Report 310
April 2017

TSINGHUA - MIT
China Energy & Climate Project

The Future of Coal in China

Xiaohan Zhang, Niven Winchester, and Xiliang Zhang

MIT Joint Program on the Science and Policy of Global Change combines cutting-edge scientific research with independent policy analysis to provide a solid foundation for the public and private decisions needed to mitigate and adapt to unavoidable global environmental changes. Being data-driven, the Joint Program uses extensive Earth system and economic data and models to produce quantitative analysis and predictions of the risks of climate change and the challenges of limiting human influence on the environment—essential knowledge for the international dialogue toward a global response to climate change.

To this end, the Joint Program brings together an interdisciplinary group from two established MIT research centers: the **Center for Global Change Science (CGCS)** and the **Center for Energy and Environmental Policy Research (CEEPR)**. These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the program's work lies MIT's Integrated Global System Model. Through this integrated model, the program seeks to discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This reprint is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn and John M. Reilly,
Joint Program Co-Directors

MIT Joint Program on the Science and Policy of Global Change

Massachusetts Institute of Technology
77 Massachusetts Ave., E19-411
Cambridge MA 02139-4307 (USA)

T (617) 253-7492 **F** (617) 253-9845
globalchange@mit.edu
http://globalchange.mit.edu/

GLOBAL CHANGE

APRIL 2017

The Future of Coal in China

Xiaohan Zhang[1,2,3], Niven Winchester[1], and Xiliang Zhang[2]

Abstract: As the world's largest consumer of total primary energy and energy from coal, and the largest emitter of carbon dioxide (CO_2), China is now taking an active role in controlling CO_2 emissions. Given current coal use in China, and the urgent need to cut emissions, 'clean coal' technologies are regarded as a promising solution for China to meet its carbon reduction targets while still obtaining a considerable share of energy from coal. Using an economy-wide model, this paper evaluates the impact of two existing advanced coal technologies—coal upgrading and ultra-supercritical (USC) coal power generation—on economic, energy and emissions outcomes when a carbon price is used to meet China's CO_2 intensity target out to 2035. Additional deployment of USC coal power generation lowers the carbon price required to meet the CO_2 intensity target by more than 40% in the near term and by 25% in the longer term. It also increases total coal power generation and coal use. Increasing the share of coal that is upgraded leads to only a small decrease in the carbon price. As China's CO_2 intensity is set exogenously, additional deployment of the two technologies has a small impact on total CO_2 emissions.

---

[1] Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA, USA

[2] 3E Institute, Tsinghua University, Beijing, China

[3] Corresponding author. Email: xh-zhang13@mails.tsinghua.edu.cn

1. Introduction

China is the world's largest consumer of both total primary energy and energy from coal (BP, 2016) and is also the world's largest emitter of carbon dioxide (CO_2). Coal accounted for 66% of China's total primary energy consumption in 2014 (National Bureau of Statistics of China, 2015), is expected to account for 50% of the total primary energy consumption by 2030 (He, 2015), and will continue to be a major source of energy until at least 2050 (Chinese Academy of Engineering, 2011). As a carbon-intensive and widely used fossil fuel, coal was responsible for 75% of total CO_2 emissions from fossil fuel consumption in China in 2011 (Mao, 2014).

China is now taking an active role in controlling its carbon emissions by agreeing to peak its CO_2 emissions before 2030 (White House, 2014), and reducing its CO_2 intensity by 60–65% from the 2005 level by 2030 (NDRC, 2015). To contribute to these emission reductions, China has outlined several policies to control total coal consumption and promote cleaner coal use. These directives include limiting the contribution of coal to total energy consumption to a maximum of 65% in 2017 by China's Air Pollution Control Action Plan (State Council of the People's Republic of China, 2013), and capping China's annual coal use at 4.2 billion tons in 2020 (General Office of the State Council of PRC, 2014). In 2015, the National Energy Administration issued the Action Plan on Clean and Efficient Utilization of Coal (2015–2020), detailing plans on a set of clean coal utilization technologies (NEA, 2015). Given current coal use in China, and the urgent need to cut emissions, 'clean coal' technologies are regarded as a promising solution for China to meet its carbon reduction targets while still obtaining a considerable share of its energy from coal (Yue, 2012). Clean coal, such as ultra-supercritical (USC) combustion for power generation and coal upgrading, decrease CO_2 emissions from coal energy by improving the energy conversion efficiency of this resource and/or reducing transportation weight. This analysis evaluates the impact of these existing advanced coal technologies on economic, energy and emissions outcomes in China under a set of policy scenarios using an economy-wide model with energy sector detail. By including a detailed representation of coal technologies in an applied general equilibrium model this paper complements previous studies that estimate the economy-wide implications of climate policy in China (Li & Lin, 2013; Hübler *et al.*, 2014; Zhang *et al.*, 2015) and research focused on the coal sector (Yue, 2012; Hao *et al.*, 2015; Tang *et al.*, 2015; Yan *et al.*, 2016; Zhao *et al.*, 2017).

This article has four further sections. Section 2 discusses the USC and coal upgrading technologies evaluated in this paper. Section 3 outlines the modeling framework employed for the analysis, details how the USC and coal upgrading technologies are represented in the model, and outlines the scenarios implemented. Results are presented and discussed in Section 4. Section 5 concludes.

2. Advanced Coal Technologies

At present, China is facing choices about which coal preparation and conversion technologies should be installed to allow the country to meet its near-term air pollution and climate mitigation goals. This analysis is intended to inform these choices by considering several near-term coal technology options that will have important implications for the country's future carbon footprint. Specifically, we consider coal upgrading and USC combustion for power generation, which are already operating in China's energy system but have scope to expand (NEA, 2015). An important question for this numerical analysis is how these technologies will contribute to reductions in greenhouse gas (GHG) emissions and interact with other energy technologies under climate policies through 2030, the year by which policymakers have pledged to achieve peak CO_2 emissions in China.

Coal upgrading technologies refer to coal washing and other coal pre-treatment. Coal upgrading is an important procedure to increase coal utilization efficiency and reduce emissions by decreasing the sulfur and ash content in raw coal and enabling more complete chemical reaction. Coal upgrading will also reduce GHG emissions from coal transportation by removing non-combustible components and ultimately reducing load weight. The share of raw coal that is upgraded is more than 80% in developed countries while only 62% of coal was upgraded in China in 2014 (China Industry Information, 2015). This share is projected to be 70% in 2017 according to China's Air Pollution Control Action Plan (State Council of the People's Republic of China, 2013), and is planned to be above 80% in 2020 (NEA, MEP, MIIT, 2014).

USC combustion is an advanced coal power generation technology which has higher steam temperature and pressure and therefore a higher energy conversion efficiency than conventional coal power technologies. The average energy conversion efficiency of USC units is 48% while the average efficiency of supercritical units is 41%. Due to the rapid development of China's manufacturing industries and the implementation of the 'Replacing Small Units with Large Ones' policy (State Council of the People's Republic of China, 2007), thermal power plants in China are now more reliable and efficient than in previous decades. China has had significant success in advanced coal-fired power generation and energy efficiency development during the Eleventh Five-Year Plan period (2006–2010) and has become a leading country in supercritical and USC power generation technologies

The share of power plants with a capacity larger than 600 megawatts (MW) is now 36.8% and the average net coal consumption rate—defined as the average coal equivalent consumption for providing 1 kilowatt hour (kWh) of electricity by a thermal power plant—has decreased from 370 grams of coal equivalent (gce) per kWh in 2005 to 318 gce/kWh (Xie, 2014). China now has more 1000 MW units than any other nation and also has some of the most advanced coal plants with the lowest net coal consumption rate in the world (The Comprehensive Research Group for Energy Consulting and Research, 2015). For example, the Waigaoqiao 3 USC power generation units, in Shanghai, achieved a net coal consumption rate of 276.8 gce/kWh in 2013 (IEA Clean Coal Centre, 2014), compared to 292.5 gce/kWh and 286.1 gce/kWh for the most advance plants in, respectively, Japan and Denmark (Peng & Xu, 2014). New-build coal power plants in China are required to have a net coal consumption rate at or below 300 gce/kWh (General Office of the State Council of PRC, 2014), and an active research program continues to investigate more efficient options for USC power generation. The Waigaoqiao 3 plant has achieved a maximum lower heating value efficiency of 46.5% (Nicol, 2013)

Between 2010 and 2020, all new-build pulverized coal power generation plants with a generation capacity above 600 megawatt (MW) in China will be supercritical, and half of them will be USC. Consequently, supercritical units will account over 30% of the total power capacity by 2020, which will have a significant impact on the economic and environmental performances of China's power industry (Huang, 2008).

Several other coal-related technologies could interact with deployment pathways for coal upgrading and USC coal power generation, but are not considered in this report. For example, we do not consider end-of-pipe technologies that reduce pollutant emissions such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM). Also, we do not consider coal conversion technologies such as coal gasification. These technologies are not considered in this research as we wish to focus on proposed policies directed at reducing GHG emissions.

3. Modeling Framework

The analysis in this paper uses version 2 of the China-in-Global Energy Model (C-GEM) (Qi *et al.*, 2016). The C-GEM is a multi-regional, multi-sector, recursive dynamic computable general equilibrium model developed collaboratively by researchers at Tsinghua University and the Massachusetts Institute of Technology as part of the China Energy and Climate Project. The model is designed to simulate existing and proposed energy and climate polices in China and analyze their impact on the deployment of new energy technologies, inter-fuel competition, the environment, and the economy within a global context.

Version 2 of the C-GEM (C-GEM2) has a base year of 2011 compared to base year 2007 used in Version 1 of the model. C-GEM2 uses Version 9 of the Global Trade Analysis Project (GTAP) Database (Aguiar *et al.*, 2016) augmented to include a detailed representation of electricity generation (Peters, 2016) for input-output data for all regions and bilateral international trade data. The C-GEM2 divides the global economy into 19 regions and 21 sectors, as shown in **Table 1**. As the model is designed to evaluate climate and energy technologies, the model represents energy extraction and production in detail, including eight electricity generation technologies, and separately represents four energy-intensive manufacturing industries. The model is solved for 2011, 2015 and every five years through to 2035. In this study, as outlined in Section 3.1, coal upgrading and USC power generation technologies are added to the C-GEM2 for this study.

3.1 Coal Upgrading

In 2011, the base year for the C-GEM2, 53.0% of total coal used in China was upgraded (China Energy News, 2012). Decomposing the aggregate number, the share of upgraded coal in total coal used for electricity was 33.0%, and 81.2% of coal used by other industries was upgraded (China Energy News, 2012). In the C-GEM2, production and use of upgraded coal in the base year is captured by the underlying input-output (GTAP) data used to calibrate the model. Without disaggregation of coal types, the model will implicitly assume that upgraded and conventional will be continued to be used in the same proportions as in the base year (Charteris & Winchester, 2010). In this study, the share of coal that is upgraded in the model is allowed to increase by adding a specific production technology for additional upgraded coal.

The coal upgrading technology added to the C-GEM2 uses conventional coal and other inputs to produce upgraded coal. Upgraded coal is modeled as a perfect substitute for conventional coal, except that, due to the higher energy conversion efficiency of upgraded coal, CO_2 emissions per megajoule (MJ) of energy from upgraded coal are lower than those from conventional. Estimates of the costs for the coal upgrading technology are sourced from Guo (2010), who analyzed coal upgrading plants in Datong, Shanxi. According to this author, the cost of upgrading one ton of conventional coal, including coal and processing costs, is 253.8 Chinese Yuan (RMB). After reducing moisture and non-combustible matter, 0.75 tons of upgraded coal is produced from each ton of conventional coal, which has a selling price of 303.5 RMB per ton. Therefore, revenue from upgrading one ton of conventional coal is 227.6 (303.5×0.75) RMB, which re-

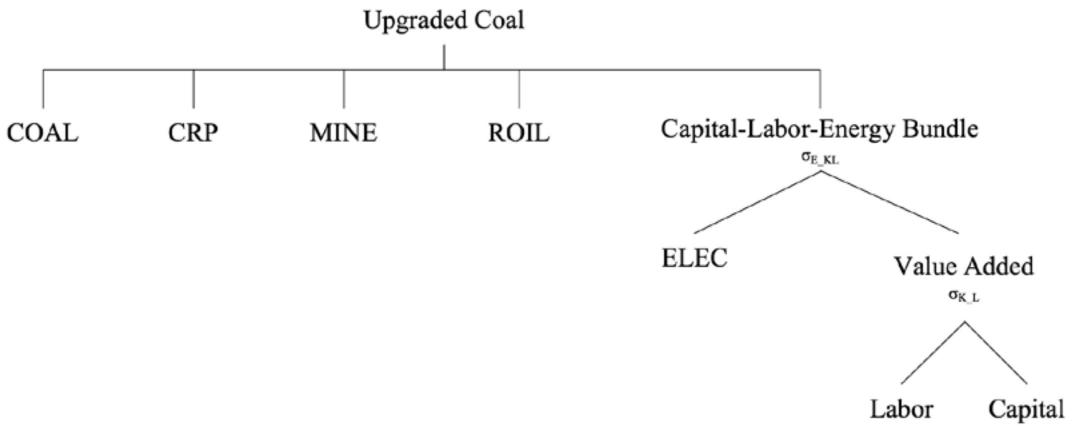

Figure 1. Coal upgrading technology production structure.

Table 1. Regions and sections in the C-GEM2.

Regions		
Developed Economies	**USA**	United States
	CAN	Canada
	JPN	Japan
	KOR	Korea
	DEA	Developed East Asia
	EUR	European Union
	ANZ	Australia-New Zealand
Developing Economies	**CHN**	China
	IND	India
	SEA	Southeast Asia
	REA	Rest of Asia
	MEX	Mexico
	MES	Middle East
	ZAF	South Africa
	AFR	Rest of Africa
	RUS	Russia
	ROE	Rest of Europe
	BRA	Brazil
	LAM	Rest of Latin America

Sectors		
-	**CROP**	Agricultural
Energy-intensive	**NMM**	Non-metallic mineral products
	I_S	Ferrous metals
	NFM	Non-ferrous metals
	CRP	Chemical materials and chemical products
Other Industry	**FOOD**	Food and tobacco
	MINE	Mining
	ELE	Electronic equipment
	TWL	Textile
	TEQ	Transport equipment
	OME	Other machinery
	OTHR	Other industries
-	**CNS**	Construction
Services	**TRAN**	Transportation
	SER	Commercial and public services
	DWE	Dwelling
Energy	**COAL**	Coal
	OIL	Oil
	GAS	Natural gas
	ROIL	Refined oil
	ELEC	Electricity
		Coal electricity
		Oil electricity
		Natural gas electricity
		Nuclear electricity
		Hydro electricity
		Wind electricity
		Solar electricity
		Electricity transmission

sults in an estimate of the cost markup for upgraded coal of 1.12 (253.8/227.6).

Based on estimates from Guo (2010) and Hui *et al.* (2014), the cost share of regular coal in the total cost of coal upgrading is 90.1%, meaning that the value of upgraded coal is 111% the value of the same amount of coal before upgrading, which is consistent with improvement of the energy conversion efficiency of coal by between 10% and 15% (China Energy News, 2013) as the value of coal reflects its heating value. Cost shares for other inputs are calculated using estimates from Couch (2002) and Laurila (2000). The production structure for upgraded coal is outlined in **Figure 1**. Although the coal upgrading production activity is not profitable at current costs, it may enter endogenously due to changes in economic conditions, such as incentives to reduce CO_2 emissions per MJ of energy from coal created by a carbon price.[1]

This study also augments the C-GEM2 model by including an option to control the minimum share of upgraded coal in total coal consumption using a permit system, which is sketched in **Figure 2**. In this system, permits are produced when coal is upgraded and are required as inputs for the production of regular coal. Specifically, each dollar of mined coal requires α permits and one permit is produced for each dollar of coal that is upgraded. Permits are also produced when regular coal is used in electricity and other industries to account for coal upgraded in the base year, which continues as a fixed share of regular coal used by each sector as the model is solved through time. Consequently, 0.33 and 0.812 permits are produced for each dollar of regular coal used in, respectively, electricity and other industries. In the permit system, the value of α determines the share of upgraded coal in total coal use and is set exogenously in the scenarios described below. If the value of α is not set, the share of coal that is upgraded is determined endogenously in the model based on the economic incentives for upgrading coal.

3.2 Ultra-supercritical Power Generation

In this analysis, the Waigaoqiao 3 power plant described in Section 2 is used as a representative case for future USC power generation in China in the C-GEM2. This technology, and others in the model, also benefit from total factor productivity growth and autonomous energy efficiency improvements through time. The parametrization of USC power generation in the C-GEM2 draws on fuel costs share estimates for this technology and conventional coal power generation from Xie (2014) and cost estimates for other inputs from Lan, Liu, Chen *et al.*

---

[1] Specifically, as the input of 'raw' coal for the same amount of energy output is reduced when coal is upgraded, CO_2 per MJ of coal energy are reduced when coal is upgraded.

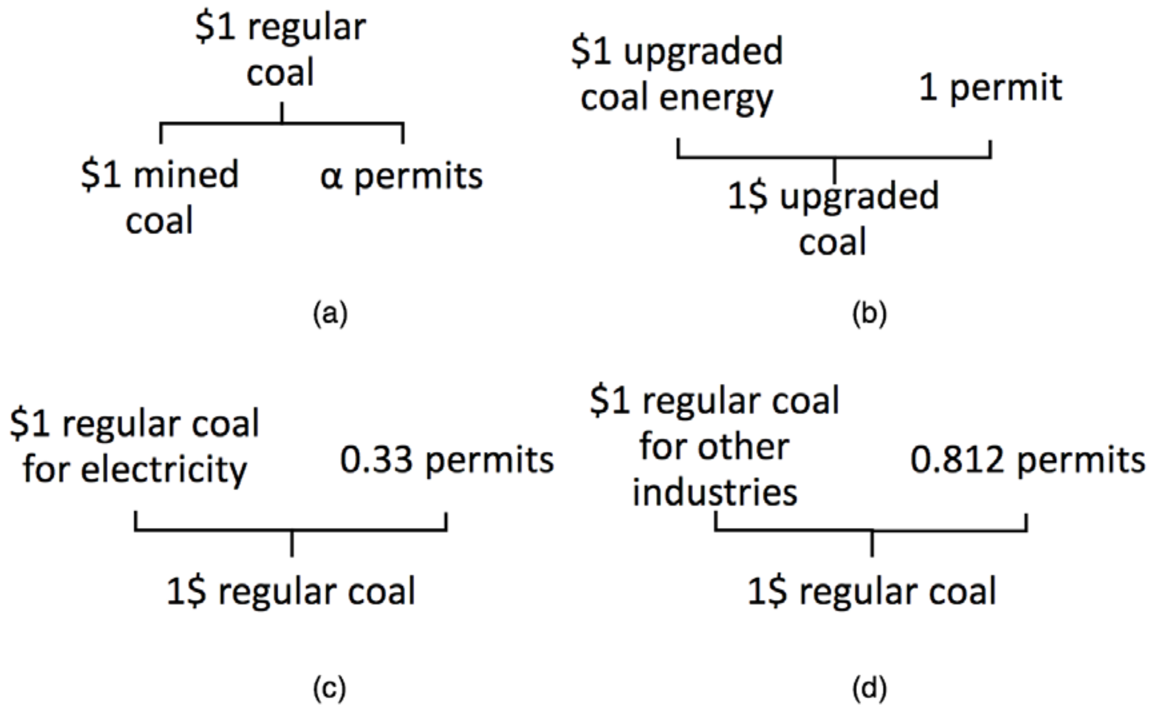

Figure 2. The permit system used to impose targets for the economy-wide share of coal that is upgraded. (a) Mined coal, (b) Additional upgraded coal, (c) Coal used in electricity, (d) Coal used in other industries.

(2013) and Enipedia (2015). These calculations result in a cost markup for USC power generation relative to conventional coal generation of 0.81, and cost share of 0.648 for coal, 0.223 for capital, and 0.129 for labor. A cost markup less than one for USC power generation indicates that costs for this technology are lower than those for subcritical and supercritical units and is consistent with estimates by Electric Power Planning & Engineering Institute (2015).

To prevent USC power generation expanding at a rate that is not technically feasible, following Morris *et al.* (2014), a technology-specific factor is included as input for the production of USC power generation. In this framework, the penetration of USC power generations is constrained by factors such as sunk costs for competing technologies, scarcity of technical resources needed for expansion, learning, and other barriers to expansion. However the expansion of advanced technologies is endogenous and depends on the cost share for the technology-specific factor, the elasticity of substitution between this factor and other inputs, and production in previous periods. Parameterization of technology specific factor for USC in the C-GEM2 follows that used for advanced electricity production in Morris *et al.* (2014). CO_2 emission from the technology is calculated based on coal input requirements per MWh and the same emission factor (2.63 tCO_2 per metric ton of coal) applied elsewhere in the model. In the C-GEM2, emissions from USC power generation are 115 tCO_2 per MWh and those from conventional coal power generation are 128 tCO_2 per MWh.

3.3 Scenarios

Five scenarios, which are summarized in **Table 2**, are implemented to investigate the role of coal upgrading and USC power generation in China under a carbon policy out to 2035. The scenarios differ with respect to whether or not carbon polices are represented and the treatment of coal upgrading and USC power generation in China. Regarding carbon policy, China plans to reduce its CO_2 intensity (CO_2 emissions divided by GDP) by 40–45% in 2020 and 60–65% in 2030 relative to its 2005 level (NDRC, 2015). During the Eleventh Five-Year, China reduced its CO_2 intensity, relative to 2005 by 21% in 2010 and the Twelfth Five Year Plan reduced China's CO_2

Table 2. Scenario description.

Scenario	Carbon intensity target	Coal upgrading	USC power generation
NoCarbonPolicy (NCP)	No	Endogenous	Endogenous
CarbonPolicy (CP)	Yes	Endogenous	Endogenous
CarbonPolicy-FIX (CP-FIX)	Yes	Fixed at the 2011 level	Fixed at the 2011 Level
CarbonPolicy-fixCU (CP-fixCU)	Yes	Fixed at the 2011 level	Endogenous
CarbonPolicy-CU (CP-CU)	Yes	Target in each year	Endogenous

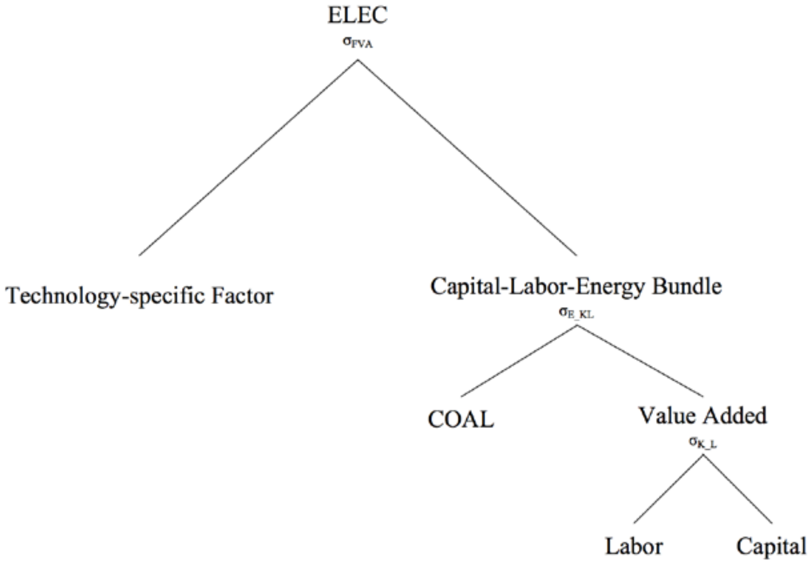

Figure 3. The production structure for USC coal power generation added to the C-GEM2.

intensity by 17% between 2011 and 2015 (Zhang *et al.*, 2015). Based on these figures, a 3.45% annual CO_2 intensity reduction rate from 2016 would allow China to achieve a 45% CO_2 intensity reduction in 2020 from the 2005 level, and annual reductions in CO_2 intensity of between 3.24% and 4.10% from 2021 to 2030 are needed to reach China's 2030 intensity target. In the carbon policy scenarios, a 17% CO_2 intensity reduction is imposed between 2011 and 2015, and a 4% annual CO_2 intensity reduction is simulated from 2016 to 2035. The carbon intensity targets are achieved using a price on CO_2 from fossil fuel combustion in the following sectors: refined oil (ROIL), electricity (ELEC), non-metallic mineral products (NMM), ferrous metals (I_S), non-ferrous metals (NFM), chemical materials and chemical products (CRP), transportation (TRAN), and other industries (OTHR). These are sectors that are most likely to be included in China's national carbon market.

In the first scenario (*NoCarbonPolicy*), there is no carbon price and the two clean coal technologies under consideration operate endogenously. The remaining scenarios simulate the CO_2 intensity targets noted above under alternative assumptions regarding the deployment of clean coal technologies. Both coal upgrading and USC power generation operate endogenously in the second (*CarbonPolicy*) scenario. To identify the combined role of the two advanced coal technologies, the share of coal that is upgraded and the share of USC coal power generation in total power generation are fixed at their current levels in the third (*CarbonPolicy-FIX*) scenario.[2] In the fourth scenario (*CarbonPolicy-fixCU*), to assist identification of the impact of each clean coal technology, the share of coal that is upgraded is fixed at its current level but USC coal operates endogenously. The final scenario (*CarbonPolicy-CU*) imposes year-specific minimum limits on the share of coal that is upgraded, as set out in policy documents (State Council of the People's Republic of China, 2013; NEA, MEP, MIIT, 2014) and USC power generation operates endogenously. The policy-mandated minimum share of total coal use that must be upgraded is 65% in 2015 and 80% from 2020 to 2035.

4. Results

A summary of results for China in 2035 is presented in **Table 3** and additional results are presented in **Tables 4 and 5** and **Figures 4 to 8**. The paper first compares the *NoCarbonPolicy* and *CarbonPolicy* scenarios to assess the impact of the CO_2-intensity target, and then discusses the remaining three scenarios to evaluate the contribu-

Table 3. Summary of results in 2035.

	No Policy	Carbon Policy	Carbon Policy-FIX	Carbon Policy-fixCU	Carbon Policy-CU
GDP (*billion 2011$*)	26,978	26,824	26,716	26,810	26,827
CO_2 emissions (*mmt*)	15,801	12,066	12,018	12,060	12,067
CO_2 price *2011$/t$CO_2$*	0.00	18.74	27.18	20.55	18.40
Total coal use *(mtce)*	4,550	3,054	2,889	3,064	3,052
Upgraded coal					
energy content *(mtce)*	2,426	2,320	1,537	1,632	2,446
share / total coal	53%	76%	53%	53%	80%
Total electricity generation *(TWh)*	12,630	9,517	8,220	9,376	9,553
Total electricity from coal *(TWh)*	7,795	3,416	1,734	3,249	3,459
USC power					
TWh	2,379	1,527	200	1,653	1,401
share / coal electricity	31%	45%	12%	51%	40%
share / total electricity	19%	16%	2%	18%	15%

---

[2] The share of coal that is upgraded and the share of USC power generation in total power generation is held fixed by making the technologies for additional coal upgrading and new USC power generation unavailable.

tions of coal upgrading and USC power generation to reducing emissions under the CO_2 intensity target.

4.1 Impact of CO_2-intensity Target: The *NoCarbonPolicy* & *CarbonPolicy* Scenarios

In the *NoCarbonPolicy* scenario, CO_2 emissions in China rise from 8,748 in 2011 to 15,801 million metric tons by 2035, an 80.6% increase relative to 2011 (**Figure 4**). This rise in emissions is driven by increases in GDP, which ultimately increase the demand for energy and fossil fuels. Coal use reaches 4,550 million (metric) tons of coal equivalent (mtce) by 2035 (**Figure 5**), which represents a 68.8% increase relative to 2011. As there are additional costs of increasing the share of coal that is upgraded, with the absence of policy incentives the share of upgraded coal in total coal use remain constant at 53% (**Figure 7**). Electricity from coal increases by 113.6% between 2011 and 2035 and the share of USC power in total power from coal reaches 31% by 2035 (**Figure 8**).

In the *CarbonPolicy* scenario, CO_2 emissions peak in 2030 and in 2035 are 23.6% lower than emissions in the *NoCarbonPolicy* scenario in that year, but still increase relative to emissions in 2011 (**Figure 4**). The carbon price nec-

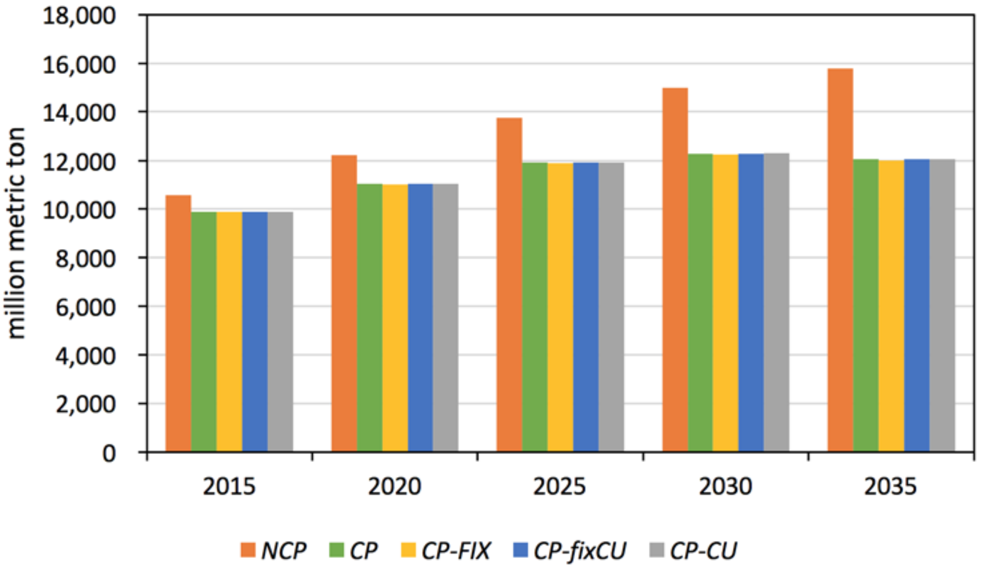

Figure 4. Projected CO_2 emissions of China from 2015 to 2035.

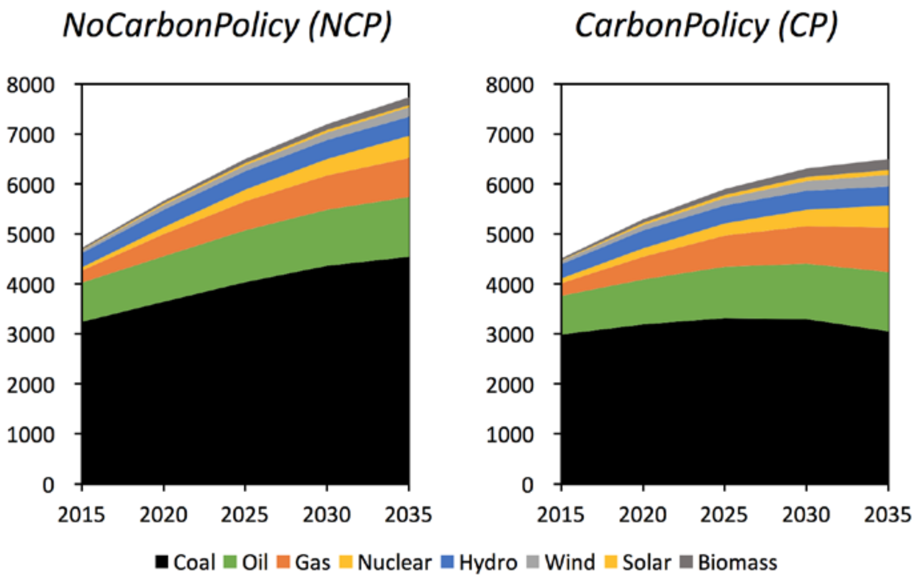

Figure 5. Primary energy consumption (mtce) in China from 2015 to 2035 in the *NoCarbonPolicy* and *CarbonPolicy* scenario.

Note: Biomass primary energy includes energy from biofuels and biomass electricity.

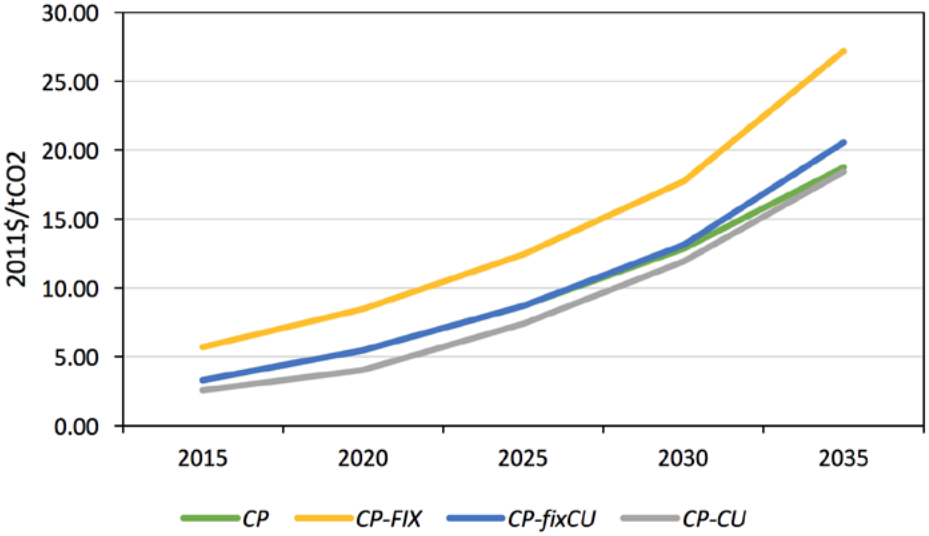

Figure 6. The Carbon price in China from 2015 to 2035.

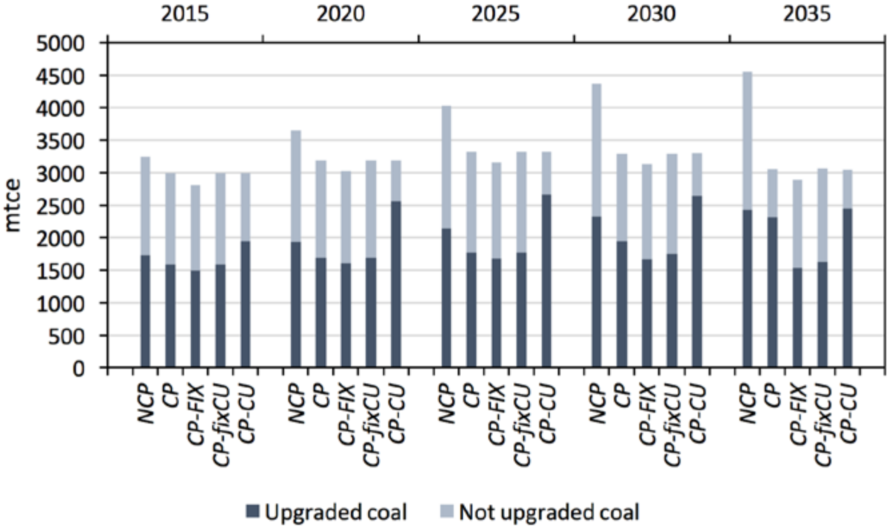

Figure 7. Upgraded coal in total coal consumption in China from 2015 to 2035.

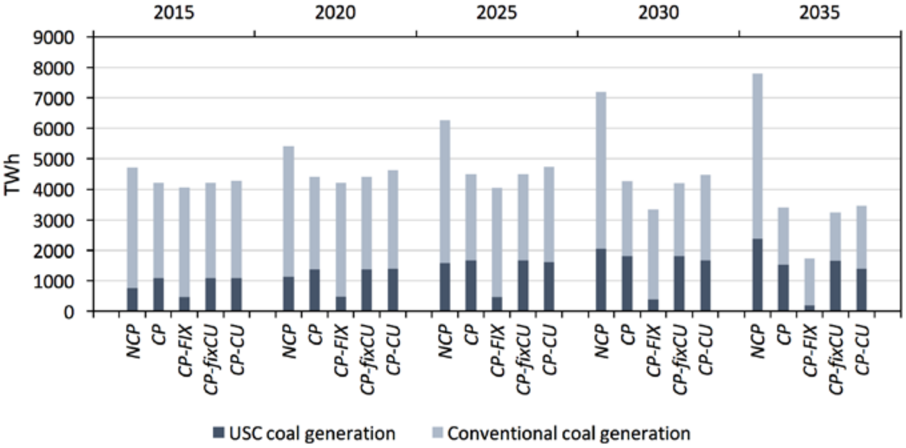

Figure 8. Advanced coal power generation in total coal power generation in China from 2015 to 2035.

Table 4. Share of upgraded coal in total coal use.

	2015	2020	2025	2030	2035
NoCarbonPolicy	53%	53%	53%	53%	53%
CarbonPolicy	53%	53%	53%	59%	76%
CarbonPolicy-FIX	53%	53%	53%	53%	53%
CarbonPolicy-fixCU	53%	53%	53%	53%	53%
CarbonPolicy-CU	65%	80%	80%	80%	80%

Table 5. Share of advanced coal electricity generation in total coal electricity generation.

	2015	2020	2025	2030	2035
NoCarbonPolicy	16%	21%	25%	29%	31%
CarbonPolicy	26%	31%	37%	42%	45%
CarbonPolicy-FIX	12%	12%	12%	12%	12%
CarbonPolicy-fixCU	26%	31%	37%	43%	51%
CarbonPolicy-CU	25%	30%	34%	37%	40%

essary to impose the CO_2 intensity target is, in 2011 dollars, \$3.27 per metric ton of CO_2 (tCO_2) in 2015 and rises to \$18.74tCO_2 by 2035 (**Figure 6**). The carbon price reduces demand for energy and in 2035 coal use is 32.9% lower than in the *NoCarbonPolicy* scenario. These estimates are in line with those from Climate Action Tracker (2016), Sha *et al.* (2015) and Cao *et al.* (2016). From 2030 onward, additional coal upgrading becomes profitable and the share of coal that is upgraded increases to 59% in 2030 and to 76% in 2035, but due to falling coal demand less coal is upgraded in 2035 than in the *NoCarbonPolicy* scenario (**Table 4** and **Figure 7**). Similarly, relative to the *NoCarbonPolicy* scenario, the carbon price decreases electricity from coal (by 56.2% in 2035), so even though there is a greater share of USC power generation in total coal power generation, the amount of electricity from USC generation falls.

4.2 Impact of Clean Coal Technologies: The *CarbonPolicy-FIX, CarbonPolicy-fixCU* and *CarbonPolicy-CU* Scenarios

The three remaining scenarios include the same CO_2-intensity target as in the *CarbonPolicy* scenario, so emissions in these scenarios are similar **(Figure 4**), with the small differences across scenarios resulting from changes in GDP due to constraints on coal upgrading and/or USC power generation. In the *CarbonPolicy-FIX* scenario, constraints on both coal upgrading and USC power generation mean that a higher carbon price is needed to achieve the CO_2 intensity target (**Figure 6**). Specifically, the carbon price in the *CarbonPolicy-FIX* scenario is \$5.71tCO_2 in 2015 and \$27.18tCO_2 in 2035, a 45.0% increase relative to the 2035 carbon price in the *CarbonPolicy* scenario. The constraints on clean coal technologies decrease coal use relative to when these technologies are unconstrained. In 2035, relative to the *CarbonPolicy* scenario, coal consumption is 5.4% lower, which is driven by a decrease in electricity generation from coal of 49.2% (**Figure 8**).

Relaxing the constraint on USC power generation in the *CarbonPolicy-fixCU* scenario results in lower carbon prices than in the *CarbonPolicy-FIX* scenario. Specifically, carbon prices in this scenario are \$3.27/tCO_2 in 2015 (42.7% lower relative to the *CarbonPolicy-FIX* scenario) and \$20.55/tCO_2 in 2035 (24.4% lower relative to the *CarbonPolicy-FIX* scenario). In the *CarbonPolicy-fixCU* scenario, there are also increases in total coal electricity generation (87.4% higher in 2035) and total coal use (6.0% higher in 2035). The main driver of these increases is increased USC coal power generation, which accounts for 51% of total coal power generation in 2035 (compared to 12% in the *CarbonPolicy-FIX* scenario).

Comparing results from the *CarbonPolicy* scenario—where both coal upgrading and USC power generation are unconstrained—to those from the *CarbonPolicy-FIX* and *CarbonPolicy-fixCU* scenario facilitates evaluation of the individual impacts of each technology under climate policy. Relatively similar carbon prices in the *CarbonPolicy* (\$18.74/tCO_2 in 2035) and *CarbonPolicy-fixCU* scenario (\$20.55/tCO_2 in 2035) compared to carbon prices in the *CarbonPolicy-FIX* scenario (\$27.18/tCO_2 in 2035) indicate that USC power generation plays a much larger role in mitigating upward pressure on the carbon price than coal upgrading.

Similarly, total electricity generation in the *CarbonPolicy* (9,517 TWh in 2035) and *CarbonPolicy-fixCU* scenario (9,376 TWh in 2035) are relatively close compared to total electricity generation in the *CarbonPolicy-FIX* scenario (8,220 TWh in 2035). These differences are driven by differences in total electricity generation from coal across the scenarios (see **Figure 8**). Total coal use follows a comparable pattern and is similar in the *CarbonPolicy* (3,054 mtce in 2035) and *CarbonPolicy-fixCU* (3,064 mtce in 2035) scenarios, but the constraint on USC power generation in the *CarbonPolicy-FIX* scenario significantly reduces total coal use (to 2,889 mtce in 2035). These results indicate that, as USC coal power generation offers a lower-emissions option for producing electricity from coal, constraining USC power generation will result in a significant decrease in coal electricity generation and total coal use.

In the *CarbonPolicy-CU* scenario, relative to the *CarbonPolicy* scenario, the policy-mandated increases in the share of coal that is upgraded reduces the carbon price by 22.3% in 2015 (to \$2.54/tCO_2) and by 1.8% in 2035 (\$18.40/tCO_2). The impact of the upgraded coal targets diminishes through time as, due to the rising carbon price, the share of coal that is upgraded in the *CarbonPolicy* scenario is closer to the levels mandated.

As upgraded coal has a higher energy conversion efficiency when used in conventional coal power generation than regular coal, relative to the *CarbonPolicy* scenario, conventional coal electricity generation increases (by 2.7% in 2015, 13.8% in 2030, and 9.0% in 2035), and USC coal power generation decreases (by 7.5% in 2030 and by 8.3% in 2035). As a result, compared to the *CarbonPolicy* scenario, the share of USC power generation in both coal power generation and total electricity generation decreases. For example, in 2035, the share of USC power in total coal generation decreases from 45% in the *CarbonPolicy* scenario to 40% in the *CarbonPolicy-CU* scenario, and the share of USC power generation in total electricity generation decreases from 16% and 15%. As the changes in power generation from conventional coal plants and USC coal plants have opposite effects on coal demand, total coal use is similar in the *CarbonPolicy* and *CarbonPolicy-CU* scenarios.

5. Conclusions

This paper analyzed coal consumption in China through 2035 using a global economy-wide model with energy sector detail. Coal consumption was considered in the context of China's Paris pledge to, relative to the 2005 level, reduce its CO_2 emissions divided to GDP by 60–65% by 2030 and extended out to 2035. The period-by-period CO_2 intensity targets were implemented using a carbon price on selected sectors and under alternative assumptions regarding the evolution of two existing advanced coal technologies: coal upgrading and USC power generation. Coal upgrading involves coal washing and other pre-treatments that increase coal utilization efficiency. USC power generation technology improves energy conversion efficiency relative to conventional coal power technologies by operating at a higher steam temperature and pressure. Both technologies reduce CO_2 emissions per usable MJ of energy derived from coal.

The results indicate that, when additional deployment of coal upgrading and USC power generation technologies is possible, a carbon price of \$3.27/tCO_2 in 2015 and rising to \$18.74tCO_2 by 2035 is needed to meet China's CO_2 intensity target. Although the carbon price reduces emissions relative to a 'business as usual' case and emissions peak in 2030, CO_2 emissions in 2035 increase by 38% relative to 2011 (compared to 81% in the absence of a carbon price). Similarly, coal consumption increases by 13% relative to 2011 under the carbon policy, down from 69% when there is no carbon price.

The analysis also revealed that additional deployment of coal upgrading and USC power generation can reduce the carbon price and alleviate the reduction in coal demand, with larger impacts due to the expansion of USC power generation than increases in the share of coal that is upgraded. For example, the 2035 carbon price is reduced from \$27.18/tCO_2 when the production shares of these technologies are fixed at their 2011 levels to \$18.74/tCO_2 when both coal technologies can expand, and was \$20.55/tCO_2 when only the share of USC power generation was able to expand. A proposed policy that sets a minimum share for upgraded coal had moderate near-term impacts but only small impacts in later years, as rising carbon prices induced a greater share of coal to be upgraded in the absence of the coal upgrading mandate.

Turing to climate change mitigation, additional deployment of coal upgrading and USC power generation resulted in a small increase in emissions relative to when output shares for these technologies were fixed at their current levels. For example, 2035 CO_2 emissions were 12,018 mmt when output shares were fixed and 12,066 mmt when additional deployment of the two coal technologies was possible. This is because, in each period, China's CO_2 intensity was set exogenously and allowing greater flexibility in meeting the CO_2 constraint resulted in a small increase in GDP.

Although the results show that advanced coal technologies can reduce the costs of meeting near- to medium- term emissions constraints, meeting more ambitious long-run targets will require replacing fossil fuel with low-carbon energy sources. In this connection, investing more capital in coal technologies now will increase the costs of moving away from fossil fuels in the future. It is, therefore, important to consider the net present value of climate policies over a long time horizon before concluding whether technologies that lower the costs of meeting near-term targets are advantageous for China. Another issue is that our results indicate that there is a Jevon's paradox: more efficient pathways for coal leads to more coal use. As China has a CO_2-inetsisty target, more coal use resulted in decreased use (and emissions) from other fossil fuels, but the increase in GDP when advanced coal technologies were available resulted in a small increase in total emissions. While these issues are complicated and beyond the scope of this paper, it is important to be aware that advanced coal technologies are not necessarily consistent with longer-term climate goals.

Acknowledgments

The authors thank John Reilly for helpful comments and suggestions, and gratefully acknowledge the financial support for this work provided by the MIT Joint Program on the Science and Policy of Global Change through a consortium of industrial sponsors and Federal grants. For a complete list of sponsors see http://globalchange.mit.edu/sponsors. The findings in this study are solely the opinions of the authors.

6. References

Aguiar, A., B. Narayanan and R. McDougall, 2016. An Overview of the GTAP 9 Data Base. *Journal of Global Economic Analysis* **1**(1): 181–208.

BP, 2016. *BP Statistical Review of World Energy*. London.

Cao, J., M.S. Ho & G.R. Timilsina, 2016. *Impacts of carbon pricing in reducing the carbon intensity of China's GDP*. World Bank Group.

Charteris, A. & N. Winchester, 2010. Dairy disaggregation and joint production in an economy-wide model. *Australian Journal of Agricultural and Resource Economics* **54**(4): 491–507.

China Energy News, 2012. *China's Coal Upgrading Share is Low*. (http://news.xinhuanet.com/energy/2012-06/27/c_123337877.htm).

China Energy News, 2013. *Coal Used Extensively in China*. (http://paper.people.com.cn/zgnyb/html/2013-02/18/content_1199542.htm).

China Industry Information, 2015. *Analysis on the Development Scale and Trend of China's Coal Washing Industry 2014-2015*. (http://www.chyxx.com/industry/201511/362750.html)

Chinese Academy of Engineering, 2011. *Research on the Energy Development Strategy of China in Mid- and Long-term (2030/2050)*. Beijing: Science Press.

Climate Action Tracker, 2016. *Climate Action Tracker's assessment on China*. (http://climateactiontracker.org/countries/china.html).

Couch, G.R., 2002. *Coal upgrading to reduce CO_2 emissions*. IEA Clean Coal Centre.

Electric Power Planning & Engineering Institute, 2012. *Review of conventional coal-fired power generation technologies in China*. Proceedings of 2012 Collaboration Network Annual Meeting of Clean and Efficient Coal-fired Power Generation Technology.

Enipedia, 2015. *Data collection China*. (http://enipedia.tudelft.nl/wiki/DatacollectionChina).

General Office of the State Council of PRC, 2014. *Notice on Issuing the Energy Development Strategy Action Plan (2014–2020)*. (http://www.gov.cn/zhengce/content/2014-11/19/content_9222.htm).

Guo, Y., 2010. Cost-benefit analysis of power coal upgrading. *Coal Preparation Technology*, 4: 61–64.

Hao, Y., Z.-Y. Zhang, H. Liao & Y.-M. Wei, 2015. China's farewell to coal: A forecast of coal consumption through 2020. *Energy Policy* **86**(November): 444–455.

He, J., 2015. Objectives and strategies for energy revolution in the context of tackling climate change. *Advances in Climate Change Research* **6**(2): 101–107.

Huang, Q., 2008. Clean and highly effective coal-fired power generation technology in China. *Huadian Technology* **3**: 002.

Hui, H., Zhu, F., Huang, Q., Wang, S., Shu, X., & Xu, X., 2014. Investigation and Technical Economic Analysis on China Thermal Coal Washing. *Electric Power*, 135–139.

Hübler, M., S. Voigt & A. Löschel, 2014. Designing an emissions trading scheme for China—An up-to-date climate policy assessment. *Energy Policy* **75**(December): 57–72.

IEA Clean Coal Centre, 2014. *Waigaoqiao Brochure*. (http://upgrading3.coalconferences.org/uploads/Waigaoqiao%20Brochure.pdf).

Lan, L., Q. Liu, Z. Chen, Q. He & X. Zhao, 2013. Is the Cost of Renewable Energy Higher Than Traditional Energy? — Comparison of the Cost between Wind Power and Heat Power in China Based on LCOE. *West Forum*, 23(3): 66–72.

Laurila, M.J., 2000. Best Practices in International Coal Preparation: Developing a Benchmark for Coal Preparation in India. *Proceedings Coal Preparation India, New Delhi*, 82–91.

Li, A. & B. Lin, 2013. Comparing climate policies to reduce carbon emissions in China. *Energy Policy* **60**(September): 667–674.

Mao, D., 2014. The influences of Coal-based primary energy structure on China. (http://dspace.xmu.edu.cn/handle/2288/82333)

Morris, J.F., J.M. Reilly & Y.-H.H. Chen, 2014. *Advanced Technologies in Energy-Economy Models for Climate Change Assessment*. Cambridge: Joint Program on the Science and Policy of Global Change **Report 272**, Massachusetts Institute of Technology.

National Bureau of Statistics of China, 2015. *China Statistical Abstract 2015*. Beijing: China Statistics Press.

NDRC, 2015. *Enhanced Actions on Climate Change: China's Intended Nationally Determined Contricutions*. (http://www4.unfccc.int/ndcregistry/PublishedDocuments/China%20First/China%27s%20First%20NDC%20Submission.pdf).

NEA, MEP, MIIT, 2014. *Suggestions on Promoting the Safe and Green Development and Clean and Efficient Utilization of Coal*. (http://zfxxgk.nea.gov.cn/auto85/201501/t20150112_1880.htm).*

NEA, 2015. *Notice on Issuing the Action Plan on Clean and Efficient Utilization of Coal (2015–2020) by NEA*. (http://zfxxgk.nea.gov.cn/auto85/201505/t20150505_1917.htm).*

Nicol, K., 2013. *Status of advanced ultra-supercritical pulverised coal technology*. London: IEA Clean Coal Centre.

Peng, Y. & Q. Xu, 2014. *With the world's highest efficiency Waigaoqiao 3 rewrites the definition for conventioanl coal power*. (http://www.cpnn.com.cn/zdzgtt/201406/t20140610_683457.html).

Peters, J.C., 2016. The GTAP-Power Data Base: Disaggregating the Electricity Sector in the GTAP Data Base. *Journal of Global Economic Analysis* **1**(1): 209–250.

Qi, T., N. Winchester, V.J. Karplus, D. Zhang & X. Zhang, 2016. An analysis of China's climate policy using the China-in-Global Energy Model. *Economic Modelling*, 52, 650–660.

Sha, F., J. Zou & L. Liu, 2015. *An Analysis of China's INDC*: China National Center for Climate Change Strategy and International Cooperation, Beijing, China, 12 pp.

State Council of the People's Republic of China, 2007. *Notice on accelerating the shutdown of small fire power plants by NDRC and the Energy Office*. (http://www.gov.cn/zwgk/2007-01/26/content_509911.htm).

State Council of the People's Republic of China, 2013. *Notice on Issuing the Air Pollution Control Plan by the State Council*. (http://www.gov.cn/zwgk/2013-09/12/content_2486773.htm).

Tang, X., S. Snowden, B.C. McLellan & M. Höök, 2015. Clean coal use in China: Challenges and policy implications. *Energy Policy* **87**(December): 517–523.

The Comprehensive Research Group for Energy Consulting and Research, 2015. Strategic Research on Clean, Efficient, Sustainable Exploitation and Utilization of Coal in China. *Engineering Sciences*.

White House, 2014. *U.S.-China Joint Announcement on Climate Change*. (https://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change).

Xie, K., 2014. *Strategic Research on Clean, Efficient, Sustainable Exploitation and Utilization of Coal in China*. Beijing: Science Press.

Yuan, J., Q. Lei, M. Xiong, J. Guo, & Z. Hu, 2016. The prospective of coal power in China: Will it reach a plateau in the coming decade? *Energy Policy* **98**, 495–504.

Yue, L., 2012. Dynamics of clean coal-fired power generation development in China. *Energy Policy* **51**(December): 138–142.

Zhang, X., V.J. Karplus and T. Qi, 2015. Carbon emissions in China: How far can new efforts bend the curve? *Energy Economics* **54**, 388–395.

Zhao, C., W. Zhang, Y. Wang, Q. Liu, J. Guo, M. Xiong, & J. Yuan, 2017. The economics of coal power generation in China. *Energy Policy* **105**, 1–9.

* *URL only accessible from China*

Joint Program Report Series - Recent Articles

For limited quantities, Joint Program Reports are available free of charge. Contact the Joint Program Office to order.
Complete list: http://globalchange.mit.edu/publications

310. The Future of Coal in China. *Zhang et al., Apr 2017*

309. Climate Stabilization at 2°C and Net Zero Carbon Emissions. *Sokolov et al., Mar 2017*

308. Transparency in the Paris Agreement. *Jacoby et al., Feb 2017*

307. Economic Projection with Non-homothetic Preferences: The Performance and Application of a CDE Demand System. *Chen, Dec 2016*

306. A Drought Indicator based on Ecosystem Responses to Water Availability: The Normalized Ecosystem Drought Index. *Chang et al., Nov 2016*

305. Is Current Irrigation Sustainable in the United States? An Integrated Assessment of Climate Change Impact on Water Resources and Irrigated Crop Yields. *Blanc et al., Nov 2016*

304. The Impact of Oil Prices on Bioenergy, Emissions and Land Use. *Winchester & Ledvina, Oct 2016*

303. Scaling Compliance with Coverage? Firm-level Performance in China's Industrial Energy Conservation Program. *Karplus et al., Oct 2016*

302. 21st Century Changes in U.S. Heavy Precipitation Frequency Based on Resolved Atmospheric Patterns. *Gao et al., Oct 2016*

301. Combining Price and Quantity Controls under Partitioned Environmental Regulation. *Abrell & Rausch, Jul 2016*

300. The Impact of Water Scarcity on Food, Bioenergy and Deforestation. *Winchester et al., Jul 2016*

299. The Impact of Coordinated Policies on Air Pollution Emissions from Road Transportation in China. *Kishimoto et al., Jun 2016*

298. Modeling Regional Carbon Dioxide Flux over California using the WRF-ACASA Coupled Model. *Xu et al., Jun 2016*

297. Electricity Investments under Technology Cost Uncertainty and Stochastic Technological Learning. *Morris et al., May 2016*

296. Statistical Emulators of Maize, Rice, Soybean and Wheat Yields from Global Gridded Crop Models. *Blanc, May 2016*

295. Are Land-use Emissions Scalable with Increasing Corn Ethanol Mandates in the United States? *Ejaz et al., Apr 2016*

294. The Future of Natural Gas in China: Effects of Pricing Reform and Climate Policy. *Zhang & Paltsev, Mar 2016*

293. Uncertainty in Future Agro-Climate Projections in the United States and Benefits of Greenhouse Gas Mitigation. *Monier et al., Mar 2016*

292. Costs of Climate Mitigation Policies. *Chen et al., Mar 2016*

291. Scenarios of Global Change: Integrated Assessment of Climate Impacts. *Paltsev et al., Feb 2016*

290. Modeling Uncertainty in Climate Change: A Multi-Model Comparison. *Gillingham et al., Dec 2015*

289. The Impact of Climate Policy on Carbon Capture and Storage Deployment in China. *Zhang et al., Dec 2015*

288. The Influence of Gas-to-Liquids and Natural Gas Production Technology Penetration on the Crude Oil-Natural Gas Price Relationship. *Ramberg et al., Dec 2015*

287. Impact of Canopy Representations on Regional Modeling of Evapotranspiration using the WRF-ACASA Coupled Model. *Xu et al., Dec 2015*

286. Launching a New Climate Regime. *Jacoby & Chen, Nov 2015*

285. US Major Crops' Uncertain Climate Change Risks and Greenhouse Gas Mitigation Benefits. *Sue Wing et al., Oct 2015*

284. Capturing Natural Resource Dynamics in Top-Down Energy-Economic Equilibrium Models. *Zhang et al., Oct 2015*

283. Global population growth, technology, and Malthusian constraints: A quantitative growth theoretic perspective. *Lanz et al., Oct 2015*

282. Natural Gas Pricing Reform in China: Getting Closer to a Market System? *Paltsev & Zhang, Jul 2015*

281. Impacts of CO_2 Mandates for New Cars in the European Union. *Paltsev et al., May 2015*

280. Water Body Temperature Model for Assessing Climate Change Impacts on Thermal Cooling. *Strzepek et al., May 2015*

279. Emulating maize yields from global gridded crop models using statistical estimates. *Blanc & Sultan, Mar 2015*

278. The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption. *Chen et al., Mar 2015*

277. Renewables Intermittency: Operational Limits and Implications for Long-Term Energy System Models. *Delarue & Morris, Mar 2015*

276. Specifying Parameters in Computable General Equilibrium Models using Optimal Fingerprint Detection Methods. *Koesler, Feb 2015*

275. The Impact of Advanced Biofuels on Aviation Emissions and Operations in the U.S. *Winchester et al., Feb 2015*

274. Modeling regional transportation demand in China and the impacts of a national carbon constraint. *Kishimoto et al., Jan 2015*
