fuels (production based account); the second way sums over the industry consumption of energy that is calibrated to the official estimates in the base year (consumption based account). First, E^{PROD}, the total sce of energy produced domestically, is:

(A102) $E_t^{PROD} = e_{coal} QP_t^{rawcoal} + e_{oil} QP_t^{oil} + e_{gas} QP_t^{gas} + e_{elect} QP_t^{PRIelec}$

where e_f is the energy content of a unit of fuel *f* (e.g. tons of sce per ton of oil) and the PRI superscript denotes primary electricity from renewables and nuclear.(In this calculation we ignore the tiny amount of heat from natural sources.) We set $\alpha^{PRIelec}$, the share of electricity produced from primary sources, exogenously by considering the projected generation of renewables and nuclear power. Then $QP^{PRIelec}$, the quantity of primary electricity produced from renewables and nuclear, is:

(A103) $QP_t^{PRIelec} = \alpha_t^{PRIelec} QP_t^{elec}$

E^{EXP}, the total sce of energy exported, on net, is:

(A104)
$$E_t^{EXP} = e_{coal} \xi_{mean}^{coal} (X_{coal,t} - M_{coal,t}) + e_{oil} \xi_{mean}^{oil} (X_{crude,t} - M_{crude,t} + X_{refine,t} - M_{refine,t})$$
$$+ e_{gas} \xi_{mean}^{gas} (X_{natgas,t} - M_{natgas,t})$$

where X_f is the value of exports of fuel *f* (in billion yuan) and M_f is the value of imports of fuel *f* (in billion yuan). Exports of electricity are not counted in this measure since it is a secondary energy, the pollution due to the generation of electricity for exports is located in the country and they are not exported.

E^{CONS}, the total energy consumed in China (in tons sce) is then given by production less net exports, less changes in inventory (E_t^{INV}):

(A105) $E_t^{CONS} = E_t^{PROD} - E_t^{EXP} - E_t^{INV}$

$$\begin{aligned} E_t^{CONS} &= e_{coal} \xi_{mean}^{coal} (QC_{coal,t} - X_{coal,t} + M_{coal,t}) \\ &+ e_{oil} \xi_{mean}^{oil} (QC_{\mathrm{crude},t} - X_{crude,t} + M_{crude,t} - X_{refine,t} + M_{refine,t}) \\ &+ e_{gas} \xi_{mean}^{gas} (QC_{natgas,t} - X_{natgas,t} + M_{natgas,t}) \\ &+ e_{elect} QP_t^{PRIelec} - E_t^{INV} \end{aligned}$$

(A106)
$$\begin{aligned} E_t^{CONS} &= e_{coal} C_t^{coal} + e_{oil} C_t^{oil} + e_{gas} C_t^{gas} \\ &+ e_{elect} QP_t^{PRIelec} - E_t^{INV} \end{aligned}$$

(A107) $CF_t^{coal} = \xi_{mean}^{coal} (QC_{coal,t} - X_{coal,t} + M_{coal,t})$, etc.

The second expression in (A105) substitute in (A102) and (A104) to show that it is the constant yuan output less net exports, multiplied by the fuel conversion coefficient, and multiplied by the energy content coefficient. In (A106), the variables $CF_t^{coal}, CF_t^{oil}, CF_t^{gas}$ denote the quantity of fuel consumed in million tons or million m^3. Here, CF^f is calculated as the sum of commodity output (*QC*) and imports (*M)* less exports (*X*), multiplied by the fuel conversion coefficient (ξ_{mean}^f) to convert the constant yuan of fuel consumed into the quantity of fuel consumed (in million tons or million m^3).

Second, in consumption-based accounting, we also calculate national energy consumption by adding over each industry, using industry specific information about the consumption of coal, coke, liquid fuels, etc. We first define consumption coefficients (ξ_j^f) by taking the data on fuel actually used (in million tons, million m^3, or billion kWh) from the China Statistical Year book (CSY 2012, Table 7-9 "Consumption of Energy by Sector") and dividing by the value of energy purchases given in the Input-Output table.

To disambiguate, the fuel conversion coefficient (ξ_{mean}^f), presented in equation (A101), is computed using the production data at the aggregate level: the *total* quantity of the commodity output divided by the *total* value of the commodity output. In contrast, the consumption coefficient (ξ_j^f), presented here, is computed using the consumption data at the industry level: industry *j*'s consumption of fuel *f* (in million tons, million m^3, or billion kWh) divided by the value of industry *j*'s purchases of fuel *f* (in billion yuan).

Secondary fuels are produced by the Petroleum Refining & Coal Products sector which we group as coke, refined liquids, and other petroleum products. The "other petroleum products," such as bitumen and lubricants, are assumed to be not combusted (i.e. not contributing to CO2 emissions). Each industry *j* purchase a different share of coke (coal products) from this sector and we write the value of coke input as a share of the value of Refining & Coal Products in the Use matrix: $\alpha_{ref\_co,j}^{coalpr} U_{refine,j}$ where $a_{s,j}^f$ is the share of fuel *f* in sector *s* that industry *j* purchases, and $U_{f,j}$ is the value (in billion yuan) of inputs of fuel *f* for industry *j* from the Use matrix.

The value of Refined liquids and Other Petroleum Products consumed are then:

$$\alpha_{refine}^{liquid}(1-\alpha_{ref\_co,j}^{coalpr})\,\mathrm{U}_{refine,j}\,; \qquad (1-\alpha_{refine}^{liquid})(1-\alpha_{ref\_co,j}^{coalpr})\,\mathrm{U}_{refine,j}$$

That is, the value of refined liquids is the product of: 1) the share of liquids in total refined petroleum products; 2) the share of *non*-coal products in the Refining & Coal Products sector that industry *j* purchases; and 3) the value of Refining & Coal Products purchased by industry *j*. Similarly, the value of Other Petroleum Products input (on the right) can be interpreted as the product of: 1) the share of *non*-liquids in total refined petroleum products; 2) the share of *non*-coal products in the Refining & Coal Products sector that industry *j* purchases; and 3) the value of Refining & Coal Products purchased by industry *j*.

The energy consumption coefficients for coke and liquid fuels are thus:

(A108) $\xi^{coke}_{j,baseyr} = \dfrac{FT^{CSY}_{coke,j,baseyr}}{\alpha^{coalpr}_{ref\_co,j} U_{refine,j,baseyr}}$; $\xi^{refliq}_{j,baseyr} = \dfrac{FT^{CSY}_{liquidfuel,j,baseyr}}{\alpha^{liquid}_{refine}(1-\alpha^{coalpr}_{ref\_co,j})U_{refine,j,baseyr}}$

where $FT^{CSY}_{coke,j,baseyr}$ is the quantity of coke consumed by *j* in million tons in the base year 2010. $FT^{CSY}_{liquidfuel}$ is the sum of the quantity of gasoline, kerosene, diesel and fuel oil consumed (given in CSY 2012), and $FT^{CSY}_{otherpetroleum}$ is the sum of the quantity of lubricant, bitumen, naphta, etc. consumed (given in the LBL's China Energy Databook).

(A109) $\alpha^{liquid}_{refine} = FT^{CSY}_{liquidfuel,j} / (FT^{CSY}_{liquidfuel,j} + FT_{\text{otherpetroleum},j})$

is the quantity share of liquids consumed in consumption of total refined petroleum products for industry *j*.

Our model distinguishes between the Gas Mining sector and the Gas Utilities (or Gas Products) sector; most industries purchase only from Gas Products, while a few purchase from Gas Mining for transformation and combustion – Chemicals, Electricity and Gas Products. For all industries *j* other than Gas Products the consumption coefficient is the *quantity* of natural gas purchased by industry *j* divided by the sum of the *values* of natural gas and gas products purchased by industry *j* in the base year:

(A110) $$\xi^{natgas}_{j,baseyr} = \xi^{gasprod}_{j,baseyr} = \frac{FT^{CSY}_{\text{natgas},j,baseyr}}{U_{\text{natgas},j,baseyr} + U_{\text{gasprod},j,baseyr}} \qquad j \neq \text{Gas Products}$$

In contrast, the energy consumption coefficient for the Gas Products industry is divided by only the value in the Gas Products cell, excluding the Gas Mining cell:

(A111) $$\xi^{gasprod}_{j=gasprod,baseyr} = \frac{FT^{CSY}_{\text{natgas},j,baseyr}}{U_{\text{gasprod},j,baseyr}}$$

We now move on from calculating energy consumption to calculating energy combustion. The above consumption coefficients refer to the purchases of the different fuels. Some of these oil and gas inputs are not combusted but converted to other products such as fertilizer or bitumen. In the Refining sector part of the crude input is combusted but most are converted to liquid fuels or other petroleum products; the un-combusted portion is represented by the "refining loss" coefficient, $\rho^{ref\_loss}_j$ where $(1-\rho^{ref\_loss}_j)$ is the fraction of un-combusted crude input. (For industries other than j=Refining, $\rho^{ref\_loss}_j$ is simply 1, reflecting that 100% of the crude input is combusted.)

In the Gas Products (Utilities) industry, gas is purchased from the Natural Gas Mining sector and sold to consumers, that is, there is assumed to be no combustion in this industry. In the Chemicals sector, raw gas is purchased from the Gas Mining sector and part of it is converted to plastics and other products. The combusted portion is represented by $\rho^{gas\_loss}_{j=Chemical}$. (For industries other than j=Chemical, $\rho^{gas\_loss}_{j=Chemical}$ is simply

1, reflecting that 100% of the raw gas is combusted). Thus, these loss adjustment coefficients can be thought of as the share of fuel *f* that *is* combusted for industry *j*.

To disambiguate in advance: FT_{fj}^{CSY} (used in the previous section) refers to the quantity of fuel *f* *purchased*, while FT_j^f (used below) refers to the quantity of fuel *f combusted*.

The quantity of fuel **combusted** (*FT*) is given by the constant yuan of fuel (A_{ij}) multiplied by the consumption coefficients (ξ_j^f that converts the value of fuel *f* to physical quantities (tons of coal, tons of oil, m[3] of gas, kWh of electricity)), and multiplied by these loss adjustments ($\rho_j^{f\_loss}$). The following equations describe the quantity of fuel combusted for coal, oil, other petroleum products (*nonliqref*), and gas in terms of fuels at a finer classification:

(A112) $$FT_{jt}^{coal} = Q_{jt}^{rawcoal} + Q_{jt}^{coke} = \xi_j^{coal}\rho_j^{coke\_loss}A_{coal,j,t} + \xi^{coalpr}\alpha_j^{coalpr}A_{refining,jt}$$

$$= \xi_j^{coal}\rho_j^{coke\_loss}U_{coal,j} / PS_{coal} + \xi_j^{coalpr}\alpha_j^{coalpr}U_{refine,j} / PS_{refine}$$

$$FT_{jt}^{oil} = Q_{jt}^{crude} + Q_{jt}^{refinedoil} = \xi_j^{oil}\rho_j^{ref\_loss}A_{oil,jt} + \xi_j^{refliq}\alpha_{refine}^{liquid}(1-\alpha_{ref\_co,j}^{coalpr})A_{refining,jt}$$

$$= \xi_j^{crude}\rho_j^{ref\_loss}U_{crude,j} / PS_{crude} + \xi_j^{refliq}\alpha_{refine}^{liquid}(1-\alpha_{ref\_co,j}^{coalpr})U_{refine,j} / PS_{refine}$$

$$= \begin{cases} \xi_j^{gas}\rho_j^{gasloss}U_{natgas,j} / PS_{natgas} + \xi_j^{gasprod}U_{gasprod,j} / PS_{gasprod} & j \neq gasprod \\ \xi_j^{gasprod}U_{gasprod,j} / PS_{gasprod} & j = gasprod \end{cases}$$

where that the constant yuan quantity of energy input is given by the value in the Use matrix divided by the fuel price: $A_{ij} = U_{ijt} / PS_{it}$. Q^i is the quantity of energy input *i* (at the finer classification) combusted, and the quantity of fuel *f* combusted is the sum over the *i* finer types to give FT^f.

For electricity, α_{elect}^{elec} is the share of electricity in Electricity, Steam & Hot Water, and we may similarly define FT^{elect}, the quantity of electricity purchased (in billion kWh) as:

(A113) $$FT_{jt}^{elect} = \xi_{elect}^{elec}\alpha_t^{elec}U_{elect,j} / PS_{elect}$$

The above equations (A112) and (A113) are for the industry purchases of energy, a similar set of equations hold for household and investment use of energy:

(A114) $FT_{HH,t}^{elect} = \xi_{elect}^{elec} \alpha_t^{elec} C_{elect}$

$$FT_{HH,t}^{coal} = \xi_{HH}^{coal} C_{coal,t} + \xi^{coalpr} \alpha_{HH}^{coalpr} C_{refining,t}$$

$$FT_{HH,t}^{oil} = \xi_{HH}^{crude} C_{oil,t} + \xi_{HH}^{refliq} \alpha_{refine}^{liquid} (1-\alpha_{HH}^{coalpr}) C_{refining,t}$$

$$FT_{HH,t}^{gas} = \xi_{HH}^{gas} C_{gas,t} + \xi_{HH}^{gasprod} C_{gasprod,t}$$

$$FT_{INVt}^{coal} = \xi^{coal} I_{coal}; \qquad FT_{INVt}^{oil} = \xi^{oil} I_{oil}; \qquad FT_{INVt}^{gas} = \xi^{gas} I_{gas}$$

where C_{elect}, C_{coal}, $C_{refining}$, C_{oil}, C_{gas}, *and* $C_{gasprod}$ denote the constant yuan value of Consumption by households of those fuels (in billion yuan). I_f is the value (in billion yuan) of purchases of fuel *f* by the Investor (these are essentially business inventories in the Investment column of the input-output accounts).

The un-combusted portions in this version are the other petroleum products ("nonliqref") and part of the gas use by the Chemicals industry. We denote the un-combusted fuel use by FU:

(A115) $FU_{jt}^{nonliqref} = \xi_j^{refother} (1-\alpha_{refine}^{liquid})(1-\alpha_{ref\_co,j}^{coalpr}) U_{refine,j} / PS_{refine}$ j=1,…33

$$FU_{jt}^{gas} = \xi_j^{gas} (1-\rho_j^{gasloss}) U_{natgas,j} / PS_{natgas} \qquad j\text{=Chemicals}$$

[In this version we have not separated out the combusted portion of "other petroleum products (nonliqref)". A more detailed accounting would have refined products divided to "refined liquids", "other combustible refined products", and "noncombustible refined products". The equations would be:

(A115n) $FT_{jt}^{ocmbref} = \xi_j^{refother} (\alpha_{refine}^{ocmb})(1-\alpha_{ref\_co,j}^{coalpr}) U_{refine,j} / PS_{refine}$

$$FU_{jt}^{noncmbref} = \xi_j^{refncmb} (1-\alpha_{refine}^{liquid} - \alpha_{refine}^{ocmb})(1-\alpha_{ref\_co,j}^{coalpr}) U_{refine,j} / PS_{refine}$$

The other combustible refined products are LPG, Refinery Gas and other gases and should be counted in the calculation of emissions. In the current version we combine them with the noncombustible refined products (wax, asphalt, etc) to give total "nonliqref".

The total energy consumed by industry *j* or households is the sum of these physical units of primary fossil fuels combusted multiplied by the energy conversion coefficient (e_f, e.g. tons of SCE per ton of coal) plus the electrical energy, plus the un-combusted portions:

(A116) $EIND_{jt} = e_{coal} FT_{jt}^{coal} + e_{oil} FT_{jt}^{oil} + e_{gas} FT_{jt}^{gas} + e_{elect} FT_{jt}^{elect} + e_{oil} FU_{jt}^{nonliqref}$

j=1,…,33,HH,INV; j≠elect

When we express energy consumption as above we are counting *j*'s use of electricity as energy consumed by *j*, not as energy consumed by the Electric Utilities when it burns coal to generate electric power. For a consistent accounting of total national consumption, the net energy consumed by Electric Utilities is only the generation loss plus the Utilities own electricity consumption ($U_{elect,elect}$).The generation loss is given by the energy embodied in the fuels combusted in the power plants *less* the energy embodied in the delivered thermal electricity (total electricity minus renewables and nuclear ($QP_t^{elec} - QP_t^{PRIelec}$). The net energy consumed by Electric Utilities, $EIND_{j=elect}$, is thus:

$$\begin{aligned} EIND_{j=elect,t} &= e_{coal} FT_{jt}^{coal} + e_{oil} FT_{jt}^{oil} + e_{gas} FT_{jt}^{gas} \\ &\quad - e_{elect}(QP_t^{elec} - QP_t^{PRIelec}) + e_{elect} U_{elect,j} / PS_{elect} \end{aligned} \quad \text{j=Elect} \tag{A117}$$

The national total energy consumption is then the sum over all industries and final demand:

$$E_{TOT,t}^{IND} = \sum_j EIND_{jt} + EIND_{HH,t} \tag{A118}$$

This should be equal to E_t^{CONS}, the total computed from the production data in equation A107.

Emissions

The national emissions of carbon dioxide may be computed from the production accounts by adding over the emissions from all fossil fuels *f*. This is given by the quantity of fuel consumed (CF_t^f), multiplied by the energy content coefficient (e_f), and multiplied by the CO_2 intensity, (c_f , tons of CO_2 per sce of fuel *f*):

$$EM_{CO2,t}^{fos} = c_{coal} e_{coal} C_t^{coal} + c_{oil} e_{oil} C_t^{oil} + c_{gas} e_{gas} C_t^{gas} \tag{A119}$$

The quantity of fuel *f* consumed, CF_t^f, is given in equation A107 above. For non-combustion sources of CO_2 we only consider those from cement production processes; this is expressed as an emission factor (c_{cement}) multiplied by the cement component of the output of the Building Materials industry:

$$EM_{CO2,t}^{noncmb} = c_{cement} \alpha_{Build}^{cement} QI_{Build,t} \tag{A120}$$

where a^{cement} is cement's share of the Building Materials industry's output, and QI_{Build} is the value of the output of the Building Materials industry (in billion yuan) which also includes glass and clay products.

Total carbon emissions are then the sum of the fossil emissions and non-combustion ones:

$$EM_{CO2,t} = EM_{CO2,t}^{fos} + EM_{CO2,t}^{noncmb} \tag{A121}$$

Local pollutants

Primary emissions of pollutant *x* from sector *j* at period *t* (EM_{jxt}) are produced from fossil fuel combustion and from non-combustion production processes. The combustion emissions are obtained by multiplying the energy input by an emission factor, ψ_{jxft}, while the process emissions are output multiplied by the emission factor, σ_{jxt}. Total emissions from j are thus:

(A122) $EM_{jxt} = \sigma_{jxt} QI_{jt} + \sum_f \left(\psi_{jxft} FT_{jft} \right)$ j=1,…,33

x = PM_{10}, SO_2, NO_X, f = coal, oil, gas

where QI_j is the output of industry *j*'s (in billion constant yuan2010) and FT_j is the quantity of fuel *f* combusted by industry *j*. The combustion emission factor (ψ_{jxft}) is given in tons of emissions of pollutant *x* per ton of fuel, while the process emission factor (σ_{jxt}) is given in tons of primary emissions of pollutant *x* per billion yuan of industry output.

Households' use of fuels also generates pollutants:

(A123) $EM_{HH,xt} = \sum_f \left(\psi_{HH,xft} FT_{HH,ft} \right)$

The estimation of emissions in 2005 is reported in *Clearer Skies* (Chapters 4-6) and an updated version for 2010 is used to calibrate theses emission factors. The emission factors are projected based on planning documents of the NDRC and other government agencies.

The emissions are then used by the GEOS-Chem atmospheric model to compute the concentration of various criteria pollutants at each grid cell as described in *Clearer Skies* (Chapter 7). We consider the impact of PM and ozone on human health, and concentrate on the main effects – mortality risks, hospital admission due to cardiovascular reasons and due to respiratory reasons, and outpatient visits. The health effect *h* due to a change in concentration of x (ΔC_x) induced by a policy change is given by (*Clearer Skies* Chap. 8):

(A124) $\Delta HE_{hx} = f_{hx}(\Delta C_x) \times Pop \times BI_h$

where ΔHE_h denotes the change in the number of cases of health endpoint *h*; *f* is the C-R function ; *Pop* represents the population exposed to the pollutant; and BI_h represents the baseline incidence of the health endpoint *h*. The total impact, say for mortality, is the sum over all pollutants for *h* = mortality, $\Delta HE_h = \sum_x \Delta HE_{hx}$.

We also consider the impact of ozone on agriculture output. There is less agreement in the literature about how to model this impact, and as discussed in *Clearer Skies* (Chap. 8) we use three different measures of ozone exposure (indices I_{O3}^{i}, i=SUM6, AOT40, W126), to compute the impact on the output of maize, rice and wheat. The percentage change in yields is given by:

(A125) $\Delta q_{crop,\mathrm{O3}} = \dfrac{\Delta Q_{crop}}{Q_{crop}} = f_{O3}(\Delta I_{O3}^{i}) \times Q_{crop} \times BI_{crop}$; crop=rice, wheat, maize

The final step is to calculate the monetary value of these damages. The value is given by the health impact from (A125) multiplied by the willingness to pay value of each type of health effect (V_{ht}), and the value of crop damages is the value of the crop ($V_{crop,t}$) multiplied by the percentage change in crop yields:

(A126) $V_t^p = \sum_h \Delta HE_{ht} V_{ht} + \sum_{crop} V_{crop,t} \Delta q_{crop,t}$

A.2 Implementing tax and subsidy policies; environmental policies

In this we describe the implementation of the main policies studied with this model. We first describe carbon tax scenarios, one that is offset by a lump sum rebate to households and one that is offset by cut in existing taxes. We then describe electricity policies, one which subsidize clean energy and one with imposes Renewable Portfolio Standards.

A.2.1 Carbon Tax

We represent a simple carbon tax with revenue neutral recycling as a tax on fossil fuels in proportion to the carbon content of fuel *j* (c_j). We put the tax upstream – on the producers of these (primary) fuels and on the imports of all fuels; the tax per unit output (constant yuan2010) is the carbon content (tons of carbon per yuan) multiplied the carbon tax rate (tx^u , yuan per ton of C):

(A130) $$t_j^{xu} = tx^u c_j \qquad \text{j=coal, crude, natgas}$$

and the unit tariff on import of fuel commodity *i* is:

(A131) $$t_i^{ru} = tx^u c_i \qquad \text{i=coal, crude, natgas, refine, gasprod}$$

The unit tax t_j^{xu} is the term that appears on the right hand side of the purchaser's price equation (A13), while the unit tariff is on the right side of the import price (A83).

The above simple setup means that all purchasers of fuel *j* will pay the carbon tax. A more complicated policy of imposing different rates on different users of fossil fuels will require a tax on intermediate input A_{ij}.

If this tax is to be recycled as a lump sum transfer to households then this is represented by a negative tax, T^{LUMP} , in income equation (A45) above. If this tax is to recycled as a tax cut we introduce a new endogenous variable, t_i^{scale}, that is applied to all tax rates in period *t*, e.g. the tax on capital income is this scaling variable multiplied by the base case rate (t_0^k):

(A132) $$t_t^k = t_t^{scale} t_0^k$$

These offsetting tax variables are chosen to maintain revenue and spending neutrality; we choose the lump sum payment or the tax rate factor such that the real level of aggregate government consumption (GG) and deficit are the same as the base case value for each period:

(A134) $$GG_t = GG_t^{base}; \qquad \Delta G_t = \Delta G_t^{base}$$

A.2.2 Renewables promotion policy

One common policy examined is the use of subsidies to promote renewables in electricity generation. In the base case there is a net output tax ($tt_{l,t}^{EL}$) on electricity generated by source l, giving the purchaser price, $P_{l,t}^{tt,EGEN}$, in equation (A21b). A new subsidy for renewables is represented by $s_{b,t}^{EL}$:

(A135) $$P_{b,t}^{tt,EGEN} = (1 + tt_{b,t}^{EL} - s_{b,t}^{EL}) P_{b,t}^{EGEN} + tt_{b,t}^{ELxu}; \qquad \text{b=hydro,wind,solar,…}$$

The total payment for this new subsidy is expressed as a negative revenue from the electricity generation sector, *R_EGEN*:

(A136) $$R\_EGEN_t = -\sum_b s_{b,t}^{EL} P_{b,t}^{EGEN} Q_{b,t}^{EGEN}$$

This is added to the total revenue term in equation (A61):

(A61') $$\begin{aligned} Rev = & \sum_j t^k (P_j^{KD} KD_j - D_j) + t^L PL.LS + t^V \sum_j (P_j^{KD} KD_j + PL_j LD_j + PT_j TD_j) \\ & + \sum_j t_j^t PI_j QI_j + R\_EXT + \sum_i t_i^r PM_i^* M_i + \sum_i t_i^c (QI_i - X_i + M_i) + FEE + T^{LUMP} \\ & + R\_EGEN \end{aligned}$$

A renewable portfolio standard (RPS) policy requires a certain minimum share of total electricity output to come from renewable sources. In practice, this may be imposed on each company, or imposed on a region and allowing companies to meet the target collectively. We represent the RPS policy in this model as requiring the national share of the kWh from source l be no less than some target, rps_{lt}:

(A137) $$\frac{Q_{lt}^{kWh}}{Q_{TOT,t}^{kWh}} \geq rps_{lt}$$

The RPS may be implemented by subsidies or by allowing producers to pass the higher costs to consumers. A simple way to implement this is a system of taxes and subsidies to the different generators such that the net fiscal burden on the government is zero, and the consumer bears the net impact on the average price of electricity. Let $t_{l,t}^{RPS}$ be the tax on the output from source l; this is negative if it is a subsidy. The price equation (A21b) is then rewritten as:

(A138) $$P_{l,t}^{tt,EGEN} = (1 + tt_{l,t}^{EL} - t_{l,t}^{rps}) P_{l,t}^{EGEN} + tt_{l,t}^{ELxu}; \qquad \text{l=coal,gas,hydro,wind,…}$$

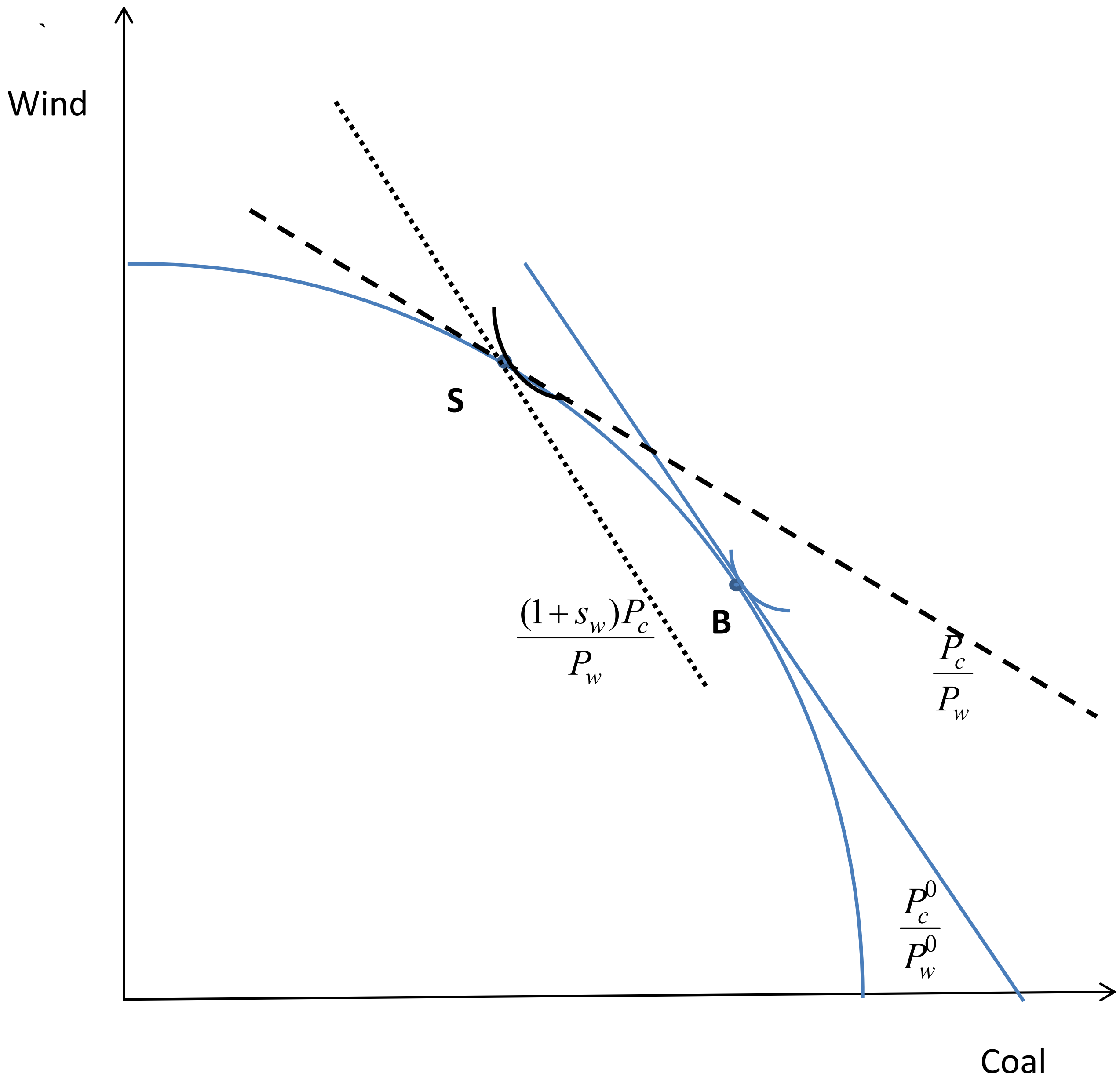
Producers will change output given this new vector of prices according to the cost functions given in A17, A19 and A21. This is illustrated in Figure A3.

Revenue neutrality requires:

(A139) $$\sum_l t_{l,t}^{rps} P_{l,t}^{EGEN} Q_{l,t}^{EGEN} = 0$$

We thus have potentially 8 rates for the $t_{l,t}^{rps}$, to hit a maximum of 8 independent target shares for the different sources of power; only relative prices matter and the shares must sum to 1.

Figure A3. Using shadow taxes to meet renewable portfolio standards



In this diagram the arc represents the production possibility frontier for coal versus wind. In the base case the producer, and consumer, relative price for coal versus wind is P_c^0 / P_w^0 and output and consumption is at point B. The small arcs represent the iso-utility curves of eq. A17. A subsidy for wind of sw will move the relative price to P_c / P_w and production to point S. The price to the consumer becomes $(1+s_w)P_c / P_w$

A.3 Parameterizing the electricity sub-model

The parameters of the electricity sub-model are based on three main sources of data – the Input-Output table, the Electric Power Industry Statistics,[21] and the International Energy Agency (2010) "Projected Costs of Generating Electricity".

The elasticities are summarized in Table A2

A.4 Parameters, exogenous variables and data sources

The key input into the model is the Social Accounting Matrix (SAM) for 2010. This traces the flow of commodities and payments among the producers, household, government and rest of the world. The SAM is assembled from the 2007 benchmark input output table.[22] A summary of this SAM is given in Figure A4, the actual matrix used is disaggregated to the 33 sectors and commodities. From this we derive the labor and capital incomes, the tax revenues for each type of tax, the expenditures on specific commodities by the household, government and foreign sectors, and government payments of all types in equation A76.

These payments are combined with employment and capital input data to give the compensation rates for labor and capital for each sector. The estimates for employment and capital stocks by sector are taken from a productivity study of China (Cao, Ho, Jorgenson, Ren, Sun and Yue 2009) that supplements the official data with labor force surveys. The various tax and subsidy rates are not statutory rates but are implied average rates derived by dividing revenues by the related denominator – value of industy output, capital income, total value added, and imports.

The exogenous variables in the model include total population, working age population, saving rates, dividend payout rates, government taxes and deficits, world prices for traded goods, current account deficits, rate of productivity growth, rate of improvement in capital and labor quality, and work force participation. These variables may, of course, be endogenous (i.e. they interact among each other) but we ignore this and specify them independently. Our assumptions for these exogenous drivers are summarized in Table A3.

The assumption that affects the growth rate the most is the household savings rate, s_t. Our assumption is to have s_t beginning at the observed 41.2% for 2010 and gradually falling to 22% in 2020 and 15% in 2050. National private savings is household savings plus the retained earnings of enterprises.

[21]电力工业统计资料汇编.

[22] The 2010 input-output table is given in NBS (2014). The benchmark IO table for 2007 is derived from detailed enterprise data, the 2010 IO table is extrapolated by the NBS using simpler aggregated data.

The share of retained earnings is assumed to fall, and dividend payouts to rise to reflect the diminishing role of state enterprises in the economy. The dividend rate, i.e. the share not used for retained earnings, was 38.9% in 2010 and we project it to rise to 58% by 2020. It should be pointed out that national savings and investment in the Chinese data includes capital such as roads and other public infrastructure, items that are excluded from the "gross fixed private investment" item in most other countries National Accounts.

In the labor supply expression eqn. (A47) we have the product of the working-age population, annual average hours and quality. In Cao and Ho (2014) we discussed various population growth scenarios including the different two-child policies. Projections by age groups are taken from projections made by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat[23] and in the central population scenario we adjust them to incorporate a looser child policy. The results are plotted in Figure A5.

The composition of the work force changes over time with a bigger portion of educated workers, bigger or smaller portion of more experienced workers, and an older average age. This quality of labor input index, q_t^L , in estimated in Cao et al. (2009) to have grown at 0.9% per year for the period 1983-2000. Given the expectation of continued higher educational attainment in the future we assume that China's aggregate labor quality continue to rise, but at a diminishing rate. By 2040 the quality index is assumed to grow at only 0.2% per year. For comparison, the U.S. labor quality growth peaked at 0.5% during the 1960s, and fell to 0.3% per year during 1995-2000 (Jorgenson, Ho and Stiroh, 2005, Table 6.5).

Total labor hours depend also on the participation rate and annual working hours. There is no comprehensive data on the number of hours worked and based on comparisons to other countries we project it to rise due to improvements in the functioning of the labor market -- lower underemployment, seasonal unemployment and other labor market frictions. We assume that hours worked per capita rises at 0.2% per year initially but slowing down over time. The results are plotted in Figure A6.

We allow for improvements in future capital "quality," or composition, as represented by the ψ_t^I coefficient in (A73). Cao et al. (2009) note how the composition of the capital stock in China has shifted towards assets with shorter life, i.e. towards a smaller share of structures and a larger share of equipment such as computers. They explain how assets which have shorter useful lives generate higher annual capital services per dollar of capital stock, and hence is of a higher quality in the terminology of Jorgenson, Ho and Stiroh (2005). While the ratio of equipment to structures has moved in different directions over the past 30 years, we believe it will return to a more typical development trend of rising equipment ratios. We project that capital quality rises by 1.5% per year initially, then gradually decelerating. For land, the supply

[23] The demographic projections are from the U.N. Population Division's *World Population Prospects: 2012 Revision*, downloaded from their web site, http://esa.un.org/unpd/wpp/unpp/panel_population.htm .

of land for agriculture, oil mining and gas mining is simply set fixed for all periods equal to the base year value.

Tax rates are set equal to those for 2010 derived from the SAM. These are summarized in Table A4. For the government deficit, ΔG, we set it at the base year 1.69% of GDP initially, declining steadily towards zero in the long run. These deficits are cumulated into the stocks of domestic and foreign debt, B_t and B_t^{G*}, assuming a constant division between domestic and foreign borrowing. Data for the stock of debt and interest paid on it comes from the China Statistical Yearbook (NBS 2012, Table 8-13), IMF's *World Economic Outlook 2012* online database and the 2010 Social Accounting Matrix. Government transfers, $G\_transfer$, are set to rise in proportion with population and average wage. The nontax fees paid by enterprises are set to be a fixed share of GDP equal to the base year's share (Table A4).

The current account balance was in a huge surplus in the mid-2000s but has since declined. There is no consensus about the future evolution of this variable, for simplicity, after setting it as a share of GDP at the observed sample period values, we set it to decline rapidly to zero. This CA_t deficit is also the assumed rate of borrowing from the world. Import prices, PM^{i*}, are assumed fixed at the base year value for every period with one important exception. World oil price forecasts are taken from the U.S. Energy Information Administration and shown in Figure A7.[24] The model also requires projections of the export share; while this has been rising rapidly in the past, it fell with during the 2008 Global Financial Crisis and never recovered. Given the aim to rebalance the economy away from exports and investment towards consumption, we simply project a constant value for the share parameter.

The base year data for 2010 was constructed in 2013 since then, the macro variables for 2011-13 is now available; these include the GDP, investment and current account surplus. The current account surplus has fallen, and the unusually high share of investment in GDP has risen even more after 2010. We take these into account in setting the savings rate and current account balance as share of GDP for these years.

Parameters

The rate of productivity growth is another factor that has a large effect on the base case growth rate of the economy but has little impact on the difference between cases. Total Factor Productivity growth at the industry level in the 1982-2000 period show a very wide range of performance as estimated by Cao et al. (2009), ranging from -10% to 5% per year. The Domar-weighted productivity growth for all industries was 2.7% for 1982-2000. To keep the base case as simple as possible we ignore this wide range of observed

[24] The projections for crude oil prices are taken from the EIA's *Annual Energy Outlook 2010*, Table 12, which is available on their web page: http://www.eia.gov/forecasts/aeo/.

TFP growth, and in our projections of sector productivity terms in eqn. (A3) we initially set all the μ_j's to the same value, 0.018. These are then adjusted to match actual GDP growth rates in the initial years for which we have actual data.

The value share parameters of the production functions (α_{Kj}, α_{Lj}, etc.) are set to the values in the 2010 IO table in the first year of the simulation. For future periods we change most of these parameters so that they gradually resemble the shares found in the US input output table for 1997. The exceptions to this are the coal inputs for all the sectors, this is set to converge to a value between current Chinese and US1997 shares.[25] The rate of reduction in energy use is set at a modest level relative to the rapid improvements in the recent Chinese history. We assume that the share of energy in industry output is reduced gradually to 60% of the 2005 levels in 40 years. This is conservative compared, for example, to the performance in the electric power industry during the 1990-99 period. In that time the thermal output grew 88% whereas coal input only rose 61%, a rate of improvement of some 1.5% per year.[26]

The α_{it}^{C} parameters of the consumption function are set in a similar way. That is, for the first period they are equal to the shares in the 2010 Social Accounting Matrix, and for the future periods they gradually approach US 1997 shares except for coal. This implies a higher projected demand for private vehicles and gasoline than that assumed in most other models of China. The coefficients determining demand for different types of investment goods (α_{it}^{I}), and different types of government purchases (α_{it}^{G}), are projected identically.

The import and export elasticities are set to the values in GTAP v4. The base share of exports and imports are taken from the SAM.

[25] We have chosen to use U.S. patterns in our projections of these exogenous parameters because they seem to be a reasonable anchor. While it is unlikely that China's economy in 40 years time will mirror the U.S. economy of 1997, it is also unlikely to closely resemble any other economy. Other projections, such as those by the World Bank (1994), use the input-output tables of developed countries including the U.S.

[26] China Energy Statistics Yearbook 1997-1999, Tables 4-5 and 4-15.

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Table A1. Selected Parameters and Variables in the Economic Model

Parameters	
s_i^e	export subsidy rate on good *i*
t_i^c	carbon tax rate on good *i*
t^k	tax rate on capital income
t^L	tax rate on labor income
t_i^r	net import tariff rate on good *i*
t_i^t	net indirect tax (output tax less subsidy) rate on good *i*
t^x	unit tax per ton of carbon
Endogenous Variables	
G_I	interest on government bonds paid to households
G_INV	investment through the government budget
G_IR	interest on government bonds paid to the rest of the world
$G\_transfer$	government transfer payments to households
P_i^{KD}	rental price of market capital by sector
PE_i^*	export price in foreign currency for good *i*
PI_i	producer price of good *i*
PI_i^t	purchaser price of good *i* including taxes
PL	average wage
PL_i	wage in sector *i*
PM_i	import price in domestic currency for good *i*
PM_i^*	import price in foreign currency for good *i*
PS_i	supply price of good *i*
PT_i	rental price of land of type *i*
QI_i	total output for sector *i*
QS_i	total supply for sector *i*
$r(B^*)$	payments by enterprises to the rest of the world
$R\_transfer$	transfers to households from the rest of the world

Table A2. Reference values for elasticities of substitution in the Electricity sector

	Description	Value	Sectors/nodes
σ^{ED}	Transmission-Generation	0.7	Electric Utilities
σ^{EG}	Baseload-Wind/Solar	1.0	Generation
σ^{BL}	Among base load sources	4.0	Baseload Generation
σ^{RE}	Wind-Solar	4.0	Wind and Solar Generation
σ^{QI}_{TD}	Materials-VE	0.7	Transmission
σ^{VE}_{TD}	Energy-Value added	0.5	Transmission
σ^{VA}_{TD}	Capital-Labor	1.0	Transmission
σ^{E}_{TD}	Among energy inputs	0.5	Transmission
$\sigma^{M}_{BL,c}$	Materials-VE	0.1	Coal, coal-ccs, gas, gas-ccs
$\sigma^{VE}_{BL,c}$	Energy-Value added	0.5	All generation sources
$\sigma^{VA}_{BL,c}$	Capital-Labor	0.4	All generation sources
$\sigma^{E}_{BL,c}$	Coal-Noncoal	0.25	Coal generation, coal-ccs
$\sigma^{NC}_{BL,c}$	Among noncoal energy	0.5	Coal generation, coal-ccs
$\sigma^{E}_{BL,g}$	Gas-Nongas	0.25	Gas generation, gas-ccs
$\sigma^{NG}_{BL,g}$	Among nongas energy	0.5	Gas generation, gas-ccs
$\sigma^{eseq}_{coalccs}$	Energy-Sequestration tech.	0	Coal-ccs
σ^{eseq}_{gasccs}	Energy-Sequestration tech.	0	Gas-ccs
$\sigma^{M}_{BL,b}$	Materials-VR	0.1	Nuclear, hydro, wind, solar, other
$\sigma^{VR}_{BLb(b)}$	Resource-VE	0.4	Nuclear, hydro, other
$\sigma^{VR}_{BLb(b)}$	Resource-VE	0.25	wind, solar
$\sigma^{E}_{BLb(b)}$	Among energy inputs	0.5	Nuclear, hydro, wind, solar, other
	Resource supply parameters		
ε^{R}_{r}	Resource supply	2.5	Nuclear

Table A3. Parameters of base case growth path

	Savings rate	Dividend rate	Popul-ation	Work force	Labor input (quality adjusted)	Total Factor Productivity index
Base year 2010	41.2%	38.9%	1360	938	100.0	100.0
2020	22.3%	57.9%	1440	930	108.5	111.5
2030	17.0%	63.2%	1470	884	108.5	122.8
2040	15.3%	64.9%	1466	838	105.9	133.9
2050	14.6%	65.5%	1434	758	97.6	144.6

Table A4. Miscellaneous Tax Rates and Coefficients

Tax rate on capital income	tk	0.0805
Indirect tax rate on output	tt	0.0 to 0.033
VAT rate	tv	0 to 0.199
Import tax rate	tr	0 to 0.198
Nontax payment share	γ^{NENT}	0.0246
Govt transfer rate	γ^{tr}	0.2846
Household savings rate (2010)		0.4125
Dividend payout rate (2010)		0.3889

Figure A4. Summary Social Accounting Matrix for China, 2010 (bil yuan)

Expend. / Receipts	Commodity	Industry	Labor	Capital	Land	House-holds	Enterprise	VAT+BT	Govt	Tariff	ROW	Capital account	Total
Commodity		98092				14030			5318		11866	19353	148659
Industry	137141												137141
Labor		16687											16687
Capital		15726											15726
Land		1619											1619
Households			16687	0	1386		5436		566		291		24367
Enterprise				15726	232						293		16251
VAT+BT		3225											3225
Government		1643				484	2273	3225		1252	0	677	9554
Tariff	1252												1252
ROW	10416		0	0					22				10438
Capital a/c						9853	8541		3648		-2067		19975
Total	148810	136991	16687	15726	1619	24367	16251	3225	9554	1252	10383	20030	
Addendum:	GDP=	40151											

Figure A5. Projections of Population (millions)

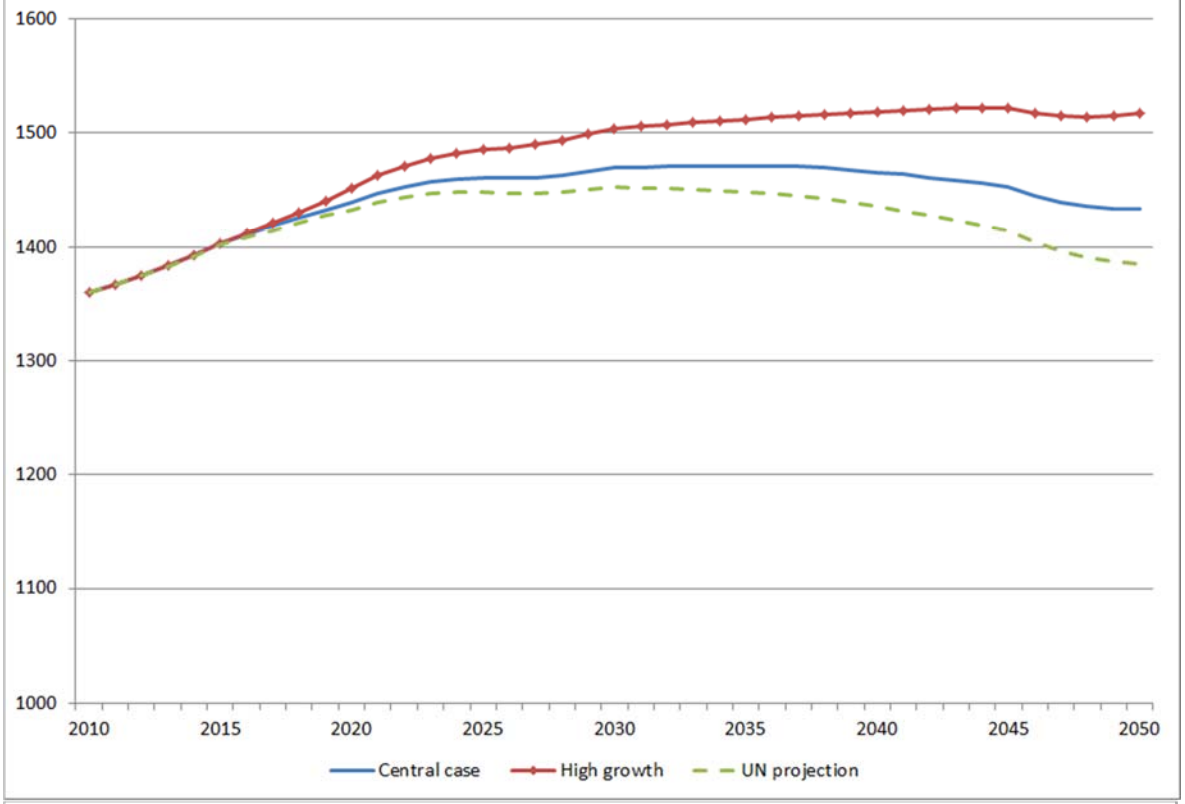
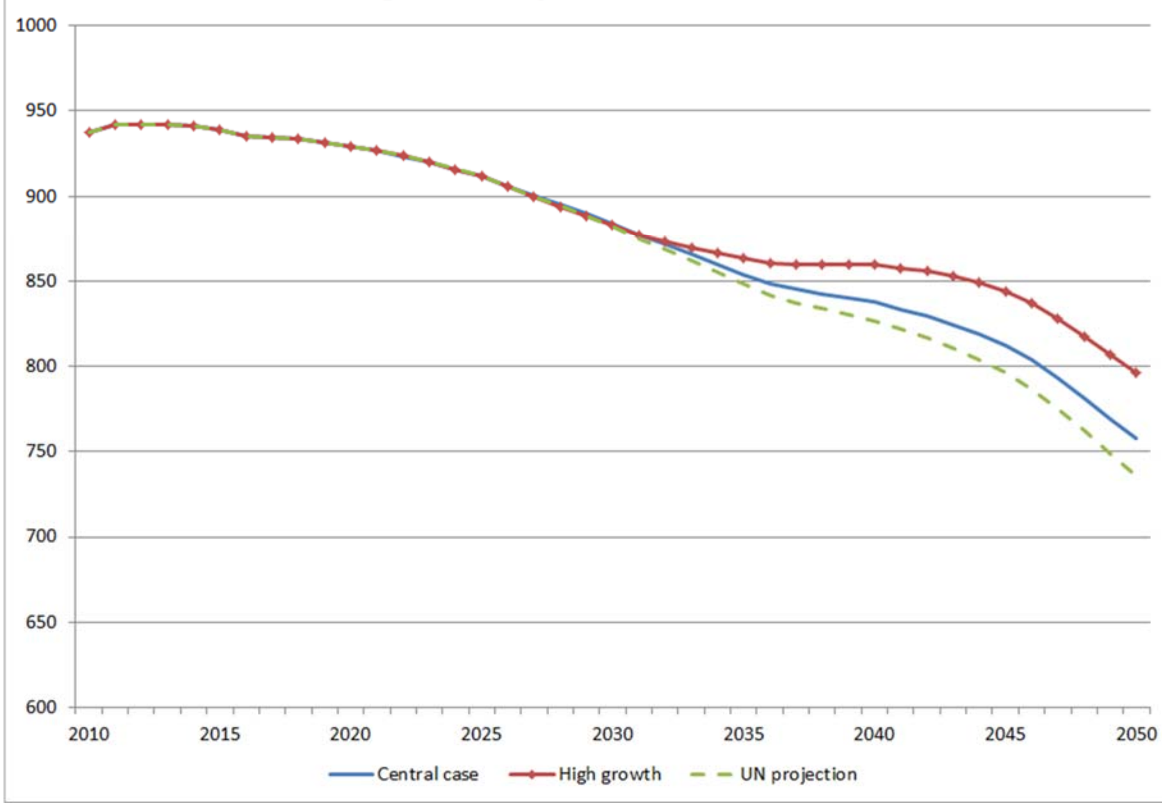
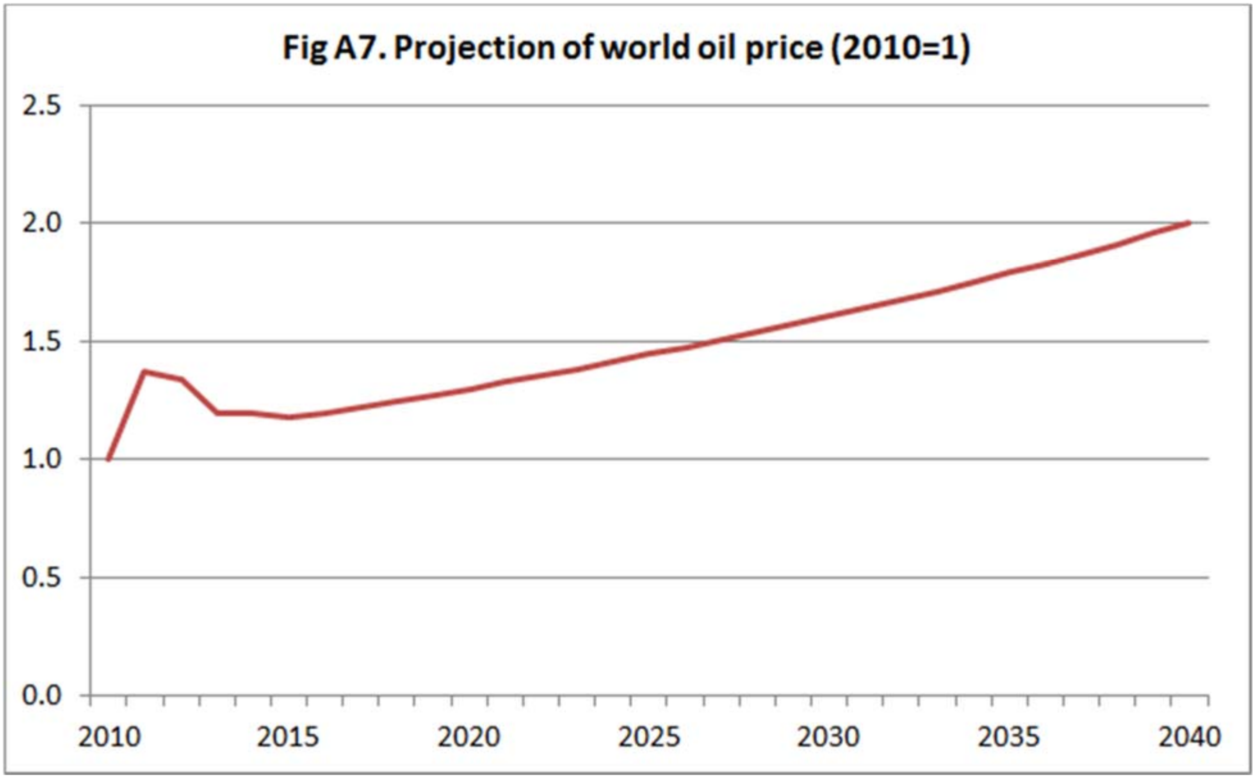


Figure A6. Projections of work force





Note: Projection taken from US EIA(2013).

Appendix B. Electricity Sector Parameterization and Projection

B.1 Electricity Sector Parameterization and Data Construction

This Appendix describes the construction of the electricity sector data set with the various generation technologies and how that is integrated with the rest of the economic accounts of the China model that is described in the Model Appendix.

The model is based on a Use matrix with 33 commodities and 33 industries and a Make (or Supply) matrix with 33 industries and 33 commodities (Table B5). Sector 22 is the "production and supply of electric power and heat power", which we label as Electricity & heat. This includes both generation and distribution, including suppliers of steam and hot water, and combined heat-and-power units. The electricity column in the Use matrix gives the values of inputs into the sector including the 33 intermediate inputs, labor and capital inputs. It also gives the value of taxes, net of subsidies, paid by that sector.

The Social Accounting Matrix (SAM) for 2010 was constructed using the official 2007 benchmark input-output matrices (Use and Make) and rebalanced to match the 2010 values for GDP, the final demand components (CIGXM), industry value added, industry gross output and government tax receipts. The key values of this 2010 SAM are given in Figure A4 of the Model Appendix.

Output and prices in electricity sector

The task here is to disaggregate this electricity and heat sector into the various generation technologies and "transmission & distribution". This is made difficult by the lack of data on prices and yuan values even though there are good data on the kWh output quantities and installed capacity (in GW). It is also made difficult because the measures of output in the National Accounts are not reconciled with in the data from the electric power industry sources.

The first step is to collect the quantity data on the generation capacity and power generated in 2010 and more recent years. The data before 2011 is assembled by LBNL (2013) from various sources of information in China including the NDRC and State Grid companies (see also NBS (2014) Tables 9-6 and 9-15) and we obtain more recent information from China Electricity Council (2014).[27] The capacity and output data are presented in Table B1. The "Others" category includes oil, biomass, geothermal, etc.

[27] *Electricity Power Industry Statistics*, China Electricity Council, Beijing (2014). (电力工业统计资料汇编)

In 2010, of the 966GW of total generating capacity, 68.3% was coal and 22.4% was hydro. The operating hours are quite different for the different technologies and of the 4228 terawatt-hours of power output, 77.1% is from coal and only 16.2% from hydro. Wind power has been rising rapidly with a doubling of output between 2010 and 2012. Solar capacity was negligible in 2010 but reached 28GW in 2014.

Table B1. Electric power sector characteristics

	2010	2011	2012
Capacity (GW)			
Coal	660.0	713.3	758.8
Gas	27.0	35.0	37.4
Nuclear	10.8	12.6	12.6
Hydro	216.1	233.0	249.5
Wind	29.6	46.2	61.4
Solar	0.3	2.2	3.4
Others	22.7	20.1	23.6
Total	966.4	1062.4	1146.8
Output (TWh, billion kWh)			
Coal	3258.9	3703.1	3719.3
Gas	78.7	111.0	109.5
Nuclear	74.7	87.2	98.3
Hydro	686.7	668.1	855.6
Wind	49.4	74.1	103.0
Solar	0.1	0.7	3.6
Others	79.1	86.3	97.2
Total	4227.7	4730.5	4986.5

The next step is to collect prices for each generation technology in order to estimate the output values. There is the feed-in tariff (or on-grid price, 上网电价) and a distribution price (输配电价) which varies by generation technology and location. The average generation price was 0.38 yuan/kWh in 2010 while the distribution price is 0.16 yuan/kWh for the National Grid and 0.20 for the Southern Grid.[28] The average end-user price was thus 0.58 yuan/kWh (0.38+0.20) in

[28] China Times May 15, 2013, given at www.wantchinatimes.com/news-subclass-cnt.aspx?id=20130515000080&cid=1102.

2010. There is no official data on average prices for each generation technology; there are some national benchmark prices set by the NDRC, for example, the price for nuclear power was set at 0.43 yuan/kWh in 2013, and there are three pricing regions for solar power set at 0.9, 0.95 and 1.0 yuan/kWh respectively, in 2013.

Table B2. Costs and prices for electricity in China

a) Feed-in tariffs (yuan/kWh)

	2009	2010	2011
Coal	0.36	0.41	0.44
Gas	0.55	0.56	0.56
Hydro	0.28	0.30	0.31
Nuclear	0.40	0.41	0.41
Wind	0.53	0.56	0.58
Solar	1.08	1.08	1.08

b) Levelized costs (LCOE) from IEA(2010), selected technologies, 5% discounting option

Technology	Lifetime (years)	Load factor	LCOE US$/MWh	Fuel	O&M	Capital	LCOE yuan/kWh
Nuclear; CPR-1000	60	0.85	30.0	9.33	7.18	13.4	0.186
Super critical coal 1119MW	40	0.85	29.5	23.1	1.54	4.99	0.183
Comb. cycle gas 1358MW	30	0.87	35.8	28.1	2.85	4.90	0.222
Hydro 6277MW	80	0.34	16.9	0	2.55	14.3	0.105
Onshore wind 35MW	25	0.22	83.2	0	23.3	60.0	0.516
Solar 10MW	25	0.18	186	0	18.0	169	1.153

c) Wind power characteristics

Capacity	Levelized costs (IEA)		Capacity	Number
MW	US$/MWh	yuan/kWh	MW	in 2012
200	51.0	0.32	200+	17
			100-150	109
50	64.2	0.40	50	1217
35	83.2	0.52		
30	89.0	0.55	20-30	801
Mean cost	67.5	0.42		

d) Levelized costs with carbon capture from IEA (2010)

	Capture rate (%)	LCOE. Ratio of CCS to Reference plant
Coal-Chem absorption 2030	85	1.49
Coal-Oxy combustion, 2030	90	1.55

Coal-IGCC-Selexol, 2030	85	1.47
Gas-CC, Chem absp, 2030	85	1.23

The main source of data are the detailed plant-by-plant data reported by the NDRC[29] and reproduced in LBNL (2013, Tables 6B.12-6B.18) for 2008, 2009 and 2011. We compute the simple average of these plant level on-grid prices separately for coal, gas and hydro plants and these are reported in the top section of Table B2. The prices for 2010 are interpolated between 2009 and 2011 that we describe in greater detail below.

Table B2 also gives the average benchmark prices for nuclear, wind and solar.[30] Some data for 2013 are deflated back to 2010 using the PPI for electricity. We can see that the prices paid by the state grid companies vary substantially by the type of technology, from 0.30 yuan for hydro to 1 yuan for solar PV. For onshore wind, four different prices are allowed for different regions: 0.51, 0.54, 0.58, 0.61 yuan/kWh respectively for Regions I, II, III and IV. Prices have generally been rising over time except for solar where the benchmark prices have fallen from very generous levels.

To provide a comparison to these estimates of average feed-in tariffs, we also report in Table B2(b) the cost estimates in IEA (2010), *Projected Costs of Generating Electricity*. This provides the levelized costs for various power generation technologies in many countries of the world, including China. We report only a sample of the technologies estimated in IEA (2010), and report the three components of the total levelized costs (LCOE) – fuel, operation & maintenance, and capital costs. The IEA report calculated LCOEs using two different rates of discount, 5% and 10%; we only report the 5% set here. The US$ estimates are converted to yuan at an exchange rate of 6.2 yuan/$.

The cost for the 1GW super critical coal plant in IEA (2010) is substantially lower than the average price allowed for the stock of existing plants in China which includes many smaller and older units, 0.18 versus 0.4. Similarly, the average feed-in tariff of hydro power in China is

[29] *NDRC Price Notices for Electricity*. For example, the Southern Grid Price Notice for 2011 (调整南方电网电价的通知， 发改价格[2011]2618号) is given at:
http://www.ndrc.gov.cn/fzgggz/jggl/zcfg/201112/t20111201_748381.html

[30] These controlled price settings are taken from China Climate Change Info-Net at
http://www.ccchina.gov.cn/Detail.aspx?newsId=28117&TId=60 ,
http://www.ccchina.gov.cn/WebSite/CCChina/UpFile/File443.pdf , and Xinhua News at
http://news.xinhuanet.com/finance/2013-07/09/c_124978789.htm

much higher than the large-unit cost estimated by IEA. The cost for wind and solar are quite close to the Chinese benchmark prices.

Wind power is expected to be expanded rapidly under the current government plans and we provide more information in Table B2(c). The first two columns give the levelized costs estimated in IEA (2010) for various wind turbine capacities under the 5% discount option. These range from 0.32 to 0.55 yuan/kWh. The last two columns give the size distribution of the wind turbines in 2012.[31] The most common type is the 50MW turbine. Using the IEA estimated costs, the average wind cost for that distribution of sizes is 0.42 yuan/kWh. This is also substantially lower than the average feed-in tariffs which depend on the region where the turbine is located. That is, the tariff takes into consideration the wind conditions and not just the cost of operating the turbine.

For technologies that are not currently used but might be considered in the future, especially if there is a carbon emission policy, we report the estimated costs of generation with carbon capture and sequestration (CCS) in part (d) of Table B2. This gives the estimated cost of a plant with CCS relative to a reference plant without CCS. The IEA (2010) projections give estimated costs for 2015, 2020 and 2030 and we report only the 2030 estimates to give readers an idea of the magnitudes involved. For coal with Chemical absorption with a 85% CO_2 capture rate, the cost ratio is projected to be 1.49, while the gas combined cycle plant with CCS has a lower cost ratio of 1.23.

With these estimates of the average feed-in tariffs of the various technologies in Table B2, and the output data in Table B1, we estimate the revenues. These output values are computed in order to be reconciled with the values in the Social Accounting Matrix. The values derived from the prices in Table B2 are given in the first column of Table B3. The value of coal power is 78.9% of the total 1,595 billion yuan. Since the price of hydro power is the lowest, the value of hydropower is only 12.4% of total output even though it is 16.2% of the TWh. The other sources of power were less than 3% of the total in 2010.

Turning back to Table B1, we see that the gross output of Electricity and Heat in the input-output table is 3,236 billion. If we take the total of 1595 billion as the generators' revenues, then the residual for transmission would be 1641 billion yuan (Table B3b), which is larger than the generating sector. As we noted above, in 2010, the average feed-in tariff was 0.38 yuan/kWh

[31] This data is given in the 2014 Report on Wind Power Market.

and the average transmission price was 0.20 giving a total end-user price of 0.58 yuan/kWh. That is, the average price for the transmission is quite a bit smaller than the average price paid to the generators.

The national accounts are most likely more comprehensive and take into account aspects of the electric power sector that is not included in these prices. To reconcile these two sets of data, we take a simple approach and scale the feed-in tariffs in Table B2 upwards so that the ratio of generator revenue to total generator plus transmission revenue is 0.38:0.58 as shown in the last two columns of Table B3b. This rescaled total generator revenue of 2121 billion yuan is then applied to the individual technologies and the revised output values are given in the third column of Table B3.

Table B3. Value of output of power generators in 2010 (billion yuan).

	Value using prices in Table B2(a)		Rescaled
	bil.yuan	%	Values
Coal	1258.4	78.9%	1673.7
Gas	41.7	2.6%	55.4
Nuclear	28.9	1.8%	38.5
Hydro	197.3	12.4%	262.4
Wind	26.2	1.6%	34.8
Solar	0.1	0.0%	0.2
Others	42.4	2.7%	56.4
Total	1595	100%	2121.3

Table B3b. Gross output and prices of Electricity sector in 2010

	Price		Value		Rescaled value	
	¥/kWh	%	bil yuan	%	bil yuan	%
Generators	0.38	65.5%	1595	49.3%	2121	65.5%
Transmission	0.20	34.5%	1641	50.7%	1115	34.5%
Total Electricity	0.58	100%	3236	100%	3236	100%

Input-output of electricity sector

With these outputs and prices of each generation technology, we can now disaggregate the Electricity & Heat sector of the Use matrix into the 7 technologies and electric power distribution. The Use column gives the inputs into this sector and is given in the first column of Table B4. We distribute this column to the 7 generation types and distribution in two steps; first divide the Use column into a Generation column and a Distribution column; then divide the Generation column into 7 technologies. We proceeded in the following manner.

First, set the target for total generation to 2,121 billion and for distribution to 1,115 as calculated in Table B3b. Second, allocate the coal mining, gas mining, and oil mining inputs entirely to Generation. Third, to allocate electricity input, we turn to the energy consumption data by industry. The consumption of electrical power by the Electricity & Heat sector is reported to be 568.8 TWh in 2010 and transmission losses are 256.8 TWh compared to the national total consumption of 4,193 TWh.[32] This means that transmission losses were 45.2% of power consumed by the electricity generation and distribution sector. We thus allocate 45.2% of the Use(electricity, electricity) cell to the Distribution column and the remainder to the Generation column. Next, we allocate the total trade and transportation margins used by

[32] China Statistical Yearbook 2011, Tables 7-6 and 7-9.

Table B4. Input-output of electricity sector, 2010 (billion yuan)

		Total electricity	Generation	Distribution
1	Agriculture	0.55	0.29	0.26
2	Coal mining	686.55	686.55	0.00
3	Oil mining	24.38	24.38	0.00
4	Gas mining	24.33	24.33	0.00
5	Nonenergy mining	8.79	4.66	4.13
6	Food	22.60	11.98	10.61
7	Textile	0.85	0.45	0.40
8	Apparel	22.04	11.69	10.35
9	Lumber	4.38	2.32	2.06
10	Paper	11.45	6.07	5.38
11	Refining & coal prod	216.11	144.79	71.32
12	Chemicals	21.01	11.14	9.87
13	Nonmetallic mineral	14.45	7.66	6.79
14	Primary metals	18.66	9.89	8.76
15	Fabricated metal	27.18	14.41	12.77
16	Machinery	69.53	36.87	32.66
17	Transportation equip	85.63	45.41	40.22
18	Electrical mach.	331.35	175.71	155.63
19	Electronics	5.07	2.69	2.38
20	Instruments	107.18	56.84	50.34
21	Other manufacturing	7.53	3.99	3.54
22	Electricity & Heat	182.89	100.30	82.58
23	Gas utilities	8.62	8.62	0.00
24	Construction	2.54	1.35	1.19
25	Transportation equip	51.86	38.89	12.97
26	Communication	29.97	15.89	14.08
27	Trade	49.17	36.88	12.29
28	Hotel & restuarants	14.52	7.70	6.82
29	Finance	218.43	115.83	102.60
30	Real Estate	2.94	1.56	1.38
31	Business services	66.07	35.04	31.04
32	Services	89.96	47.70	42.25
33	Public admin.	0.76	0.41	0.36
	Labor	226.73	120.23	106.49
	Capital	431.96	229.07	202.89
	Land	0.00	0.00	0.00
	Taxes	150.29	79.70	70.59
	Total gross output	3236.30	2121.31	1114.99

electricity to fossil fuels versus non-fuel goods. That is, we assume that these margins only apply to inputs 1 through 21 out of the 33 commodities in the Model.

Up to this point we have allocated the fuel inputs (commodity numbers 2,3,4), electricity (22) and a portion of the trade (27) and transportation (25) margins to Generation and to Distribution. Of the 2,121 billion yuan target total for Generation, 1,080 remains unallocated, and for Distribution 957 remain unallocated. Each of the remaining intermediate inputs (1,5,6,…33), and each of the value added items, is allocated to Generation and to Distribution in proportion to these unallocated amounts. In this way, the sum of all inputs for Generation equals the target 2,121 billion yuan. The results of this exercise are given in the second and third columns in Table B4.

The second step disaggregates the total Generation column to the 7 technologies, where the output targets are given in Table B3 in the "rescaled values" column. First, we allocate the entire coal mining input of Generation to "Coal generation", oil mining to "Others", and gas mining and gas utilities to "Gas generation". See Table B5. Then for each technology we compute the unallocated total as the output target minus these allocated fuels. Each of the non-fuel rows in the Generation column (including the value added rows) is then allocated to the 7 technologies in proportion to these unallocated totals.

The results of this disaggregation are given in Table B5. Coal generation is 79% of total generation output but since fuel input is such a big factor here, its share of capital value-added in total Generation is only 72%. For hydro, the situation is reversed, it has 12.4% of Generation output value but 19.0% of value added.

The above simple disaggregation procedure preserves the Use column of the electricity & heat sector, that is, the sum of generation and distribution output is the electricity & heat output, and for each commodity input, the sum across the 7 generation technologies and distribution is the value in that row of the Use column. This means that the rest of the SAM for the other sectors is undisturbed.

Table B5.Disaggregation of Generation inputs to the different technologies

		Generation	Coal	Gas	Nuclear	Hydro	Wind	Solar	Other
1	Agriculture	0.29	0.21	0.00	0.01	0.06	0.01	0.00	0.01
2	Coal mining	686.55	686.55	0.00	0.00	0.00	0.00	0.00	0.00
3	Oil mining	24.38	0.00	0.00	0.00	0.00	0.00	0.00	24.38
4	Gas mining	24.33	0.00	24.33	0.00	0.00	0.00	0.00	0.00
5	Nonenergy mng	4.66	3.34	0.08	0.13	0.89	0.12	0.00	0.11
6	Food	11.98	8.59	0.20	0.33	2.28	0.30	0.00	0.28
7	Textile	0.45	0.32	0.01	0.01	0.09	0.01	0.00	0.01
8	Apparel	11.69	8.38	0.19	0.33	2.23	0.30	0.00	0.27
9	Lumber	2.32	1.66	0.04	0.06	0.44	0.06	0.00	0.05
10	Paper	6.07	4.35	0.10	0.17	1.16	0.15	0.00	0.14
11	Refining & coal	144.79	103.76	2.36	4.04	27.58	3.66	0.02	3.37
12	Chemicals	11.14	7.98	0.18	0.31	2.12	0.28	0.00	0.26
13	Nonmetallic min.	7.66	5.49	0.13	0.21	1.46	0.19	0.00	0.18
14	Primary metals	9.89	7.09	0.16	0.28	1.88	0.25	0.00	0.23
15	Fabricated metal	14.41	10.33	0.24	0.40	2.75	0.36	0.00	0.33
16	Machinery	36.87	26.42	0.60	1.03	7.02	0.93	0.00	0.86
17	Transportation eq	45.41	32.54	0.74	1.27	8.65	1.15	0.01	1.06
18	Electrical mach.	175.71	125.92	2.87	4.91	33.47	4.44	0.02	4.08
19	Electronics	2.69	1.93	0.04	0.08	0.51	0.07	0.00	0.06
20	Instruments	56.84	40.73	0.93	1.59	10.83	1.44	0.01	1.32
21	Other manuf.	3.99	2.86	0.07	0.11	0.76	0.10	0.00	0.09
22	Electricity	100.30	71.88	1.64	2.80	19.11	2.54	0.01	2.33
23	Gas utilities	8.62	0.00	8.62	0.00	0.00	0.00	0.00	0.00
24	Construction	1.35	0.96	0.02	0.04	0.26	0.03	0.00	0.03
25	Transportation	38.89	27.87	0.64	1.09	7.41	0.98	0.00	0.90
26	Communication	15.89	11.39	0.26	0.44	3.03	0.40	0.00	0.37
27	Trade	36.88	26.43	0.60	1.03	7.02	0.93	0.00	0.86
28	Hotel & rest.	7.70	5.52	0.13	0.22	1.47	0.19	0.00	0.18
29	Finance	115.83	83.01	1.89	3.23	22.06	2.93	0.01	2.69
30	Real Estate	1.56	1.12	0.03	0.04	0.30	0.04	0.00	0.04
31	Business svcs	35.04	25.11	0.57	0.98	6.67	0.89	0.00	0.81
32	Services	47.70	34.18	0.78	1.33	9.09	1.21	0.01	1.11
33	Public admin.	0.41	0.29	0.01	0.01	0.08	0.01	0.00	0.01
	Labor	120.23	86.16	1.96	3.36	22.90	3.04	0.01	2.79
	Capital	229.07	164.15	3.74	6.40	43.63	5.79	0.03	5.32
	Land	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Taxes	79.70	57.11	1.30	2.23	15.18	2.02	0.01	1.85
	Gross output	2121.3	1673.6	55.44	38.46	262.37	34.83	0.17	56.39

In order to compare this disaggregation with the other sources of data, we compute the costs shares implied by this input-output data for coal and hydro (the predominant sources of electricity in 2010), and report them in Table B6. The cost shares are given for fuels, other non-fuel intermediate inputs, labor and capital costs in order to compare them with the categories in the IEA (2010) levelized cost calculations. In the IO tables, the finance row contains a large entry which we interpret to include interest margins on loans. When we compute the "capital cost share," we include both the value added row and the finance row of the Use column in order to be closer to the accounting concepts in IEA (2010). Similarly, the fuel cost share is the sum of the coal row (in factory gate prices) and the trade and transportation margins in order to be consistent with the accounting concepts. The IEA estimated costs for selected technologies were given in Table B2c, and we also report in Table B6 the cost shares averaged over all the coal technologies given in IEA (2010). The average over all the hydro technologies is also given.

Table B6. Input cost structure for generation; input-output table versus IEA (2010).

	Fuel	Other intermediates	Labor	Capital (inc. Finance)
Coal power generation				
Table B5 cost shares	0.446	0.353	0.053	0.148
IEA (2010) costs	0.768	0.047	0.007	0.177
Hydro power				
Table B5 cost shares	0.000	0.657	0.093	0.250
IEA (2010) costs	0.000	0.206	0.032	0.762

We can see that these cost shares are very different; for coal generation, the IEA (2010) projections allocates 76.8% to fuel and 17.7% to capital compared with the input-output table allocation of 44.6% for fuel, 14.8% to capital and 35.3% to non-fuel intermediates. These differences may be due to:

(a) distinction between average and marginal fuel costs (some coal input is allocated at the controlled price which is much lower than the market price, the IEA calculations are based on the market price);

(b) differences in the cost of capital assumptions (the IEA likely assumes a long run cost of capital in a deregulated capital market, the actual profits in 2010 that is embodied in the National Accounts may be much lower than such a long-run rate of return given that the feed-in tariffs are controlled by the government);

(c) size and vintage of the coal units (the IEA estimates are for new large plants to be constructed now whereas the current stock includes many older and smaller units, the maintenance costs may be quite different for the older units, the old plants may be allowed less generous tariffs);

(d) different coverage of enterprises included in the electricity and heat sector (the National Accounts may include enterprises that are not simple generators or distributors).

Given these distinctions we regard the 2010 SAM values as the correct ones to represent the base year cost structures, and use the IEA (2010) cost shares to represent future cost structures. That is, in our projections of the share parameter in the cost functions (or production functions), we will begin with the estimates in Table B4 and B5 and then gradually trend them towards the cost shares in the IEA rows of Table B6.

B.2 Projections in the base case

The exogenous drivers of economic growth are this model are the demographics (population and working-age population), saving rates, and total factor productivity growth as described in Appendix A. The future structure of the economy is affected by projected consumer preferences, biases in technical change and world commodity prices; production parameters are based on US input-output tables and consumption parameters are estimated using consumer expenditure surveys. This appendix focuses on the projection of the electricity sector which is treated in a distinct manner compared to the other production industries.

As explained in the Appendix A, we regard the investment in the electricity sector as being externally determined by the Plan. There is the detailed 5-year plans and also long-term targets; in the case of electricity generation there are targets for nuclear capacity, wind and solar capacities. IEA (2014) contains projections of China's energy use, including projections of various electricity generation technologies, based on their reading of these plans and their projections of economic growth.

The IEA (2014, Table 1.1) uses the GDP projections from the IMF and these are given in Table B7. These are very close to our GDP projections (somewhat slower than Cao and Ho 2014), with about 7% in the current decade and slowing to 5% during 2020-30.

IEA (2014) projects three energy scenarios: "Current Policies" scenario is based on "policies that were enacted as of mid-2014", "New Policies" is based on "the continuation of existing policies and measures as well as the implementation (albeit cautiously) of policy proposals, even if they are yet to be formally adopted", while the "450 Scenario" is intended to illustrate "what it would take to achieve an energy trajectory consistent with limiting the long-term increase in average global temperature to 2°C."[33]

We take the "Current Policies" projections of the generation capacities and power output to guide our base case projection of the composition of electricity output. The IEA (2014) report also gives the estimates of actual capacities in 2012. The Chinese data reported in the China Energy Yearbook (and China Statistical Yearbook) that are given in Table B1 are slightly different in that they only include sources that are connected to the grid. We first rebase the 2012 IEA figures to these official data for 2012, and adjust their projections. These rebased projections out to 2040 are plotted in Figure B1 and summarized in Table B7.

Total electricity output is projected to rise from 4,986 TWh in 2012 to 6,930 in 2020, and to 10,333 in 2030. These translate to growth rates of 5.2% per year (2012-20), 3.2% (2020-30) and 1.9% (2030-40). By 2040, with a projected population of 1,466 million, the annual per-capita production will be 8.50 MWh. For comparison, the U.S. net generation in 2010 was 13.3 MWh per capita and Japan's consumption was 8.34 MWh per capita.[34]

[33] IEA (2014) page 33.
[34] Electricity output is given in Table 7.1 of the *Monthly Energy Review* published by the US EIA; world consumption is given in the World Bank's *World Development Indicators*.

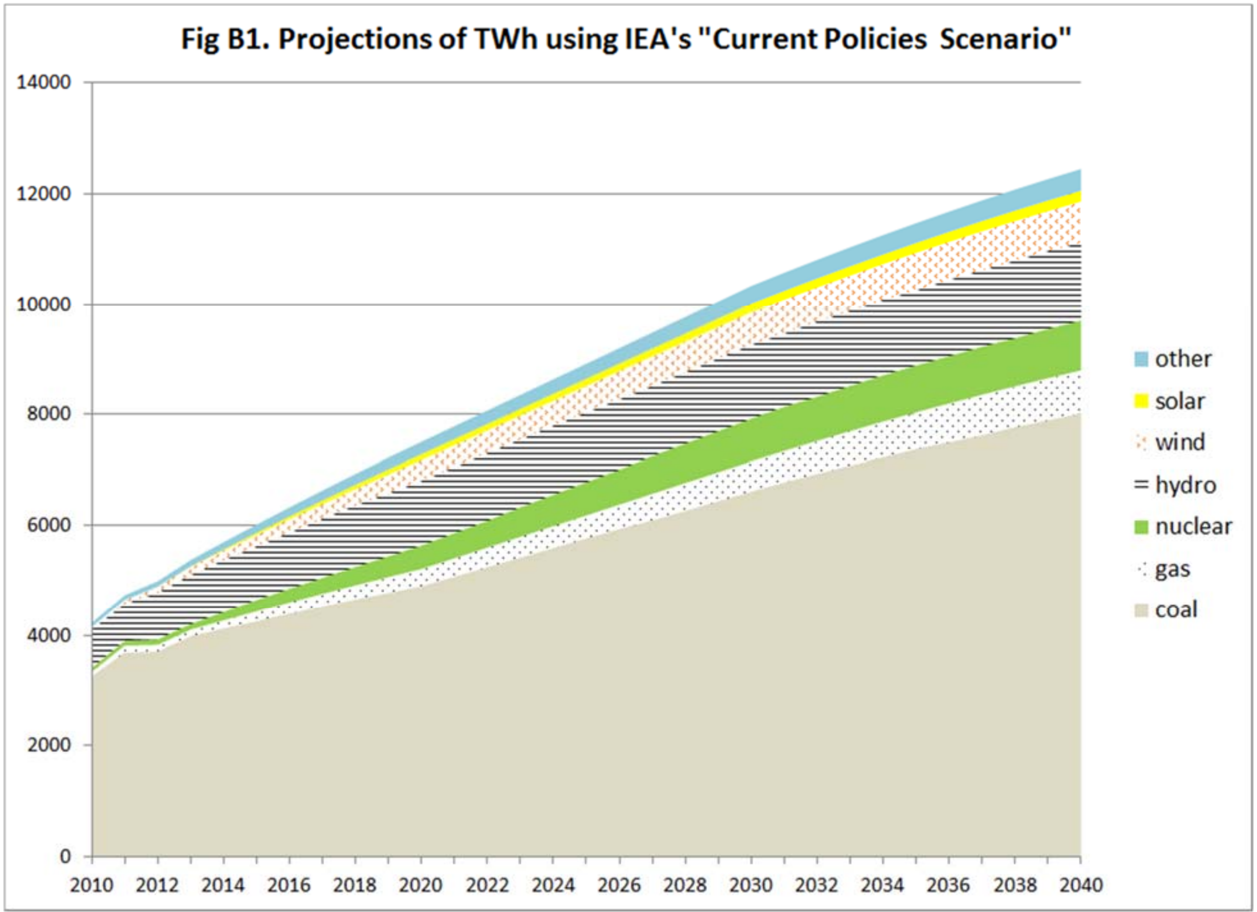


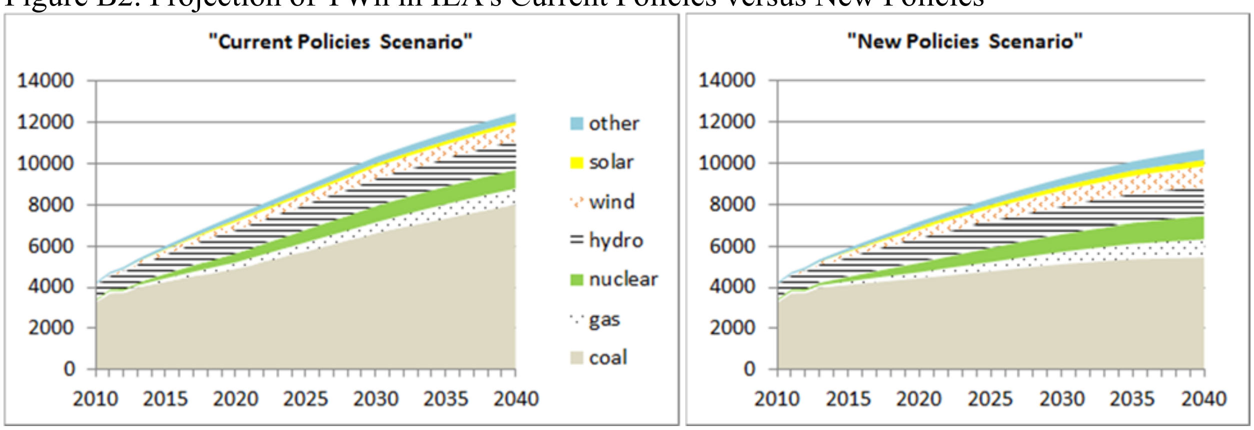
Table B7. Growth and energy projections (% per year).

	2012-20	2020-30	2030-40
Base Case (IEA "Current Policies")			
GDP (Cao & Ho 2014)	7.0	5.0	3.6
GDP (IEA vis IMF)	6.9	5.3	3.2
Primary energy (IEA)	2.9	1.9	0.89
Electricity (IEA)	5.2	3.2	1.9
Elect: Coal	3.5	3.0	1.9
Elect: Gas	14.6	6.2	3.9
Non-fossil electricity	9.3	3.4	1.4
Policy (IEA "New Policies")			
Primary energy (IEA)	2.4	1.4	0.41
Electricity (IEA)	4.6	2.6	1.4
Elect: Coal	2.2	1.4	0.6
Elect: Gas	14.9	7.3	4.0
Non-fossil electricity	10.1	3.9	2.1

In this Current Policies scenario (CPS) the coal share of total output falls from quickly 77.1% in 2010 to 67.3% in 2020 and then decline slowly to 64.1% in 2030, and remain at about 64% thereafter. In terms of growth rates, coal generation grows at 3.5% during 2012-20 compared to 5.2% for total electricity output. Wind and solar together rise from 1.2% of total output in 2010 to 5.5% in 2020, and then continue to rise to 7.3% in 2030.

In the New Policies scenario (NPS) a more aggressive conservation path is assumed, with an even bigger shift to renewables. Figure B2 put the two scenarios for power output in TWh side by side. In the New Policies scenario total output rises only to 9,274 TWh in 2030 compared to 10,333 in the CPS. The annual growth rates of total electricity output are only 4.6% (2012-20), 2.6% (2020-30) and 1.4% (2030-40) compared to 5.2%, 3.2% and 1.9%, respectively, in the CPS. The NPS projects more renewables and the coal share of output here is 61.9% in 2020 versus 67.3% in the CPS, and 55.3% in 2030 versus 64.1%. In terms of absolute output, the CPS has 6620 TWh of coal-generated power in 2030 compared to 5129 TWh in the New Policies scenario.

Figure B2. Projection of TWh in IEA's Current Policies versus New Policies



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