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Carbon emissions in China: How far can new efforts bend the curve?

Xiliang Zhang[§*], Valerie J. Karplus[†‡], Tianyu Qi[§], Da Zhang[§‡], and Jiankun He[§]

Abstract

While China is on track to meet its global climate commitments through 2020, China's post-2020 CO_2 emissions trajectory is highly uncertain, with projections varying widely across studies. Over the past year, the Chinese government has announced new policy directives to deepen economic reform, protect the environment, and limit fossil energy use in China. To evaluate how new policy directives could affect energy and climate change outcomes, we simulate two levels of policy effort—a Continued Effort scenario that extends current policies beyond 2020 and an Accelerated Effort scenario that reflects newly announced policies—on the evolution of China's energy and economic system over the next several decades. Importantly, we find that both levels of policy effort would bend down the CO_2 emissions trajectory before 2050 without undermining economic development, although coal use and CO_2 emissions peak about 10 years earlier in the Accelerated Effort scenario.

Contents

1. INTRODUCTION

Recent shifts in internal policy suggest that China's policymakers are serious about transforming the country's energy system in ways that will reduce both energy-related CO_2 emissions and air pollution faster than previously expected. The Third Plenum of the Eighteenth Congress of the Chinese Communist Party, held in November 2013 in Beijing, established major new directions for reforming China's economic, political, and social system. Environmental protection took center stage at the Plenum as policymakers pledged to support slower but more sustainable economic growth, market-based approaches to pollution control, and new efforts to build an "ecological civilization" (*China Daily*, 2013a). To support these objectives, specific actions announced at the Plenum included liberalizing energy prices, taxing energy-intensive and highly polluting industries, and developing taxes or quotas to control emissions of CO_2 and other pollutants. The newly announced National Air Pollution Action Plan aims to reduce the share of coal in primary energy below 65% by 2017 by implementing higher resource taxes or caps on coal use (MEP, 2013). Delivered with an unprecedented sense of urgency and importance, the Chinese government's very recent energy and environmental policy announcements necessitate new analysis to understand their impact on China's energy system and CO_2 emissions trajectory.

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More aggressive action at home will inform China's domestic and international commitments to mitigate climate change. At the Copenhagen climate talks in 2009, China made a commitment to reduce the carbon intensity (CO_2 emission divided by GDP) by 40–45% in 2020, relative to 2005 levels, and to have at least 15% of primary energy produced from non-fossil energy sources by 2020 (non-fossil electricity is converted to primary energy equivalent using the average efficiency of a coal-fired power plant in China). China achieved a CO_2 intensity reduction of 21% over the Eleventh Five-Year Plan (2005–2010), and targets a further reduction of 17% over the Twelfth Five-Year Plan (2011–2015). If China can achieve a carbon intensity reduction of 3% per year during the Thirteenth Five-Year Plan (2016–2020), it will accomplish a carbon intensity reduction of approximately 44% from 2005 to 2020, well within the range of its Copenhagen CO_2 intensity reduction pledge. While China is on track to meet its Copenhagen targets (*China Daily*, 2013b), China's CO_2 emissions trajectory after 2020 is highly uncertain. Model projections of CO_2 emissions vary significantly, and are sensitive to assumptions about future economic growth, technology cost, and climate policy (Calvin *et al*., 2012; Paltsev *et al*., 2012).

2. SCENARIO ANALYSIS

To understand the sustained impact of the new measures proposed above on China's economy, energy system, and CO_2 emissions, we simulate two scenarios that represent different levels of policy effort using the China-in-Global Energy Model (C-GEM) (Qi *et al.*, 2014a) and compare them to a counterfactual (*No Policy*) scenario. The scenarios are described in **Table 1**. First, we model a *Continued Effort* (CE) scenario that maintains the pace set by China's existing CO_2 intensity reduction targets through 2050. Importantly, we find the current rate of reduction cannot be sustained by efficiency improvements that would naturally result from the turnover of capital equipment and baseline rates of technological progress adopted in our *No Policy* scenario. To maintain a CO_2 intensity reduction rate of approximately 3% per year (corresponding to an extension of the targeted reduction pace for the Thirteenth Five-Year Plan, 2016–2020), a carbon tax is introduced. The CE scenario also includes existing resource taxes (taxes on crude oil and natural gas at 5% of the base price, and a tax on coal of 4 CNY per ton).

The *Accelerated Effort* (AE) scenario includes additional policies consistent with government announcements made recently (in late 2013 and early 2014), including the National Air Pollution Action Plan and commitments to continue economic reform, accelerate deployment of solar and nuclear electricity, and develop environmental pollution markets. In the AE scenario, we model a carbon tax consistent with a more aggressive CO_2 reduction scenario (4% per year), in addition to higher resource taxes (*ad valorem* taxes on crude oil and natural gas at 8% and coal at 10%) (*Natural Gas Daily*, 2013).

Both scenarios include variants of existing policies to promote low carbon energy. Consistent with existing renewable electricity policy, both the CE and AE scenarios include a feed-in tariff (FIT) for wind, solar, and biomass electricity that is funded by a surcharge on the price of electricity. Surcharges are endogenously set to match current FIT levels (described in the Appendix). In both the CE and AE scenarios, nuclear targets of 40 GW by 2015 and 58 GW by

2020 are achieved. The AE scenario reflects a more aggressive assumption about deployment beyond 2020, relative to the CE scenario. We model nuclear power deployment rates as limited by government plans rather than technology cost, given that approvals and expansion are expected to closely follow state directives and nuclear electricity is currently cost competitive with existing conventional (coal) generation.

Table 1. Policy assumptions in each scenario.

Measures	No Policy	Continued Effort	Accelerated Effort
Carbon tax	No carbon tax	Carbon tax required to achieve CI reduction (~3% per year, \$26/ton in 2030 and \$58/ton in 2050)	Carbon tax rises to achieve CI reduction (~4% per year, \$38/ton in 2030 and \$115/ton in 2050)
Fossil resource tax	No fossil resource tax	*Crude oil/natural gas:* price + 5% *Coal:* 4 CNY/ton (~\$0.6/ton)	*Crude oil/natural gas:* price + 8% *Coal:* 10% of the price
Feed-in tariff (FIT) for wind, solar and biomass electricity	No FIT	Surcharge is applied to electricity prices to finance FIT	Surcharge is applied to electricity prices to finance FIT; scaling costs are lower than *Continued Effort* assumption
Hydro resource development	Only economically viable hydro resources are deployed with no policy constraint	Achieve the existing target of 350 GW in 2020 and slowly increase to 400 GW by 2050	Same as the *Continued Effort* assumption
Nuclear power development policy	No targets or measures to promote nuclear energy development	Achieves the existing target of 58 GW in 2020 and increases to 350 GW by 2050	Same as the *Continued Effort* assumption in 2020 and increases to 450 GW by 2050

We compare the CE and AE scenarios to a *No Policy* (NP) (counterfactual) scenario that assumes no energy or climate policies are implemented from 2010 onwards. All scenarios assume a gradually declining savings rate in China as the economy develops, consistent with historically observed trajectories for advanced economies and with the stated objectives of China's government policy. Scenarios also assume modest levels of ongoing energy efficiency improvement resulting from turnover and equipment upgrading over time (details and sensitivity analysis can be found in the Appendix in Sections A2, A3 and A4). In all scenarios, we assume that energy prices are determined by the market in future periods, representing a retreat from remaining controls on energy prices, specifically, prices for natural gas, gasoline, diesel, and electricity.

Total primary energy trajectories for the three scenarios, and the composition by energy type for the AE scenario, are all shown in **Figure 1**. **Figure 2** shows the corresponding CO_2 emissions trajectories. In the *No Policy* scenario, we find that while CO_2 emissions intensity continues to fall modestly, total emissions continue to rise through 2050. Rising CO_2 emissions are mainly due to continued reliance on China's domestic coal resources. While we do not explicitly assess economic damages due to either pollution or climate change, this level of coal use is widely recognized in China's policy circles as untenable without aggressive deployment of carbon capture and storage as well as pollution removal technology.

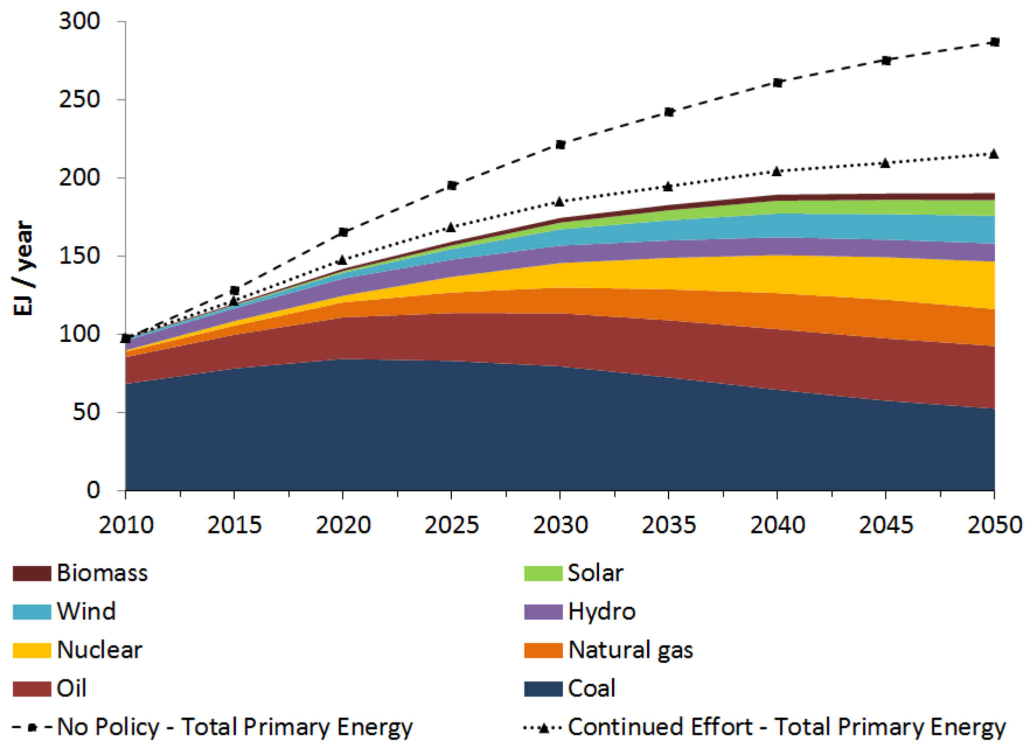

Figure 1. Energy demand in the *No Policy*, *Continued Effort*, and *Accelerated Effort* scenarios, with the primary energy mix shown for the *Accelerated Effort* scenario.

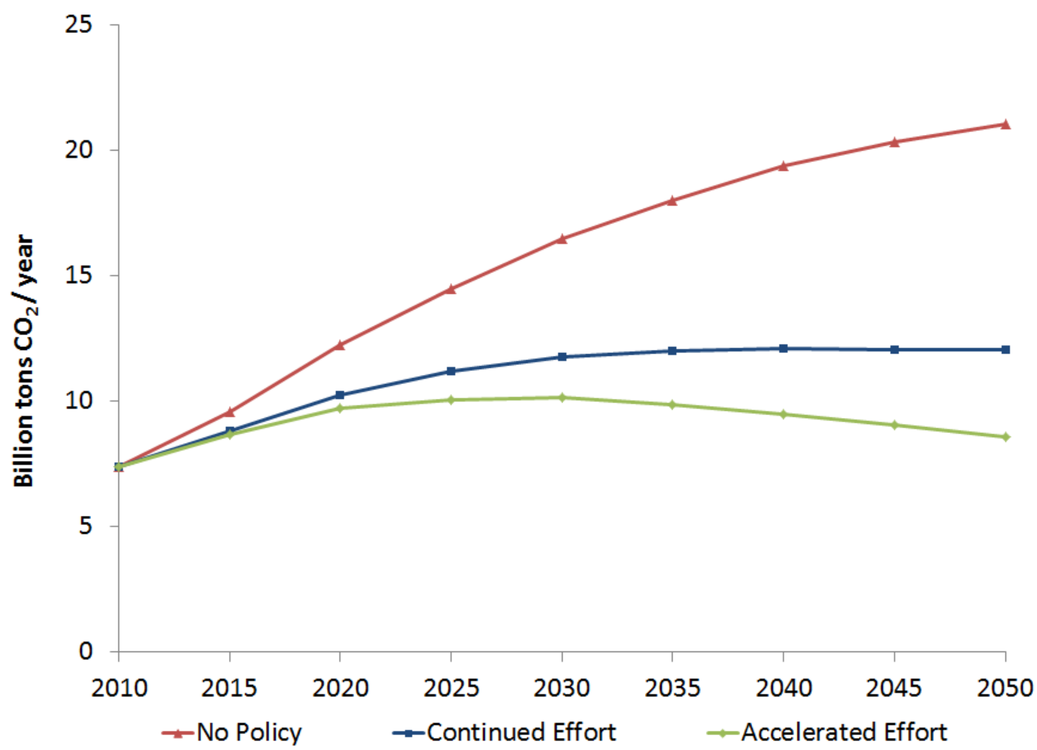

Figure 2. Total CO_2 emissions in China in the *No Policy*, *Continued Effort*, and *Accelerated Effort* scenarios.

Turning to the *Continued Effort* scenario, we find that if China's policymakers implement a CO_2 charge at the level needed to reduce CO_2 intensity by 3% per year beyond 2020 and incentivize an increase in the non-fossil share of primary energy, CO_2 emissions level off at around 12 bmt in the 2035 to 2045 time frame. The CO_2 charge that supports this goal reaches \$26/ton CO_2 in 2030 and \$58/ton CO_2 in 2050. Deployment of non-fossil energy is significant, with the share of non-fossil energy climbing from 15% in 2020 to around 26% through 2050. The oil share in total primary energy demand rises from 18% in 2010 to 21% in 2050 (17 EJ to 45 EJ), while coal continues to account for a significant share of primary energy demand (39% in 2050 or 85 EJ). Natural gas rises to 14% of total demand in 2050 (30 EJ). Nuclear power expands significantly to around 11% of total primary energy in 2050 (24 EJ).

The *Accelerated Effort* scenario simulates the impact of more aggressive measures relative to the CE scenario, including a higher CO_2 charge and a higher resource tax on coal. Under these assumptions, we find that carbon emissions level off in the 2025 to 2035 time frame at around 10 bmt. The carbon tax rises from \$38/ton CO_2 in 2030 to \$115/ton CO_2 in 2050, as low cost CO_2 reduction opportunities are exhausted and deeper reductions become ever more expensive to achieve.

Policies in the AE scenario result in significant deployment of non-fossil energy (which accounts for 39% of the primary energy mix by 2050), while natural gas plays a less important role relative to the existing effort scenario, approaching only 12% of the energy mix by 2050. Natural gas growth declines eventually because it is not carbon free, and is penalized by the CO_2 price. Oil as a share of primary energy use increases from 18% in 2010 to 21% in 2050, even as demand growth levels off by 2050 at about 40 EJ. The oil demand projection reflects the combined effect of ongoing improvements in technical efficiency across all transport modes, an increase in household demand for private vehicle ownership and travel, and stabilizing commercial transport demand as consumption overtakes fixed asset investment as an important driver of economic growth. The coal share, by contrast, drops dramatically, from 70% in 2010 to around 28% by 2050. Coal demand in 2050 is 23% lower than 2010, after reaching a peak in 2020 at 84 EJ. Coal is the least expensive fuel to displace, given the wide range of substitutes for its various uses—including wind, solar, nuclear, and hydro in the power sector, natural gas in district heating systems, and natural gas or biomass in direct industrial uses. The use of petroleum-based liquid fuels in transportation, on the other hand, has fewer (and currently, only more expensive) substitutes, such as bio-based fuels and electric vehicles. Wind, solar and biomass electricity also continue to grow through 2050 in both policy scenarios (**Figure 3**), with the share of total primary energy reaching 10% in 2030 and 17% in 2050 in the AE scenario, compared to 7% (2030) and 10% (2050) in the CE scenario.

Without further policy action, China's carbon emissions are projected to reach levels that threaten any global effort to stabilize climate change (see Figure 2). But with an immediate start and long-term targets, China will minimize the impact of emissions control costs on the country's economic development. By 2050, policy cost due to the additional measures rises to 1.2% of consumption in the CE scenario and to 2.6% of consumption in the AE scenario, relative

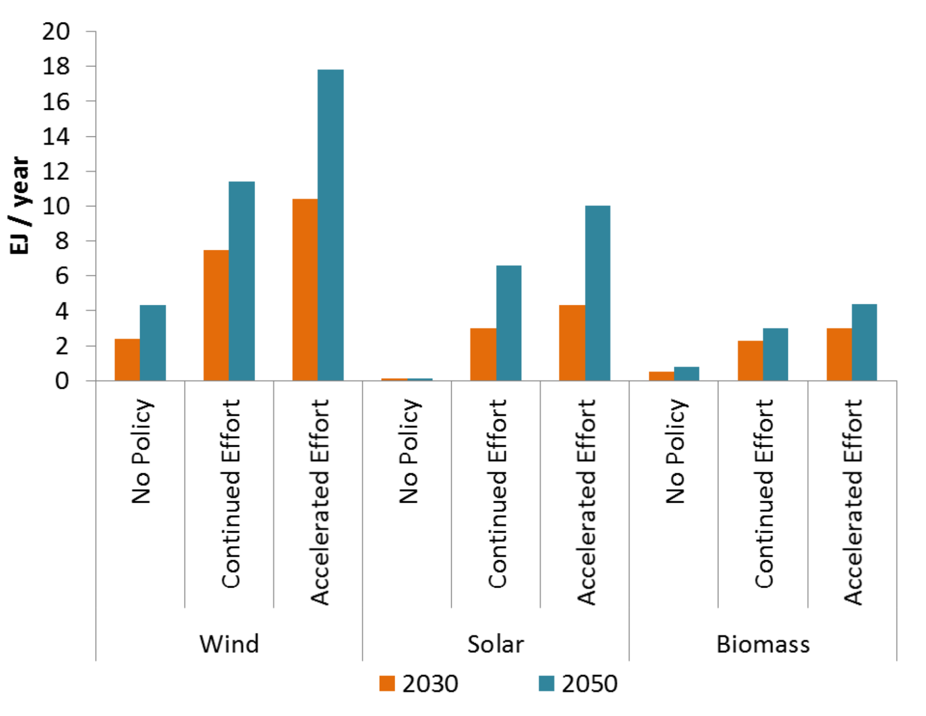

Figure 3. Deployment of renewable energy in 2030 and 2050 under the *No Policy*, *Continued Effort*, and *Accelerated Effort* scenarios.

to the *No Policy* scenario. These losses are relatively modest, and will be offset by reductions in the environmental and health costs of China's coal-intensive energy system (which we do not quantify here). We also note modest "leakage" of CO_2 emissions outside of China in both scenarios, as reduced fossil fuel use in China puts downward pressure on prices globally, causing modest increases in CO_2-intensive fuel demand and associated emissions in other countries. Relative to a case that only considers reductions in China, we find that cumulative global CO_2 emissions are +3.3% in the CE scenario and +3.8% in the AE scenario, with most of the increase due to higher coal use in the Asian regions outside of China, particularly in emerging Southeast Asia.

Based on our analysis of alternative policy paths in China, we find that a modest CO_2 price results in significant emissions reductions. The challenge ahead will be managing the transition to a slower growth path (anticipated in all three scenarios) and creating incentives to reduce system-wide inefficiencies in resource allocation within China's economy, while appropriately and efficiently pricing the societal costs of energy use—all goals reaffirmed at China's Third Plenum. If the pledges of the Third Plenum are effectively implemented, China will have a strong domestic policy foundation to underpin its post-2020 contribution to mitigating global climate change.

3. METHODS

For this analysis, we use the China-in-Global Energy Model, a multi-regional simulation model of the global energy and economic system. The C-GEM is an empirically-calibrated global energy-economic simulation model that is capable of capturing the impact of policy through its effect on the relative prices of energy and other goods, which in turn affects fuel and technology choices, the composition of domestic economic activity, and global trade dynamics. Developed collaboratively over the past three years by researchers at Tsinghua University and the Massachusetts Institute of Technology as part of the China Energy and Climate Project, the C-GEM is constructed using methods well-established in the energy systems and economic modeling literatures. However, the C-GEM differs from other models in that it reflects China's domestic economic and energy system data and trends, as well as China-specific cost estimates for advanced energy technologies (see Appendix Section A1). The C-GEM is calibrated using energy and economic data from global and domestic Chinese data sets for the model base year, 2007, and the first simulated period, 2010. The basic structure of the model reflects the circular flow of the economy in which households supply factor inputs (labor and capital) to production sectors, which are combined with energy and intermediate inputs to produce final goods and services purchased by households. The model is formulated as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995) in the Mathematical Programming System for General Equilibrium (MPSGE) (Rutherford, 1999) and the General Algebraic Modeling System (GAMS) modeling language (Rosenthal, 2012). The system of equations is solved using the PATH solver (Dirkse and Ferris, 1995) to determine prices and quantities of all factors of production (labor, capital, resources) as well as goods and services produced by represented economic sectors.

In the C-GEM, policy acts primarily through changes in the relative prices of goods as economic activities adjust to reflect a new equilibrium that meets all policy constraints at least cost. Energy policies that can be represented in a CGE framework range from market-based instruments such as a carbon charge or tax on fuels to command-and-control policies that directly constrain the quantity or efficiency of energy use, or require the application of specific energy technologies. Examples of policy modeling efforts employing CGE models with structural similarities to C-GEM—used independently or in connection with natural systems models in integrated assessment studies—are numerous (Babiker *et al*., 2003; Babiker *et al*., 2004; Böhringer and Löschel, 2006; Melillo *et al*., 2009; Böhringer *et al*., 2012).

The C-GEM model has been applied in previous peer-reviewed studies, including Qi *et al.* (2014b, 2014c). Further information is available in the Appendix (Section A1) as well as the model documentation (Qi *et al*., 2014a).

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APPENDIX[1]

Contents

This appendix provides additional supporting documentation and sensitivity analysis related to the analysis described in the main text. Specifically, we include a detailed and transparent description of the model structure and parameter assumptions. We also test the sensitivity of model outcomes to several key parameters. Recognizing the inherent uncertainty in forecasting complex systems over long time scales, our goal in this work is to develop projections that allow readers to understand the relationship between incentives created by newly announced policies and future energy and CO_2 emissions trends in China.

A1. MODEL STRUCTURE AND DISTINCTIVE FEATURES

The structure of the C-GEM is similar to other recursive-dynamic global computable general equilibrium models with a detailed representation of the energy system, such as the Applied Dynamic Analysis of the Global Economy (ADAGE) Model (Ross, 2008), Policy Analysis based on Computable Equilibrium (PACE) (Böhringer *et al*., 2004), Global Trade and Environment Model (GTEM) (Pant, 2007), GTAP in GAMS (Rutherford, 2005), and the MIT Emissions Prediction and Policy Analysis (EPPA) model (Paltsev *et al*., 2005). Among these models, the C-GEM's closest relative is the MIT Emissions Prediction and Policy Analysis (EPPA) model, which has been used to analyze the evolution of the global energy and economic system and the impact of energy and climate policy. Previous assessments using the MIT EPPA model have focused largely on the United States and Europe, although several studies have focused on China (Paltsev *et al*., 2012; Nam *et al*., 2013). The C-GEM differs from the EPPA (Version 5) model in terms of the model base year, the data used for China, and the representation of trends in economic growth, the savings rate, and technology costs in China. The C-GEM was constructed using the eighth release of the Global Trade Analysis Project data set (GTAP8) (Narayanan *et al*., 2012). In the C-GEM, data for the China region in GTAP8 are replaced with China's officially-released national input-output tables (NBS, 2009). Production sectors in the C-GEM model are described in **Table A1**. Countries and regional aggregates included in the C-GEM model are described in **Table A2**.

[1] This is an appendix to Zhang *et al*. (2014): Carbon emissions in China: How far can new efforts bend the curve? MIT Joint Program on the Science and Policy of Global Change *Report 267* (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt267.pdf).

Table A1. Production sectors included in the C-GEM.

Type	Sector		Description
Agriculture	CROP	Crops	Food and non-food crops produced on managed cropland
	FORS	Forest	Managed forest land and logging activities
	LIVE	Livestock	Animal husbandry and animal products
Energy	COAL	Coal	Mining and agglomeration of hard coal, lignite and peat
	OIL	Oil	Extraction of petroleum
	GAS	Gas	Extraction of natural gas
	ROIL	Petroleum	Refined oil and petro chemistry products
	ELEC	Electricity	Electricity and heat generation, transmission and distribution
Energy-Intensive Industry	NMM	Non-Metallic Minerals Products	Cement, plaster, lime, gravel and concrete
	I&S	Iron & Steel	Manufacture and casting of iron and steel
	NFM	Non-Ferrous Metals Products	Production and casting of copper, aluminum, zinc, lead, gold and silver
	CRP	Chemical Rubber Products	Basic chemicals, other chemical products, rubber and plastics
	FMP	Fabricated Metal Products	Sheet metal products (except machinery and equipment)
Other production	FOOD	Food & Tobacco	Manufacture of food products and tobacco
	MINE	Mining	Mining of metal ores, uranium, gems and other mining/quarrying
	CNS	Construction	Construction of houses, factories, offices and roads
	EQUT	Equipment	Machinery and equipment, including electronic equipment
	OTHR	Other Industries	Other industries
Service	TRAN	Transportation Services	Pipeline transport, and water, air and land transport (passenger and freight)
	SERV	Other Service	Communication, finance, public services, dwellings and other services

Table A2. Regional aggregation in the C-GEM.

C-GEM Regional aggregation	Countries and regions included
Developed Economies	
United States (USA)	United States of America
Canada (CAN)	Canada
Japan (JPN)	Japan
South Korea (KOR)	South Korea
Developed Asia (DEA)	Hong Kong, Taiwan, Singapore
Europe Union (EUR)	Includes EU-27 plus countries in the European Free Trade Area (Switzerland, Norway, Iceland)
Australia-New Zealand (ANZ)	Australia, New Zealand, and other territories (Antarctica, Bouvet Island, British Indian Ocean Territory, French Southern Territories)
Developing and Undeveloped Economies	
China (CHN)	Mainland China
India (IND)	India
Developing South-East Asia (SEA)	Indonesia, Malaysia, Philippines, Thailand, Vietnam, Cambodia, Laos, Southeast Asian countries not classified elsewhere
Rest of Asia (ROA)	Bangladesh, Sri Lanka, Pakistan, Mongolia and Asian countries not classified elsewhere
Mexico (MEX)	Mexico
Middle East (MES)	Iran, United Arab Emirates, Bahrain, Israel, Kuwait, Oman, Qatar, Saudi Arabia
South Africa (ZAF)	South Africa
Rest of Africa (AFR)	African countries not classified elsewhere
Russia (RUS)	Russia
Rest of Eurasia (ROE)	Albania, Croatia, Belarus, Ukraine, Armenia, Azerbaijan, Georgia, Turkey, Kazakhstan, Kyrgyzstan, European countries not classified elsewhere
Brazil (BRA)	Brazil
Latin America (LAM)	Latin American countries not classified elsewhere

Given the large number of modeling studies conducted for China, it is worth emphasizing why our modeling framework is at once methodologically rigorous, uniquely representative of current reality in China, and well suited for studying long-term energy system evolution and the impacts of policy. First, we choose a modeling approach that accounts for interdependencies among economic sectors by capturing how changes in input costs affect the prices of final goods and services consumed across the economy. Representing these interdependencies is particularly important because fossil energy types are inputs to a broad range of productive activities. Projecting how policy-induced changes in the cost of fossil energy affect final demand would be impossible without an economy-wide, multi-sector model. Moreover, our model endogenously captures how producers and consumers reduce demand or shift the composition of production or consumption in response to changes in relative prices. An economy-wide model built on microeconomic foundations also allows us to evaluate the aggregate cost of policy.

Second, our model is calibrated based on the latest available data and expectations about China's energy system, economic activity, and growth trends. We use national data (rather than provincial or other more disaggregated data) to calibrate the model. While discrepancies between national energy and emissions totals and national totals based on provincially-reported data are well documented (Guan *et al*., 2012), we choose to use the national totals, as they are widely considered less susceptible to inconsistencies and over-reporting of economic output compared to China's regional data. National totals are also used in the formulation of China's national climate policy.

Third, our model introduces many relevant trends specific to China's economy and stage of development, including a reduction in the savings rate over time (discussed in Section A2.1) as well as technology costs that reflect available estimates and expectations (Section A2.2). As such, the C-GEM baseline (*No Policy*) projection provides a counterfactual scenario against which we evaluate the impact of China's post-2020 energy and climate policy proposals.

A2. ASSUMPTIONS

A2.1 Economy

To develop our *No Policy* counterfactual scenario, we calibrate an economic growth path driven by changes in the labor productivity growth rate and a process of capital accumulation. For all countries except for China, the depreciation rate is assumed to be 5%, while in China we assume that the depreciation rate converges linearly from about 12% in 2010 (following Bai *et al*., 2006) to 6% in 2050. The savings rate convergence path follows OECD analysis (OECD, 2012), reflecting the intuition that China's (currently high) savings rate will fall over time and the share of consumption in total national income will increase as shown in **Table A3**. The impact of this assumption is discussed in Section A4.

Table A3. Relative shares of consumption and investment in total national income.

	Consumption	Investment
2010	0.520	0.480
2015	0.535	0.465
2020	0.570	0.430
2025	0.610	0.390
2030	0.640	0.360
2035	0.670	0.330
2040	0.700	0.300
2045	0.700	0.300
2050	0.700	0.300

A2.2 Technology Costs and Improvement Rates

A central modeling assumption is the long-run rate of efficiency improvement attributable to technological change and capital stock turnover. We assume an energy efficiency improvement rate of 1.7% per year in China, which is applied to all production sectors and household final demand. To avoid double counting, we do not apply the rate in the electric power sector; this also reflects the fact that by 2010, electric power generation efficiency reflected significant new capacity operating near global frontier efficiency levels, as most of the less efficient, outdated capacity had been phased out during the Eleventh Five-Year Plan. We consider sensitivity to this assumption by considering three alternative (lower) assumptions for the rate of energy efficiency improvement as follows: 1) 0% per year for the household sector only, 2) 1% per year for all production sectors (not including the household sector), and 3) the combined effect of a 0% per year for the household sector and 1% per year for all production sectors.

Assumptions in the C-GEM for the cost of advanced technologies (expressed as a mark-up relative to the price of pulverized coal technology in 2010) reflect the latest available data and views based on expert elicitation conducted in China. We provide our assumptions for the relative cost of each advanced technology in **Table A4** below.

Table A4. Relative prices of advanced electric power generation technologies assumed for this study (cost of pulverized coal generation is normalized to 1.0).

Year	Markup relative to pulverized coal generation[1]				
	Wind[2]	Solar PV[3]	Bioelectricity[4]	Natural gas w/carbon capture and storage[5]	Integrated gasification combined cycle[6]
2010	1.3	2.5	1.8	2.35	1.55
2015	1.3	2.0	1.8	2.35	1.55
2020–2050	1.3	1.5	1.8	2.35	1.55

[1]Note: The base cost of conventional power generation is assumed to be 0.4 yuan/KWh, the national average cost for producing coal-fired electricity in 2010.

[2]Wind power costs are based on expert elicitation and refer to average wind electricity production costs (0.5–0.55 yuan/KWh).

[3]Solar PV costs in 2010 (1.0–1.15 yuan/KWh) are based on estimates from NDRC (NDRC, 2011). These costs decrease in 2015 (to 0.8 yuan/KWh) and again in 2020 (0.6 yuan/kWh). These reductions are based on the cost reduction targets issued by the Ministry of Industry and Information Technology (MIIT, 2012).

[4]Biomass power costs (0.7 yuan/KWh) are based on expert elicitation.

[5]NGCC-CCS costs (0.94 yuan/KWh) are based on literature estimates (Rubin and de Coninck, 2005) and expert elicitation.

[6]IGCC-CCS costs (0.65 yuan/KWh) are based on literature estimates (Rubin and de Coninck, 2005) and expert elicitation.

A2.3 Policy Description and Modeling Approach

The two policy scenarios modeled in this analysis, *Continued Effort* and *Accelerated Effort*, are described in Table 1 in the main text. China achieved a carbon intensity reduction of 21% over the Eleventh Five-Year Plan (2005–2010), and targets a further reduction of 17% over the Twelfth Five-Year Plan (2011–2015). As a result, if China can achieve a carbon intensity reduction of 3% per year over the Thirteenth Five-Year Plan (2016–2020), it can accomplish a carbon intensity reduction of approximately 44% from 2005 to 2020, well within the range of its Copenhagen carbon intensity reduction pledge. We assume that China will maintain its Copenhagen pledge momentum, and achieve a carbon intensity reduction rate of approximately 3%

per year from 2016 through 2050 in the *Continued Effort* scenario. We choose a carbon price instrument to enforce the carbon intensity target, acknowledging that China has exhausted much of the abatement achieved through updating outdated equipment and introducing market-based economic reforms. Further rationale for our policy representation is that China has begun piloting emissions trading systems in seven cities and provinces in order to support achievement of the carbon intensity targets included in the Twelfth Five-Year Plan. In the *Accelerated Effort* scenario, we implement a higher carbon tax at the level needed to achieve a steeper decline in CO_2 intensity (approximately 4% per year). Through a fossil resource tax as well as support for renewable energy (through a feed-in tariff for wind, solar, and biomass), hydro-electric power, and nuclear power, the *Continued Effort* scenario assumes that existing targets will be achieved and extended. On the other hand, in the *Accelerated Effort* scenario we assume that technical and non-technical (e.g. regulatory) barriers to renewable expansion are lower, reducing the cost associated with integrating intermittent renewables, and so the same feed-in tariff results in a higher level of adoption; hydro-electric power development according to existing plans, given that available resources are expected to be maximized; and nuclear power resource expansion from 350 GW to 450 GW, representing a more aggressive assumption about long-term available nuclear power potential.

Carbon taxes and fossil resource taxes are either modeled as a percentage of the underlying price or computed on a mass basis, as described above. Taxes introduce a wedge between the production cost and consumer price, with all tax revenue paid to a central planner and rebated lump-sum to households. All resources taxes are applied as an output tax at the point of production, following current practice in China. Resource taxes for oil and natural gas are set at 5% of output value, while coal is taxed on a mass basis at the rate of 4 CNY/ton (a very small percentage of current output value, <5%) (State Council, 2011). Policymakers are currently discussing whether or not to tax coal based on output value or quantity. Thus we simulate a transition to a coal resource tax of 10% by value in the AE scenario. The tax on crude oil and natural gas is also higher in the AE scenario, although we assume it is not taxed at the same level as coal, given the larger associated environmental damages.

Hydro and nuclear resource availability is modeled following representation in the MIT Emissions Prediction and Policy Analysis (EPPA) model (Paltsev *et al*., 2005). We model economically-available resource as a function of central plans to exploit these two energy types, given that development is highly policy-driven (due to conservation objectives, safety concerns associated with rapid deployment, and other reasons).

The feed-in tariff for wind, solar, and biomass electricity is modeled as a surcharge on the electricity price to consumers, reflecting current practice in China (SCNPC, 2006). The surcharge on output of the three generation types is set endogenously to a level that results in the corresponding targeted increase in the price of electricity equivalent to the assumed FIT level (the current FIT level in 2013 for wind is 0.51–0.61 CNY/KWh (NDRC, 2009), 0.90–1.00 CNY/KWh for solar (NDRC, 2013), and 0.75 CNY/KWh for biomass power (NDRC, 2010)).

A3. MODEL OUTPUTS

Below are detailed tables (**Tables A5, A6 and A7**) of model outputs for a set of economy-wide indicators, the primary energy mix, CO_2 emissions, and prices for the three main scenarios (and in Section A4, several sensitivity cases).

Table A5. Key outputs and indicators in the *No Policy* (NP) scenario.

Economy-wide indicators	2010	2015	2020	2025	2030	2035	2040	2045	2050
Population (millions)	1336	1369	1391	1402	1409	1414	1403	1387	1373
GDP *USD 2007 bil*	4690	6699	9395	12198	15227	18350	21819	25553	29651
GDP growth *%/year*	---	7.4%	7.0%	5.4%	4.5%	3.8%	3.5%	3.2%	3.0%
Consumption *USD 2007 bil*	2066	3149	4788	6679	8779	11090	13807	16175	18782
CO_2-price *2007 USD/ton*	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.57	1.43	1.30	1.19	1.08	0.98	0.89	0.80	0.71
CO_2-intensity change *%/year*	---	-1.9%	-1.8%	-1.8%	-1.9%	-2.0%	-2.0%	-2.1%	-2.3%
Primary energy use (EJ)									
Coal	68.3	88.5	113.4	134.2	152.5	165.8	177.4	185.0	189.0
Oil	17.1	22.2	28.4	33.4	37.6	41.1	44.6	47.3	49.9
Natural gas	3.5	4.7	6.5	8.4	10.4	12.5	15.0	17.8	21.2
Nuclear	0.8	2.9	4.2	5.7	7.1	8.3	8.9	9.4	10.2
Hydro	6.3	8.2	11.0	11.0	11.2	11.2	11.4	11.3	11.6
Wind	1.1	1.3	1.6	2.0	2.4	2.8	3.4	3.8	4.3
Solar	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
Bio-electricity	0.2	0.3	0.2	0.3	0.3	0.4	0.4	0.5	0.5
Bio-oil	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3
Total	97.4	128.3	165.4	195.1	221.8	242.4	261.4	275.4	287.1
China Emissions									
CO_2 *(mmt)*	7382	9561	12249	14511	16491	18000	19370	20359	21057
Prices (Normalized to 2007 price level)									
Coal	1.02	1.09	1.16	1.22	1.29	1.36	1.44	1.53	1.64
Oil	1.00	1.16	1.32	1.48	1.64	1.78	1.91	2.03	2.14
Natural gas	1.03	1.10	1.15	1.19	1.22	1.26	1.29	1.34	1.38

Table A6. Key outputs and indicators in the *Continued Effort* (CE) scenario.

Economy-wide indicators	2010	2015	2020	2025	2030	2035	2040	2045	2050
Population (millions)	1336	1369	1391	1402	1409	1414	1403	1387	1373
GDP *USD 2007 bil*	4690	6739	9359	12115	15095	18137	21522	25158	29157
GDP growth *%/year*	---	7.5%	6.8%	5.3%	4.5%	3.7%	3.5%	3.2%	3.0%
Consumption *USD 2007 bil*	2066	3172	4774	6650	8730	11000	13672	15991	18549
CO_2-price *2007 USD/ton*		$7	$14	$19	$26	$33	$41	$50	$58
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.57	1.31	1.10	0.93	0.78	0.66	0.56	0.48	0.41
CO_2-intensity change *%/year*	---	-3.7%	-3.4%	-3.3%	-3.4%	-3.2%	-3.2%	-3.1%	-3.0%
Primary energy use (EJ)									
Coal	68.3	79.6	90.4	96.2	97.8	96.0	92.5	88.6	84.7
Oil	17.1	21.7	27.1	31.5	35.1	38.1	40.9	43.0	45.0
Natural gas	3.5	5.7	8.8	11.6	15.0	18.6	22.9	26.5	29.9
Nuclear	0.8	2.9	4.2	8.5	12.8	16.0	18.7	21.0	23.5
Hydro	6.3	8.2	11.0	11.0	11.2	11.2	11.4	11.3	11.6
Wind	1.1	1.8	3.7	6.0	7.5	8.6	9.9	10.7	11.4
Solar	0.0	0.3	1.1	2.0	3.0	4.1	5.2	5.9	6.6
Bio-electricity	0.2	0.7	1.4	1.7	2.1	2.3	2.4	2.5	2.7
Bio-oil	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3
Total	97.4	121.1	147.8	168.7	184.8	195.0	204.2	209.9	215.8
China Emissions									
CO_2 *(mmt)*	7382	8803	10269	11216	11774	12000	12102	12084	12046
Prices (Normalized to 2007 price level)									
Coal	1.02	1.07	1.10	1.11	1.12	1.12	1.11	1.11	1.11
Oil	1.00	1.16	1.31	1.46	1.61	1.75	1.87	1.99	2.10
Natural gas	1.03	1.14	1.21	1.27	1.33	1.39	1.45	1.51	1.57

Table A7. Key outputs and indicators in the *Accelerated Effort* (AE) scenario.

Economy-wide indicators	2010	2015	2020	2025	2030	2035	2040	2045	2050
Population (millions)	1336	1369	1391	1402	1409	1414	1403	1387	1373
GDP *USD 2007 bil*	4690	6766	9349	12069	15028	18055	21377	24899	28726
GDP growth *%/year*	---	7.6%	6.7%	5.2%	4.5%	3.7%	3.4%	3.1%	2.9%
Consumption *USD 2007 bil*	2066	3187	4771	6632	8702	10963	13594	15844	18299
CO_2-price *2007 USD/ton*		$9	$20	$29	$38	$49	$64	$85	$115
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.57	1.28	1.04	0.84	0.68	0.55	0.44	0.36	0.30
CO_2-intensity change *%/year*	---	-4.0%	-4.1%	-4.3%	-4.1%	-4.1%	-4.0%	-3.9%	-3.9%
Primary energy use (EJ)									
Coal	68.3	78.1	84.2	82.9	79.4	72.3	64.4	57.4	52.3
Oil	17.1	21.6	26.6	30.6	34.0	36.6	38.8	39.9	40.1
Natural gas	3.5	5.8	9.6	13.2	16.5	19.8	23.1	24.8	23.7
Nuclear	0.8	2.9	4.2	10.0	15.6	20.1	24.3	27.1	30.3
Hydro	6.3	8.2	11.0	11.0	11.2	11.2	11.4	11.3	11.6
Wind	1.1	1.8	3.7	6.8	10.4	12.9	15.2	16.3	17.8
Solar	0.0	0.3	1.1	2.3	4.3	6.4	8.2	9.1	10.0
Bio-electricity	0.2	0.7	1.4	2.2	2.8	3.2	3.6	3.8	4.0
Bio-oil	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4
Total	97.4	119.7	142.0	159.1	174.4	182.7	189.2	190.1	190.1
China Emissions									
CO_2 *(mmt)*	7382	8674	9738	10072	10158	9875	9497	9049	8565
Prices (Normalized to 2007 price level)									
Coal	1.02	1.04	1.06	1.05	1.04	1.02	0.99	0.98	0.98
Oil	1.00	1.15	1.30	1.45	1.60	1.74	1.85	1.97	2.07
Natural gas	1.03	1.14	1.24	1.30	1.36	1.42	1.49	1.56	1.63

Abbreviations: N.A. – Not applicable (e.g. no carbon price), mmt – million metric tons, EJ –Exajoule.

A4. SENSITIVITY ANALYSIS

We further investigate the effect of changing assumptions used in our modeling analysis on outcomes of interest, focusing on economy-wide indicators. **Table A8** shows the results for all three scenarios assuming that no economic structural change occurs (e.g. the 2010 structure of GDP, 52% consumption and 48% investment, is preserved). Without structural change, we find that in the year 2050, GDP is higher by 13% and primary energy use is higher by 10%.

Table A9 shows the impact of making carbon capture and storage (CCS) available in each of the policy scenarios. CCS provides an important and cost-effective substitute for conventional power as the carbon price increases, becoming economically viable in 2040 (CE scenario) and in 2035 (AE scenario), respectively. CCS makes an increasing contribution to abatement as the price of carbon increases, with a projected 1793 mmt of CO_2 reduced through CCS in the AE scenario relative to baseline in 2050, or 14% of total abatement in that year (measured relative to 2050 projections for the *No Policy* case).

Table A10 shows the impact of assuming slower energy efficiency improvement, taking the *No Policy* case as an example. If instead of improving at 1.7% per year, household energy efficiency were to remain stable over time, total CO_2 emissions in China would be about 12% higher in 2050. Meanwhile, if industrial energy efficiency were to improve at a rate of 1% per year rather than 1.7% per year, by 2050 total CO_2 emissions in China would be about 20% higher. The combined effect of assuming a lower rate of efficiency improvement in both the residential and industrial sectors is an increase in China's total CO_2 emissions by about 31% in 2050.

Table A8. Scenario results with no shift from investment to consumption on energy use and CO_2 emissions.

No Policy	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GDP *USD 2007 bil*	4690	6700	9489	12592	16129	19872	24161	28793	33529
GDP growth *%/year*	---	7.4%	7.2%	5.8%	5.1%	4.3%	4.0%	3.6%	3.1%
Consumption *USD 2007 bil*	2066	3061	4414	5888	7571	9336	11375	13564	15787
CO_2-price *2007 USD/ton*	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.57	1.43	1.31	1.20	1.09	0.98	0.88	0.79	0.69
CO_2-intensity change *%/year*	---	-1.9%	-1.7%	-1.8%	-1.9%	-2.0%	-2.1%	-2.3%	-2.5%
Primary energy use *(EJ)*	97.4	128.4	167.4	201.8	234.7	260.9	285.7	304.3	315.9
China CO_2 emissions *(mmt)*	7382	9573	12419	15069	17553	19511	21313	22608	23215
China CO_2 change *(mmt)*	0	12	170	558	1062	1510	1943	2249	2157
Current Effort	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GDP *USD 2007 bil*	4690	6741	9450	12494	15967	19607	23790	28307	32948
GDP growth *%/year*	---	7.5%	7.0%	5.7%	5.0%	4.2%	3.9%	3.5%	3.1%
Consumption *USD 2007 bil*	2066	3084	4401	5857	7519	9244	11245	13392	15584
CO_2-price *2007 USD/ton*	---	$7	$14	$19	$26	$33	$41	$50	$58
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.57	1.31	1.10	0.94	0.79	0.68	0.58	0.49	0.43
CO_2-intensity change *%/year*	---	-3.6%	-3.4%	-3.2%	-3.3%	-3.2%	-3.1%	-3.0%	-3.0%
Primary energy use *(EJ)*	97.4	121.1	149.4	174.2	195.4	210.2	224.2	234.0	240.8
China CO_2 emissions *(mmt)*	7382	8813	10412	11691	12663	13248	13727	13994	13999
China CO_2 change *(mmt)*	0	10	143	475	889	1248	1625	1910	1953
Accelerated Effort	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GDP *USD 2007 bil*	4690	6768	9441	12446	15893	19513	23616	27987	32403
GDP growth *%/year*	---	7.6%	6.9%	5.7%	5.0%	4.2%	3.9%	3.5%	3.0%
Consumption *USD 2007 bil*	2066	3098	4398	5839	7493	9211	11174	13255	15349
CO_2-price *2007 USD/ton*	---	$9	$20	$29	$38	$49	$64	$85	$115
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.57	1.29	1.05	0.85	0.70	0.57	0.47	0.38	0.31
CO_2-intensity change *%/year*	---	-4.0%	-4.0%	-4.1%	-3.9%	-3.9%	-3.9%	-3.9%	-4.0%
Primary energy use *(EJ)*	97.4	119.9	143.7	164.7	184.9	197.4	207.8	211.1	210.2
China CO_2 emissions *(mmt)*	7382	8702	9895	10571	11049	11106	11027	10702	10080
China CO_2 change *(mmt)*	0	28	157	499	891	1231	1530	1653	1515

Table A9. The impact of carbon capture and storage (CCS) availability.

No Policy	2010	2015	2020	2025	2030	2035	2040	2045	2050
GDP *USD 2007 bil*	4690	6699	9395	12198	15227	18350	21819	25553	29651
GDP growth per year	---	7.4%	7.0%	5.4%	4.5%	3.8%	3.5%	3.2%	3.0%
Consumption *USD 2007 bil*	2066	3149	4788	6679	8779	11090	13807	16175	18782
CO_2-price *2007 USD/ton*	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.57	1.43	1.30	1.19	1.08	0.98	0.89	0.80	0.71
CO_2-intensity change per year	---	-1.9%	-1.8%	-1.8%	-1.9%	-2.0%	-2.0%	-2.1%	-2.3%
Primary energy use *(EJ)*	97.4	128.3	165.4	195.1	221.8	242.4	261.4	275.4	287.1
China CO_2 emissions *(mmt)*	7382	9561	12249	14511	16491	18000	19368	20357	21054
China CO_2 change *(mmt)*	0	0	0	0	0	0	0	0	0
CCS % share of coal generation	0%	0%	0%	0%	0%	0%	0%	0%	0%
Current Effort	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GDP *USD 2007 bil*	4690	6739	9359	12115	15095	18137	21524	25178	29203
GDP growth per year	---	7.5%	6.8%	5.3%	4.5%	3.7%	3.5%	3.2%	3.0%
Consumption *USD 2007 bil*	2066	3172	4774	6650	8730	11000	13673	16004	18575
CO_2-price *2007 USD/ton*	---	$7	$14	$19	$26	$33	$40	$48	$54
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.57	1.31	1.10	0.93	0.78	0.66	0.56	0.48	0.41
CO_2-intensity change per year	---	-3.7%	-3.4%	-3.3%	-3.4%	-3.2%	-3.2%	-3.1%	-3.0%
Primary energy use *(EJ)*	97.4	121.1	147.8	168.7	184.8	195.0	205.0	211.8	220.1
China CO_2 emissions *(mmt)*	7382	8803	10269	11216	11774	12000	12106	12084	12046
China CO_2 change *(mmt)*	0	0	0	0	0	0	0	0	0
CCS % share of coal generation	0%	0%	0%	0%	0%	0%	2%	5%	13%
Accelerated Effort	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GDP *USD 2007 bil*	4690	6766	9349	12069	15028	18059	21410	24981	28934
GDP growth per year	---	7.6%	6.7%	5.2%	4.5%	3.7%	3.5%	3.1%	3.0%
Consumption *USD 2007 bil*	2066	3187	4771	6632	8702	10965	13615	15893	18424
CO_2-price *2007 USD/ton*	---	$9	$20	$29	$38	$48	$61	$77	$93
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.57	1.28	1.04	0.84	0.68	0.55	0.44	0.36	0.30
CO_2-intensity change per year	---	-4.0%	-4.1%	-4.3%	-4.1%	-4.1%	-4.1%	-4.0%	-4.0%
Primary energy use *(EJ)*	97.4	119.7	142.0	159.1	174.4	183.9	191.8	196.6	205.9
China CO_2 emissions *(mmt)*	7382	8674	9738	10072	10158	9881	9497	9049	8565
China CO_2 change *(mmt)*	0	0	0	0	0	0	0	0	0
CCS % share of coal generation	0%	0%	0%	0%	0%	4%	14%	46%	91%

Table A10. The impact of reducing the household and industrial energy efficiency improvement rate in the reference *(No Policy)* case.

Household low efficiency only	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GDP *USD 2007 bil*	4683	6668	9320	12051	14977	17961	21242	24757	28592
GDP growth *%/year*	---	7.3%	6.9%	5.3%	4.4%	3.7%	3.4%	3.1%	2.9%
Consumption *USD 2007 bil*	2063	3135	4752	6606	8649	10877	13476	15718	18173
CO_2-price *2007 USD/ton*	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.59	1.46	1.36	1.27	1.18	1.09	1.01	0.92	0.83
CO_2-intensity change *%/year*	---	-1.6%	-1.4%	-1.4%	-1.5%	-1.5%	-1.6%	-1.8%	-2.0%
Primary energy use *(EJ)*	98.1	130.7	170.7	204.4	235.8	261.9	287.3	306.7	323.8
China CO_2 emissions *(mmt)*	7439	9758	12679	15254	17603	19525	21348	22683	23683
China CO_2 change *(mmt)*	58	197	430	743	1112	1525	1979	2323	2626
Industry low efficiency only	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GDP *USD 2007 bil*	4686	6681	9348	12101	15057	18083	21427	24996	28883
GDP growth *%/year*	---	7.4%	6.9%	5.3%	4.5%	3.7%	3.5%	3.1%	2.9%
Consumption *USD 2007 bil*	2064	3140	4762	6623	8676	10921	13549	15810	18278
CO_2-price *2007 USD/ton*	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.63	1.52	1.43	1.34	1.25	1.15	1.06	0.97	0.88
CO_2-intensity change *%/year*	---	-1.4%	-1.2%	-1.3%	-1.4%	-1.5%	-1.6%	-1.8%	-2.0%
Primary energy use *(EJ)*	100.4	135.4	178.6	215.3	249.6	278.0	304.8	326.4	345.1
China CO_2 emissions *(mmt)*	7624	10146	13332	16157	18749	20857	22799	24296	25362
China CO_2 change *(mmt)*	242	585	1083	1646	2258	2857	3429	3936	4305
Combined household and industry low efficiency	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GDP *USD 2007 bil*	4679	6650	9272	11952	14802	17684	20833	24173	27780
GDP growth *%/year*	---	7.3%	6.9%	5.2%	4.4%	3.6%	3.3%	3.0%	2.8%
Consumption *USD 2007 bil*	2060	3126	4726	6549	8543	10703	13208	15336	17643
CO_2-price *2007 USD/ton*	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
CO_2-intensity *mmt CO_2/bil 2007 USD*	1.64	1.56	1.48	1.41	1.34	1.26	1.18	1.09	0.99
CO_2-intensity change *%/year*	---	-1.1%	-0.9%	-1.0%	-1.1%	-1.2%	-1.3%	-1.6%	-1.9%
Primary energy use *(EJ)*	101.0	137.7	183.8	224.2	263.0	296.3	328.6	354.4	377.1
China CO_2 emissions *(mmt)*	7681	10340	13751	16870	19796	22258	24562	26283	27491
China CO_2 change *(mmt)*	299	779	1502	2359	3305	4258	5192	5924	6434

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