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

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

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

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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, to protect the environment, and to 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. We perform simulations using the China-in-Global Energy Model, C-GEM, a bespoke recursive-dynamic computable general equilibrium model with global coverage and detailed calibration of China's economy and future trends. Importantly, we find that both levels of policy effort would bend down the CO_2 emissions trajectory before 2050 without undermining economic development. Specifically, in the accelerated effort scenario, we find that coal use peaks around 2020, and CO_2 emissions level off around 2030 at 10 bmt, without undermining continued economic growth consistent with China reaching the status of a "well-off society" by 2050.

1. Introduction

Recent shifts in internal policy suggest that China's policy makers 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 policy makers 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 as well as locally acting pollutants. In addition to end-of-pipe controls to reduce emissions of air 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.

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 nation's carbon intensity (CO_2 emissions 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% during the Eleventh Five-Year Plan (2005–2010) (Zhen et al., 2013)[1] and targets a further reduction of 17% during the Twelfth Five-Year Plan (2011–2015). If China can

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[1] We use emissions data from China from Zhen et al. (2013), which is provided by the National Bureau of Statistics (NBS) and current as of the date of publication.

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0140-9883/

Table 1
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, and 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
Services	TRAN	Transportation Services	Pipeline transport, and water, air and land transport (passenger and freight)
	SERV	Other Services	Communication, finance, public services, dwellings, and other services

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). The objective of this analysis is to assess the impact of these recent policy announcements on China's energy system and CO_2 emissions through 2050.

Table 2
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, and Singapore
Europe Union (EUR)	Includes EU-27 plus countries in the European Free Trade Area (Switzerland, Norway, and Iceland)
Australia-New Zealand (ANZ)	Australia, New Zealand, and other territories (Antarctica, Bouvet Island, British Indian Ocean Territory, and French Southern Territories)
Developing and undeveloped economies	
China (CHN)	Mainland China
India (IND)	India
Developing Southeast Asia (SEA)	Indonesia, Malaysia, Philippines, Thailand, Vietnam, Cambodia, Laos, and 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, and 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, and European countries not classified elsewhere
Brazil (BRA)	Brazil
Latin America (LAM)	Latin American countries not classified elsewhere

At the Asia-Pacific Economic Cooperation Summit in November of 2014, China and the United States jointly announced post-2020 commitments for climate change action. China's goals include reversing the rise in energy-related CO_2 emissions before 2030 and increasing the non-fossil share of primary energy to 20%, also by 2030 (in 2015, this share was just over 11%). In June 2015, China officially submitted its intended nationally determined contribution (INDC) to the UNFCCC, adding a target to cut CO_2 emissions per unit of GDP by 60–65% from 2005 by 2030 to its earlier pledge to peak CO_2 emissions and increase the non-fossil share in primary energy consumption to 20% by the same year (UNFCCC, 2015). The United States committed to reduce total CO_2 emissions by 26–28% in 2025, relative to 2005 levels. Given that China and the United States together accounted for around 41% of global CO_2 emissions in 2010 (WDI, 2014), the pledges offer substantial contributions to global mitigation efforts. China's pledge in particular may set a precedent for other large emerging countries or regions to lay out their own reduction goals ahead of global climate talks in Paris in late 2015. This analysis seeks to quantify the impact of new policies on China's future emissions trajectory, as well as the role of several sources of uncertainty.

2. Modeling China's energy and climate policies

For this analysis, we use the China-in-Global Energy Model (C-GEM), 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 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.

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

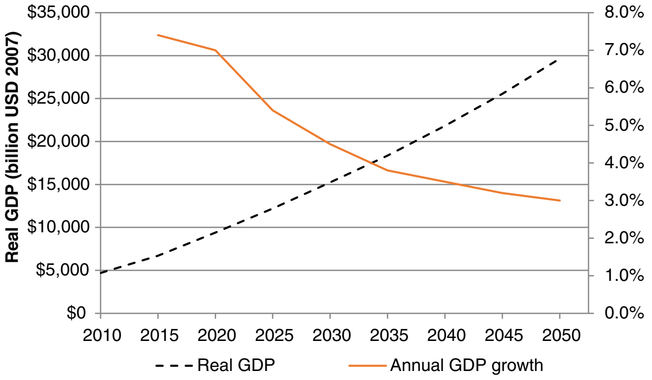

Fig. 1. China's GDP trajectory and corresponding annual GDP growth rate in the *No Policy* scenario.

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 price 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 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), the Policy Analysis based on Computable Equilibrium (PACE) (Böhringer et al., 2004), the Global Trade and Environment Model (GTEM) (Pant, 2007), the 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) (Tables 1 and 2).

The C-GEM includes several features that distinguish it among previously developed recursive-dynamic CGE models. Similar to the EPPA model (Paltsev et al., 2005), the C-GEM incorporates a Hotelling-based representation of resource depletion and region-specific representation of advanced technologies. Unlike models that treat the energy-intensive industries as a single aggregated sector, the C-GEM represents them as five disaggregated sectors to reflect in more detail the activities that contribute a substantial share of energy use and greenhouse gas emissions in China and other emerging markets. The C-GEM further calibrates historical model years using the latest available domestic energy and economic data, capturing the changes in China's growth rate and sectoral structure over the past ten years. The C-GEM was constructed using the eighth (latest available as of the paper submission date)[2] release of the Global Trade Analysis Project data set (GTAP8)[3] (Narayanan et al., 2012). Data for China are replaced with China's officially released national input–output tables (National Bureau of Statistics of China, 2009). The dynamic calibration from 2007 to 2010 was adjusted to match observed data for 2010 as closely as possible. In projections, the C-GEM also simulates structural change anticipated in the Chinese economy by exogenously reducing the savings rate to shift from investment to consumption as a primary economic growth driver through 2050, with savings rates falling to levels observed in OECD nations (Qi et al., 2014a). China-specific costs were used to represent low-carbon technology options, which become available as cost conditions change endogenously in the model in response to policy. The implications of these features are discussed below in Section 3. The C-GEM model has been applied in previous studies, including Qi et al. (2014b) and Qi et al. (2016).

Table 3
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

3. Scenario analysis

Our scenario analysis begins by constructing a counterfactual scenario that reflects anticipated trends in China's economic growth and economic structure through 2050. We base our representation of these trends on forecasts by experts in China and historical global experience, as described below. We then use our *No Policy* scenario as a basis for evaluating the impacts of policy in two policy scenarios that represent alternative levels of effort.

3.1. No Policy scenario

To develop a *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 economic growth path for the *No Policy* scenario is shown in Fig. 1. Our assumptions lead to economic growth rates falling from just over 7%/year in 2020 to around 3%/year in 2050, while the total size of the economy grows about six times between 2010 and 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 3. Since savings is equivalent to current period investment in the model, over time a lower savings rate reduces investment, which at present is largely directed into energy-intensive industries with large export shares. As a result, this shift lowers the emissions trajectory relative to a no-shift scenario (in which the share of consumption and investment remain constant at 2010 levels), reducing annual national emissions by 8.5% (2.2 bmt) in 2050. Without this structural change, we find that in the year 2050,

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[2] Statistics in China are occasionally revised. The NBS has recently revised China's 2013 GDP data (NBS, 2014), and new revisions to current and historical energy totals are expected in late 2015. We adopt the numbers for 2007 and 2010 that were available as of mid-2014.

[3] The GTAP 8 dataset includes consistent national accounts on production and consumption (input–output tables) together with bilateral trade flows for 57 sectors and 129 regions for the year 2007.

Table 4
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[a]				
	Wind[b]	Solar PV[c]	Bio-electricity[d]	Natural gas with carbon capture and storage[e]	Integrated gasification combined cycle[f]
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

[a] 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.
[b] Wind power costs are based on expert elicitation and refer to average wind electricity production costs (0.5–0.55 yuan/KWh).
[c] 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).
[d] Biomass power costs (0.7 yuan/KWh) are based on expert elicitation.
[e] NGCC-CCS costs (0.94 yuan/KWh) are based on literature estimates (Rubin and de Coninck, 2005) and expert elicitation.
[f] IGCC-CCS costs (0.65 yuan/KWh) are based on literature estimates (Rubin and de Coninck, 2005) and expert elicitation.

Table 5
Policy assumptions in each scenario.

Measures	No Policy (NP)	Continued Effort (CE)	Accelerated Effort (AE)
Carbon price	No carbon price	Carbon price required to achieve CI reduction (~3% per year, \$26/ton in 2030 and \$58/ton in 2050)	Carbon price 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: 10% of the price; coal: 4 CNY/ton (~\$0.6/ton)	Crude oil/natural gas: 8% of the price; 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

GDP is higher by 13% and primary energy use is higher by 10%. Relative to a no-shift scenario in 2030, the output of energy-intensive sectors falls significantly, with energy-intensive industry, heavy manufacturing, and construction sector output falling by 12.5%, 12.8% and 25%, respectively.

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.

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 as an exogenous trend. 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 much of the less efficient, outdated capacity had been phased out during the Eleventh Five-Year Plan. We consider sensitivity of outcomes to these assumptions in Section 3.3.

Assumptions in the C-GEM for the cost of advanced technologies (expressed as a markup relative to the price of pulverized coal technology in 2010) reflect the latest available data and views based on expert elicitation[4] conducted in China. We provide our assumptions for the relative cost of each advanced technology in Table 4 below.

3.2. Policy scenarios

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 C-GEM (Qi et al., 2014a) and compare them to the counterfactual (*No Policy*) scenario. The scenarios are described in Table 5. 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 must be 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

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[4] To formulate technology cost assumptions, the Tsinghua University co-authors interviewed experts from power companies and industry associations to obtain the latest available cost estimates for specific projections. The cost of NGCC/IGCC electric power generation is collected from experts working in the Huaneng Group, the largest power company in China. Wind farm cost is based on a technical handbook describing wind farm cost indicators used in actual projects carried out by the Huaneng Company.

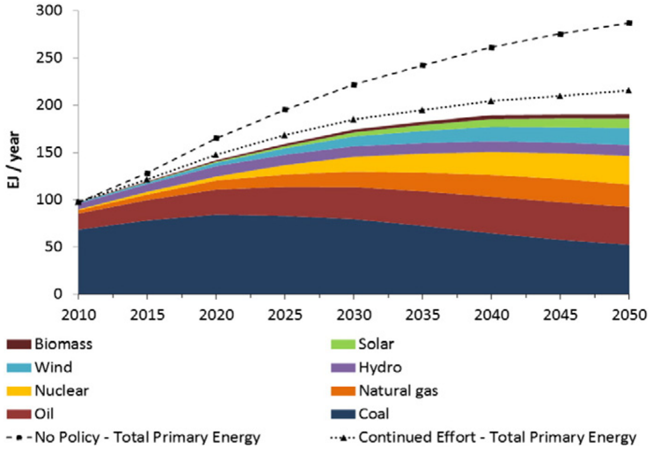

Fig. 2. Energy demand in the *No Policy*, *Continued Effort*, and *Accelerated Effort* scenarios, with the primary energy mix shown for the *Accelerated Effort* scenario (EJ–exojoules).

of electricity. Surcharges are endogenously set to match current FIT levels. 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.

We compare the CE and AE scenarios to the *No Policy* (NP) (counterfactual) scenario described above that assumes no energy or climate policies are implemented from 2010 onward. 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.

Total primary energy trajectories for the three scenarios, and the composition by energy type for the AE scenario, are all shown in Fig. 2. Fig. 3 shows the corresponding CO_2 emissions trajectories. In the *No Policy* scenario, we find that while CO_2 emissions intensity continues to fall at a moderate rate, total emissions 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 the aggressive deployment of carbon capture and storage as well as pollution removal technology. Detailed indicators for the NP scenario are summarized in Table 6.

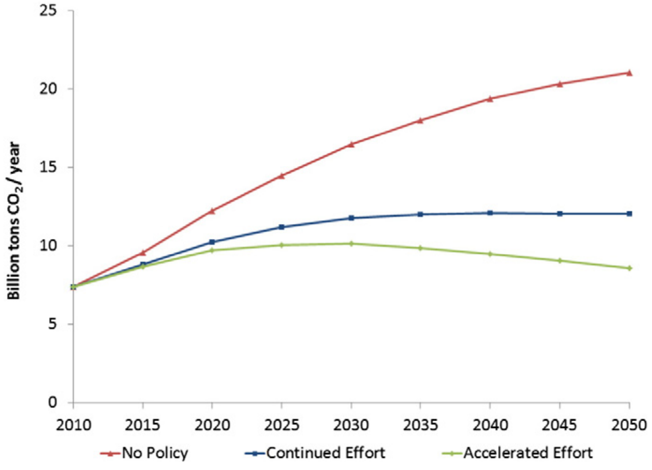

Fig. 3. Total CO_2 emissions in China in the *No Policy*, *Continued Effort*, and *Accelerated Effort* scenarios.

Turning to the *Continued Effort* scenario, we find that if China's policy makers 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. The deployment of non-fossil energy is significant, with the share of non-fossil energy climbing from 15% in 2020 to around 26% in 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). Detailed indicators for the CE scenario are summarized in Table 7.

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 the 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 CE 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 (Fig. 4), 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. Detailed indicators for the AE scenario are summarized in Table 8.

3.3. Sensitivity analysis

The projections in this analysis are subject to substantial uncertainty. We quantified a few representative uncertainties in several sensitivity cases. First, we consider the impact of making a potential transformation low-carbon technology, 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 projected CO_2 emissions in the *No Policy* case).

We also examine the impact of assuming slower energy efficiency improvement, taking the *No Policy* case as an example. If household energy

Table 6
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 billion*	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 billion*	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/billion 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

efficiency were to remain stable over time instead of improving at 1.7% per year, 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

Table 7
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 billion*	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 billion*	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/billion 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

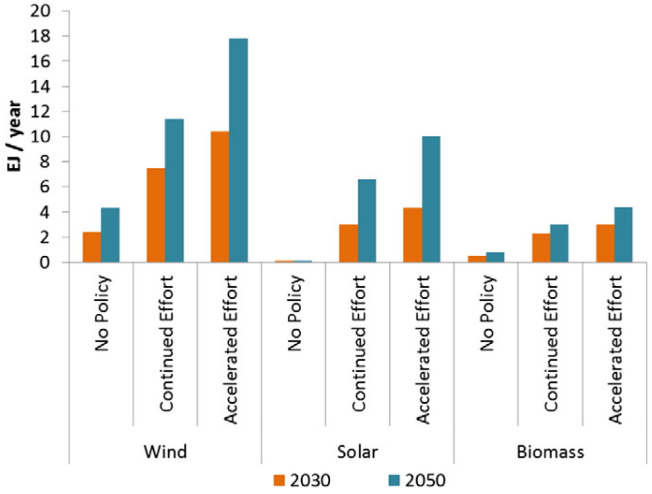

Fig. 4. Deployment of renewable energy in 2030 and 2050 under the *No Policy*, *Continued Effort*, and *Accelerated Effort* scenarios (EJ–exojoules).

industrial sectors results in an increase in China's total CO_2 emissions by about 31% in 2050.

We emphasize that the above are just a subset of the relevant uncertainties involved in this analysis. One of the most important uncertainties is the rate of GDP growth, which directly drives energy requirements. More rapid GDP growth would place upward pressure on the prices of resource-limited fossil fuels, accelerating the shift to alternatives even as an increase in total energy demand would tend to increase emissions overall. Slower GDP growth have the opposite effect—indeed, if China's economy does not grow as fast as assumed in this analysis, emissions could peak well before 2030. In this sense, China's peak emissions pledge is to some degree robust to its future economic growth trajectory—if GDP growth is slower, emissions will peak sooner, while if GDP growth is faster, more resources will be available for decarbonization. However, the 20% non-fossil energy target could be difficult to meet under a slower GDP growth scenario if alternatives directly threaten incumbent generation, rather than adding on top. Changes in the prices of labor, capital, fuels, and technologies could further alter the energy mix, relative to our projections in the scenarios presented here. Additional sensitivity analysis to GDP, fuel price, and other parameters can be found in Qi et al. (2014a).

4. Conclusions

Based on developments since 2013, including recent progress in piloting CO_2 emissions trading and China's climate pledge, the country seems to be heading into the *Accelerated Effort* scenario. This scenario would lead to a peak in China's carbon emissions at 10 bmt around 2030, about 15–20% higher than present levels, followed by a gradual decline to 8.6 bmt in 2050, about 16% higher than the 2010 level. This scenario will represent a significant departure from China's coal-dominated past, requiring massive scale-up of both nuclear and renewable energy, and will not be easy. The challenges associated with a dramatic reduction in the country's reliance on coal will be significant. Ongoing reforms and institutional changes that support full implementation of new policies will be necessary to manage the transition from a coal-dominant to a low-carbon energy system.

The direct costs of this transition will not undermine China's economic growth aspirations, especially when potential co-benefits are considered. Without further policy action, China's carbon emissions are projected to reach levels that threaten any global effort to stabilize climate change. However, with an immediate start and long-term targets, China will minimize the cost of this transformation on the country's economic development. By 2050, policy cost due to the additional measures rises to 1.2% of the value of economic consumption (a

Table 8
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 billion*	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 billion*	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/billion 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.

component of GDP used to approximate the impact of domestic consumer welfare) in the CE scenario and to 2.6% of consumption in the AE scenario, relative 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).

Our finding that significant CO_2 emissions can be reduced at modest cost depends on the choice to adopt a CO_2 price, which does most of the heavy lifting in the two policy scenarios. Our CO_2 price instrument is consistent with a nationwide emissions trading system with full sectoral coverage that targets reductions in CO_2 intensity. While the level of the CO_2 price required rises to a substantial level in both policy scenarios, as time goes on, it is applied to an ever smaller share of fossil energy within China's energy system and will play an important role in creating markets for low-carbon technology and in encouraging energy efficient behavior. China's pilot emissions trading systems for CO_2 are an important exercise that will inform the design of a national system, which is expected to launch during the Thirteenth Five-Year Plan (2016–2020).

We also underscore the importance of pricing or otherwise limiting emissions in surrounding regions. We find modest “leakage” of CO_2 emissions outside of China in both policy 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. This occurs mainly due to higher coal use in the Asian regions outside of China, particularly in emerging Southeast Asia.

The prospect of a large-scale energy transition in China offers both challenges and opportunities. The challenge will be to manage 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. However, China has a unique opportunity to steer efforts to upgrade and reform the economy, improve governance, and clean up the local environment in ways that simultaneously contribute to reducing CO_2 emissions. If China successfully pursues measures embodied in the *Accelerated Effort* scenario, the country will possess a strong domestic policy foundation to underpin its post-2020 commitment to mitigating global climate change.

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