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Quantifying the potential impacts of China's power-sector policies on coal input and CO_2 emissions through 2050: A bottom-up perspective

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ABSTRACT

This study evaluates four recent policies for China's power sector—mandatory renewable targets, green dispatch, carbon capture and sequestration development, and coal-fired generation efficiency improvements—and quantifies their energy and carbon dioxide (CO_2) emissions reduction potential through 2050 using bottom-up energy modeling and scenario analysis. We find renewable targets and green dispatch have crucial interlinked impacts on energy and CO_2 emissions that could change the shape and peak year of China's power-sector emissions outlook. Without either renewable targets or green dispatch, coal will likely continue dominating China's power mix and could delay the power-sector CO_2 emissions peak to the late 2030s.

1. Introduction

In recent years, China has signaled its intent to pursue strategic long-term economic and energy development while balancing rapid growth and urbanization through a commitment to unprecedented energy and carbon-intensity reduction targets. As part of its national five-year plans (FYP) for economic and social development, China has introduced national energy consumption reduction targets for 2010 and 2015 and carbon dioxide (CO_2) reduction targets for 2015 and 2020 (both relative to gross domestic product (GDP)). Despite these targets and national energy efficiency and conservation efforts, recent studies expect China's energy consumption to continue growing significantly from 4300 million tonnes of coal equivalent (Mtce)[1] in 2014 (NBS, 2015a) to around 5500 Mtce by 2030 (Zhou et al., 2013). Similarly, the International Energy Agency's World Energy Outlook 2013 also expects China's total energy consumption to grow from 2743 million tonnes of oil equivalent (Mtoe) in 2011 to 4360 Mtoe in 2030 under its Current Policies Scenario (IEA, 2013).[2] In November 2014, the possibility of a slowdown in energy consumption by 2030 was introduced when, in a joint US-China government announcement, China committed to peaking its CO_2 emissions by 2030 and boosting its share of non-fossil fuel energy to 20% by 2030 (U.S. White House, 2014).[3] These goals were reaffirmed, along with a new target to lower CO_2 emissions per unit of GDP by 60%–65% from 2005 levels by 2030, in China's intentions as submitted in advance of the 2015 United Nations Climate Change Conference in Paris (NDRC, 2015a). China's draft plan for the 13th FYP period from 2016 to 2020 also included a lower energy intensity reduction goal of 15% but higher carbon intensity reduction goal of 18% by 2020 relative to 2015 levels.

The power sector clearly has been impacted by China's rapid economic and urban development, and will be crucial to helping China meet its 20% non-fossil fuel energy consumption target for 2030 as well as the broader national CO_2 reduction and peak year targets. China's electricity demand has grown at an annual average rate of 13% during the past decade. At the same time, installed capacity has nearly quadrupled, from 320 GW to 1360 GW from 2000 to 2014 (NEA, 2015). Since the end of the 11th FYP in 2010, the power sector has become the target of new national policies aimed at improving generation efficiency and increasing the adoption of non-fossil generation. These include aggressive renewable generation targets for 2015 and 2020 coupled with proposed power

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[1] Tonne of coal equivalent (tce) is the standard unit for energy in China. 1 tce is equal to 29.27 gigajoules (GJ). Kilogram of coal equivalent (kgce) and gram of coal equivalent (gce) are also widely used for energy in China.

[2] China's National Bureau of Statistics (2015a, 2015b) and the Zhou et al. (2013) study calculate China's total primary energy consumption using China's coal equivalent method while International Energy Agency (2013) uses a slightly different calculation method for total primary energy consumption.

[3] Zhou et al. (2013) also demonstrated the possibility for China's energy-related CO_2 emissions to peak in 2029 or 2033 under their accelerated and continued improvement scenarios, respectively.

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sector reforms, including a green dispatch policy that prioritizes renewable generation followed by lowest-polluting fossil-fuel generators. However, the impact of these recent policies related to China's power sector on the future national energy and CO_2 emissions outlook has not yet been fully evaluated. Quantifying the potential of each of these power sector policies is crucial for understanding the impact of each policy on national energy consumption and CO_2 emissions. The findings can then be used to help policymakers prioritize future policy implementation by identifying the most effective policy options.

Previous research has focused on China's electricity sector and the potential impact of different policies on power-sector energy requirements and CO_2 emissions, but recent studies have mainly focused on individual technologies or policy options. Cai et al. (2007) conducted one of the earlier bottom-up energy modeling and scenario analyses of China's power sector using baseline, current, and new policy scenarios, but they did not evaluate the impacts of specific policies. More recently, Chen et al. (2011) modeled the potential impact on CO_2 emissions of different technology options for the Chinese power sector, but they did not evaluate the policies and policy implications associated with the proposed technology roadmaps. Li et al. (2011) reviewed key energy conservation and emission-reduction policies in China's power sector, including national targets, renewable development, phase-out of small thermal generators, demand-side management, and energy-efficiency dispatch, and progress made in recent years based on key indicators, but they did not attempt to model potential impacts of these policies on energy and emissions reduction. Mathews and Tan (2013) and Hu et al. (2013) assessed the implications of specific power-sector policies that promote renewable and natural gas generation, respectively, but they did not address other important power-sector policies under consideration in China. Kwan (2010) evaluated the role for and benefits of further developing renewable power resources, but limited his analysis to the Inner Mongolia region. Bazilian et al. (2012) conducted a similar scenario analysis and outlook to evaluate the potential impact of universal access to electricity in sub-Saharan Africa through 2030, but the application of this type of analysis to China's power sector has been extremely limited. This paper therefore presents one of the first comprehensive and long-term modeling analyses utilizing different sets of scenarios to quantify the discrete impacts of China's energy and emissions policies.

To understand the magnitude of energy, carbon, and related impacts of key energy and efficiency policies that have been introduced in China's power sector since 2010, we used the bottom-up, sector-based China End-Use Energy Model developed at Lawrence Berkeley National Laboratory to conduct a scenario analysis of these policies for the period 2015 to 2050. Section 2 introduces the modeling approach and key policy drivers and assumptions for the different sets of baseline and policy scenarios. Section 3 discusses the potential energy and CO_2 emissions results for each policy scenario. We conclude with key findings and broader policy implications in Section 4.

2. Materials and methods

2.1. China energy end-use model

The primary analytical tool in this study was an accounting framework for China's energy and economic structure, built using the Long-Range Energy Alternatives Planning (LEAP) modeling software developed by the Stockholm Environment Institute. This framework enables detailed consideration of technological development—industrial production, equipment efficiency, residential appliance usage, vehicle ownership, power-sector efficiency, lighting and heating usage—to evaluate in detail China's energy and emissions paths in the context of the country's interrelated macro energy and economic-development trajectories.

In-depth discussion of the overall modeling methodology, key sectoral drivers and modeling parameters, and the assumptions and basis for future projections of energy-demand drivers are covered in previous studies (Zhou et al., 2013; Fridley et al., 2013). The validity of our chosen model and modeling applications has been examined by others, including Li and Qi (2011) and Bellevrat (2012). Zheng et al. (2010) has also compared the underlying assumptions and modeling approaches of the China Energy End-Use Model with other bottom-up energy and emissions models for China, finding that the reference scenario results for electricity (discussed in section 2.2) are within the range of other recently published energy and emissions outlooks for China. Unlike previous publications that focused on demand sectors and scenario analysis of demand-side efficiency improvements, we focus on the power sector within the model's energy-transformation module and its related inputs and policy scenarios. Zhou et al. (2013) and Fridley et al. (2013) evaluated the potential impact of comprehensive efficiency improvements across all demand sectors by building overall scenarios for energy and emissions trends in China. In contrast, we evaluate the potential impact of discrete policies. Here, we briefly summarize the overall model structure and energy demand drivers as context for electricity demand forecasting and discuss the modeling approach for the power sector within the energy transformation module.

The China Energy End-Use Model consists of both the energy-demand sectors (including residential buildings, commercial buildings, industry, and transportation) and the energy transformation[4] sectors. Within the energy-demand sector, key drivers of energy use include activity drivers (total population growth, urbanization, building and vehicle stock, and commodity production), economic drivers (total GDP and income), and energy-intensity drivers related to energy-using equipment and appliances. These factors in turn are affected by changing consumer preferences, settlement patterns, infrastructure, and technologies. We used published energy sector statistics to prepare a time-series database representing primary energy use that take supply-side losses into account. After the model was built from the bottom up, sector and fuel-specific consumption data were calibrated by comparing the end-use energy results with the reported data for the base year.

For all scenarios considered in this study, macroeconomic parameters (such as economic growth, population, and urbanization) are assumed to be the same for all scenarios. International experiences and China's recent experience with economic development have highlighted the important linkages between industrialization and rising energy demand, particularly in the industrial and transportation sectors. GDP growth is expected to continue in China but the rate of growth is expected to gradually slow over time, based on China's latest expectation of a slower rate of 6.5% annual GDP growth for the period 2015 to 2030. From 2030 onward, GDP growth is expected to slow more dramatically as the Chinese economy matures and shifts away from industrialization (see Table 1). Another key driver in the model is the rate of urbanization (i.e., the growth of the urban population), which directly influences China's built environment. Nearly 410 million new urban residents were added from 1990 to 2012, and nearly 310 million new urban

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[4] Energy transformation includes energy extraction, processing and distribution subsectors such as electricity generation, electricity transmission and distribution, district heating generation, coal, oil and natural gas extraction, oil refining, and coking.

Table 1
Assumptions for macroeconomic drivers in all scenarios.

	2015	2030	2050
Population	1.37 billion	1.43 billion	1.37 billion
Urbanization rate	56%	68%	78%
GDP annual growth rate			
2015–2030		6.5%	
2030–2050		3.6%	

residents are expected from 2013 to 2050. The addition of new mega-cities and second-tier cities will drive commercial and residential demand for energy services and infrastructure development, and will also spur inter- and intra-city passenger transport activity. To account for the potential effects of urbanization on energy demand in China, the model uses widely accepted population growth assumptions and projections from the United Nations and China's national Energy Research Institute as macro-drivers in all scenarios.

2.1.1. Energy demand

Regarding demand, the China Energy End-Use Model encompasses the four main economic sectors of residential buildings, commercial buildings, industry, and transportation.[5] For the residential building sector, urbanization and growth in household income drive energy consumption because urban households generally consume more commercially supplied energy than rural households, and rising household incomes correspond to increases in housing unit size (and thus in heating, cooling, and lighting loads) as well as appliance ownership. Similarly, commercial-building energy demand is driven by two key factors: building area (floor space) and end-use intensity related to heating, cooling, and lighting (MJ per m^2). For the industrial sector, the model includes seven energy-intensive subsectors (cement, iron and steel, aluminum, ammonia, glass, paper and ethylene) that are driven by key physical drivers related to expanding demand for the built environment for housing, agricultural products, and plastics. Transportation demand is driven by freight and passenger transport trends. Freight transport is calculated as a function of economic activity, measured by GDP; passenger transport is based on average vehicle-kilometers traveled by mode of transportation (i.e., bus, train, or car). Within the energy demand module, the model addresses sectoral patterns of energy consumption, including trends in saturation and operation of energy-using equipment, technological change including efficiency improvements, and complex linkages among economic growth, urban development and energy demand.

2.1.2. Energy transformation

Within the energy-transformation module, the power generation sector includes adaptive practices that reflect changes in generation-dispatch algorithms, supply-side efficiency, generation mix, carbon capture and sequestration (CCS) technologies, and demand-side management. The different power generation technologies considered include coal, natural gas, biomass, nuclear, wind, hydro, solar, and geothermal power generation. Coal generation is further distinguished into six categories by size and efficiency, with units ranging from less than 100 MW generating capacity and an average efficiency of 32% to ultra-supercritical units with generating capacity greater than 1000 MW and average efficiency of 40%. For each technology type, the model includes parameters on total installed capacity, process efficiency, availability, and dispatch order. Following specified parameters, the model uses algorithms to calculate the amount and type of capacity required to meet electricity demand. The model also allows consideration of different rules for dispatching electricity to meet demand: (1) dispatch based on proportional shares from each fuel source, (2) dispatch based on environmental merit (carbon emissions) that prioritize non-fossil generation before fossil generation (referred to as “green dispatch”), or (3) cost-optimized economic dispatch if capital and fuel cost data for each power generation technology are available.

2.2. Reference scenario for energy demand

The reference scenario for China's 2050 energy demand outlook assumes that the Chinese economy will continue lowering its energy intensity by means of efficiency gains consistent with the moderate pace of “market-based” improvement in all sectors as well as continuation of government-directed efficiency programs. These gains are based on moderate efficiency improvements in appliance, heating, cooling, and lighting efficiency and in commercial and residential building shells. For the transport and industrial sectors, they are based on moderate fuel-economy improvements in transport fleets and continued rail electrification following stated goals as well as continued technological advances across energy-consuming industrial sectors. A detailed description of the sectoral end-use assumptions underlying the reference scenario outlook for China's 2050 energy and emissions is provided in Zhou et al. (2013).

Fig. 1 shows the electricity demand by end-use sector under the reference scenario. Electricity demand nearly triples between 2010 and 2050, from 3940 TWh to 10,730 TWh, driven by rapid growth in residential and commercial-building electricity demand, whose shares jump from 15% to 13%, respectively, in 2010 to 30% and 26%, respectively, in 2050. This projected reference electricity demand is used as the basis for analyzing the policy-based scenarios for the power sector described in section 2.3.

2.3. Power sector baseline and policy scenarios

To evaluate each of the four power-sector policies, we developed a baseline scenario and one or two scenarios to evaluate the potential impact of successfully implementing a given policy. We combined mandatory market share for renewable power generation and green dispatch into one set of policy scenarios because their implementation and impacts are closely related. For each scenario, different parameters (such as installed renewable capacities and coal capacity with CCS), and specified dispatch order are used to evaluate the four policies for China. The policy context and the basis for the assumptions behind each set of baseline and policy scenarios are described below.

2.3.1. Mandatory market share (MMS) for renewable power generation and green dispatch

China's landmark 2005 Renewable Energy Law provided a national framework that established national renewable targets, grid access for renewables, a national fund for renewables, and pricing and cost-sharing mechanisms for some renewables. In 2007, the subsequent “Medium and Long-term Development Plan for Renewable Energy in China” set the first official targets for renewable-power capacity for 2010 and 2020 by establishing a “Mandatory Market Share (MMS)” requirement for non-hydro renewable power for grid companies and generators (Zhang et al., 2013). After years of rapid growth in renewable-energy

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[5] Agricultural sector is also included in the model but its energy consumption is negligible, particularly in terms of electricity demand, and not discussed in this paper.

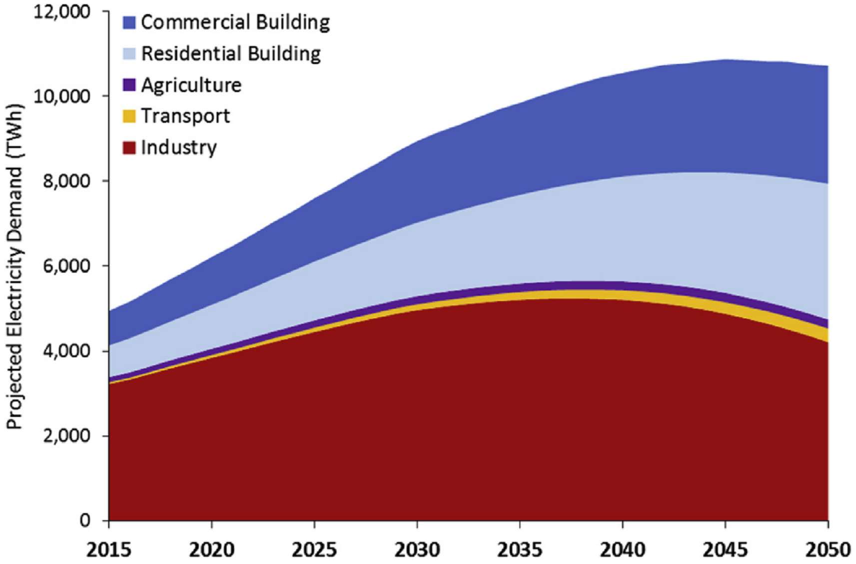

Fig. 1. China's projected electricity demand by end-use sector.

industries, particularly wind and solar PV, and with a 12th FYP target of 11.4% non-fossil energy consumption by 2015, several capacity targets have been revised upward. For example, the solar PV capacity target for 2020 was revised to 20 GW in 2011 and that target was surpassed in 2014 with 26.5 GW of installed solar capacity (NEA, 2015). Subsequent targets of 15% of non-fossil energy consumption by 2020 and 20% by 2030 were also announced by China.

In addition to generation-share targets for clean fuel sources, dispatch rules and priority order reforms thereof, also influence the generation fuel mix. In China, power-sector dispatch has historically followed an “equal-shares” formula, under which generators of different types are all guaranteed approximately the same number of operating hours through long-term contracts in order to ensure sufficient revenues for cost recovery (Kahrl et al., 2011). Unlike cost-based dispatch, equal-shares dispatch is economically inefficient as well as environmentally unsound because generators with high heat rates and low efficiency may receive the same number of hours as more efficient units with low heat rates. China has started to address the lack of incentives for more efficient and cleaner generation and dispatch, but reforms have not yet been fully implemented. The State Council issued “Detailed Rules for Implementing Energy Saving Generation Dispatch” in 2007 to prioritize renewable (including hydro) energy and nuclear generation over fossil-fuel generation. Pilot tests of this new dispatch order are being conducted on some provincial grids, with estimated annual coal reductions of 300,000 tons in the pilot province of Guizhou (Hu et al., 2013; Liu et al., 2010). In March 2015, the State Council also issued “Opinions Regarding Further Deepening of Power Sector Reform” to focus on improving integration and dispatch of renewable and demand side resources (State Council, 2015). This was followed by the national commitment to adopt the “green dispatch” policy in June 2015 and additional power sector policies were issued in November 2015.

In spite of these policies and targets, there is still a disconnect between China's rapidly growing renewable capacities and actual dispatch and utilization. Hong et al. (2013) found that the 2011 capacity factors of 35% for hydro, 22% for wind, and 15% for solar power in China were all significantly lower than the U.S. capacity factors of 48, 32%, and 24%, respectively. From 2011 to 2014, total renewable capacity nearly doubled from 294 GW to 442 GW, but the average capacity factors for wind and solar in China actually decreased to 19% and 10%, respectively. From 2011 to 2014, thermal capacity factor declined only slightly from 57% in 2010 to 52% in 2014 (NBS, 2015b). This suggests that significant portions of new renewable installed capacities are not being fully dispatched and utilized in China and that curtailment of renewable generation remains a key barrier to fully implementing green dispatch. Curtailment has persisted due to both infrastructural (e.g., weak grid structure, geographic resources imbalance and coal dominance) and operational factors (e.g., insufficient market mechanisms for renewable grid connection and dispatch, and technical challenges in balancing variable loads) (Zhao et al., 2012). In October 2015, Inner Mongolia and Gansu provinces were chosen as pilots for testing green dispatch, with coal-fired power designated for meeting peak load (NDRC, 2015b). In March 2016, the National Energy Administration announced that new wind capacity would not be added in the Northeastern and Western provinces of Jilin, Heilongjiang, Inner Mongolia, Gansu, Ningxia and Xinjiang because of the high curtailment rates in these provinces during 2015 (NEA, 2016). At the same time, China is also trying to rein in excess coal-fired capacity by halting plans for new plants and postponing construction of approved plants through 2018 (NDRC and NEA, 2016). While these recent reforms signal that more steps are being taken to reduce curtailment, the timeline and outlook for achieving full implementation of green dispatch nationwide remains uncertain.

Based on the most recent changes in renewable capacity targets and the remaining uncertainty over green dispatch implementation, we developed three scenarios to test the related policy impacts of renewable MMS and green dispatch in China:

1. **Base Renewable MMS with Equal Shares Dispatch Scenario:** a counterfactual baseline scenario reflecting the 2010 outlook on renewable power development and continued use of the existing “equal-shares” generation dispatch through 2050, assuming no new policies to successfully resolve curtailment and renewable dispatch barriers are adopted through 2050.
2. **Base Renewable MMS with Green Dispatch Scenario:** assumes that China continues to pursue renewable energy development following the revised 2011 renewable capacity targets and

assumes successful implementation of green dispatch as a result of supporting policies adopted since 2011.

3. **Strengthened Renewable MMS with Green Dispatch Scenario:** assumes that China adopts more aggressive renewable energy capacity build-out to meet the new non-fossil targets and successfully implements green dispatch.

Table 2 shows the key parameters of these three scenarios. As seen in Table 2, the difference between the counterfactual Baseline Renewable MMS Scenario with Equal Shares Dispatch and the Base Renewable MMS with Green Dispatch Scenario can be attributed solely to green dispatch. The difference between the Base Renewable MMS and Strengthened Renewable MMS with Green Dispatch Scenarios can then be attributed solely to the impact from accelerated renewable MMS targets.

2.3.2. *Carbon capture and sequestration in coal-fired power generation*

China's ongoing interest in adopting carbon capture and sequestration (CCS) technologies in the power sector is reflected in plans to build 12 CCS pilots over the next ten years. China issued national policy documents during the 12th FYP period to continue supporting CCS research and development, and jointly established the U.S.-China Clean Energy Research Center for Advanced Coal Technology in 2009. Although CCS technologies are now in the demonstration stage, various barriers to full commercialization include reliable storage capacity, high capital cost, environmental and ecological impacts, lack of societal support, and policy uncertainty (Viebahn et al., 2015). Several recent studies of China's future energy outlook, as well as the "Roadmap for CCS Demonstration and Deployment in China," found that CCS is unlikely to be commercially deployed on a large-scale until 2030 at the earliest (CERI, 2009; McKinsey and Co., 2009; Wang and Watson, 2010; ADB, 2015).

For this analysis, we developed a baseline scenario with no CCS and a base CCS policy scenario to evaluate the potential impact of policies promoting retrofits and installation of post-combustion CCS in existing and new ultra-supercritical coal-fired generation units after 2030. An additional sensitivity analysis scenario of doubling the pace of CCS deployment was used given the highly uncertain outlook of CCS adoption in China. These scenarios include:

1. **Baseline Scenario**: assumes no adoption of CCS technologies in the power sector through 2050 due to existing barriers to scale-up and commercialization in the absence of additional policies.
2. **Base CCS Policy Scenario**: assumes commercialization of CCS after 2030 with accelerate growth of post-combustion CCS installed capacity to a level capable of sequestering 500 Mt CO_2/year by 2050 based on the NDRC and ADB Roadmap analysis (ADB, 2015).
3. **Accelerated CCS Policy Scenario**: assumes more aggressive CCS deployment after 2030, resulting in doubling of post-combustion CCS installed capacity capable of sequestering 1000 Mt CO2/year by 2050.

Both CCS scenarios take into consideration the energy penalty of post-combustion CCS, with the amount of electricity required for post-combustion capture and sequestration assumed to stay constant at 0.33 kWh per kWh generated based on the Joint UK-China Net Zero Emissions Coal Initiative findings (NZEC, 2009). Fig. 2 shows the growth in assumed CCS installed capacity after 2030 for the two CCS policy scenarios.

2.3.3. *Improved efficiency in coal-fired power generation*

Beginning in the 11th FYP period, from 2006 to 2010, China mandated the retirement of small and inefficient coal-fired power generation plants and promoted the construction of larger and more efficient coal power plants. From 2006 to 2010, a total of 73.8 GW coal-fired generation capacity was decommissioned, resulting in an improved average thermal efficiency from 370 gce/kWh in 2005 to 333 gce/kWh in 2010 (Xu et al., 2013). The mandated retirement of inefficient coal power plants continued under the 12th FYP with accelerated coal-fired boiler retrofits and retirements of 50,000 small coal-fired boilers expected to save 23 Mtce by 2015 (State Council, 2014). The 2014–2020 Action Plan on Coal-fired Power Efficiency and Emission Reduction Upgrade and Retrofits further set targeted heat rate of 300 gce/kWh for new coal-fired power units and 310 gce/kWh for retrofitted coal-fired power units by 2020 (NDRC, 2015c). The plan also emphasized that new coal-fired power plants after 2020 should be ultra-supercritical units with capacity of 600 MW or greater. Based on these trends and policies, we developed two scenarios to evaluate the impact of continued implementation of mandates to transform the coal-fired generation fleet:

1. **Baseline Coal-fired Efficiency Scenario:** assumes continuation of the early-retirement policies for small inefficient coal-fired generation initiated during the 11th FYP period.
2. **Accelerated Coal-fired Efficiency Scenario:** assumes policies in support of the 2014–2020 Action Plan mandating faster retirement of small and medium-sized subcritical units are successful and accelerated adoption of efficient supercritical and ultra-supercritical coal-fired generation, with no new units of less than 600 MW capacity after 2020.

Table 3 shows the assumed shares of different coal-fired generation technologies under these two scenarios.

Table 2
Renewable installed capacity assumptions for renewable MMS and green dispatch scenarios.

	Base renewable MMS with equal shares scenario			Base renewable MMS with green dispatch scenario			Strengthened renewable MMS with green dispatch scenario		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Renewable capacity (GW)	545	926	1777	545	926	1777	677	1132	3067
Biomass	10	16	47	10	16	47	10	16	47
Hydropower	300	350	380	300	350	380	333	400	500
Wind	150	300	400	150	300	400	184	366	720
Solar[a]	85	260	950	85	260	950	150	350	1800
Dispatch order	Equal shares			Green dispatch			Green dispatch		

[a] Note: 2020 solar installed capacity was set at 85 GW in the counterfactual baseline and base MMS scenarios to account for faster-than-expected achievement of the original 2020 target of 20 GW.

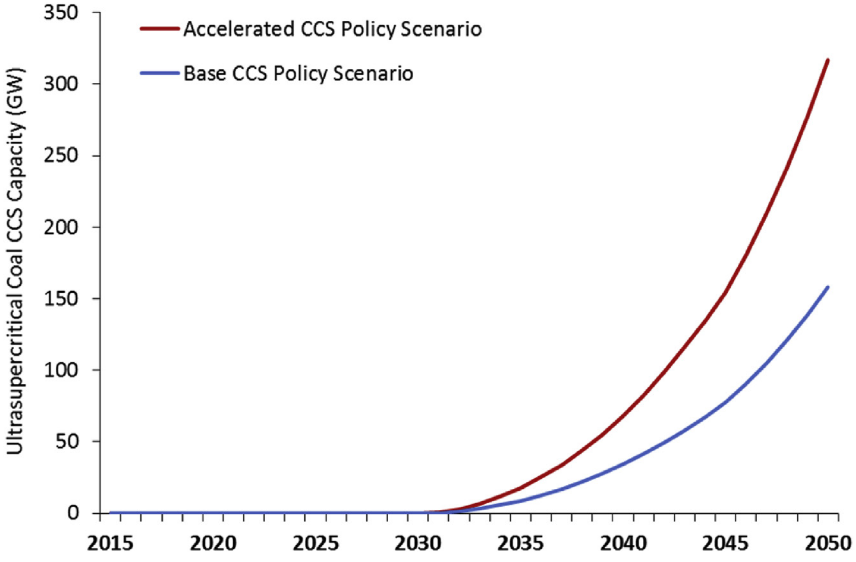

Fig. 2. Growth in assumed installed CCS capacity for CCS policy scenarios.

3. Results and discussion

3.1. *Mandatory market share for renewable power generation*

Fig. 3 shows the electricity generation by fuel source for each of the three renewable target and dispatch scenarios, given the electricity demand discussed in section 2.2. The generation fuel mix between the Base Renewable MMS with Equal Shares Dispatch and Base Renewable MMS with Green Dispatch scenarios are very similar. By 2050, the green dispatch scenario has a slightly lower 40% share for coal generation and a 24% share for renewable generation versus 43% coal generation and 22% renewable generation in the equal-shares dispatch scenario. In contrast, the share of coal-fired generation drops from 59% to 40% in 2030 and 2050, respectively, in the Base Renewable MMS with Green Dispatch scenario to 53% and 14% in 2030 and 2050, respectively, in the Accelerated Renewable MMS with Green Dispatch scenario. By 2050, the annual renewable generation will reach 4472 TWh in the Accelerated Renewable MMS Scenario, versus only 2511 TWh in the Base Renewable MMS Scenario with Green Dispatch. Most of the increased renewable generation will be from wind and solar generation, with additional 752 TWh from wind and 1208 TWh from solar generation possible per year by 2050 if the more aggressive renewable installed capacities are fully dispatched. This will require not only effectively implementing much more aggressive renewable-capacity targets, but also resolving existing grid integration challenges to realize national adoption of green dispatch. Policies that could help achieve these objectives include expediting the renewable energy quota system to increase investment in solar PV power, refining existing national feed-in tariff schemes to mitigate curtailment of wind and solar power, and developing technical standards for grid-connected solar PV power (Zhang et al., 2013). In addition, expansion of ultra-high voltage transmission lines can help further alleviate the regional imbalances among renewable resources and electricity demand and reduce surplus wind power and subsequent curtailment (Wang et al., 2014).

Table 3
Assumed coal-fired generation shares by capacity size for coal efficiency scenarios.

Percentage of generation fleet	Baseline coal-fired efficiency scenario			Accelerated coal-fired efficiency scenario		
	2020	2030	2050	2020	2030	2050
Coal <100 MW	5%	0%	0%	0%	0%	0%
Coal 100–200 MW	5%	2%	0%	0%	0%	0%
Coal 200–300 MW subcritical	5%	5%	2%	3%	0%	0%
Coal 300–600 MW subcritical	30%	18%	8%	20%	5%	0%
Coal 600–1000 MW supercritical	35%	25%	15%	45%	35%	5%
Coal >1000 MW ultra-supercritical	20%	50%	75%	32%	60%	95%
Total installed coal capacity (GW)	1044	1343	1234	1044	1343	1234

Figs. 4 and 5 compare the coal and CO_2 impacts resulting from the full implementation of green dispatch and adoption of accelerated renewable MMS policies. Without adopting more aggressive renewable targets, national green dispatch will result in annual savings of 118 Mtce of coal in 2050 with cumulative reduction of 5740 Mtce of coal from 2015 through 2050. If more aggressive renewable targets are adopted, the annual coal savings will double by 2030 and increase eight-fold by 2050 as a result of the significant displacement of coal by higher solar and wind generation from 2030 to 2050. Cumulatively, the additional savings of more aggressive renewable MMS could reach 13,960 Mtce of coal over the next 35 years.

In terms of CO_2 emissions, green dispatch with base renewable MMS policies can reduce power-sector CO_2 emissions with annual reduction of 313 Mt CO_2 by 2050 compared to the Base Renewables with Equal Shares Dispatch baseline scenario. Green dispatch could also cause power sector CO_2 emissions to peak two years earlier, with 5.37 gigatonne (Gt) CO_2 in 2038 instead of 5.83 Gt CO_2 in 2040 based on continuation of equal shares dispatch. If more aggressive renewable MMS policies were adopted in addition to green dispatch, power-sector CO_2 emissions could peak as early as 2030, with additional reductions of 2.61 Gt CO_2 annually in 2050. Overall, the carbon intensity of electricity generation could decrease from the 2014 level of 0.61 kg CO_2/kWh to 0.39 kg CO_2/kWh by 2050 as a result of fully implementing green dispatch, and further decrease to only 0.14 kg CO_2/kWh by 2050 with accelerated renewable MMS policies.

These results suggest that significant energy-related CO_2 reductions can only be achieved if green dispatch is implemented system-wide *and* if renewable MMS policies are accelerated. Both of these policy conditions require that regulatory and policy mechanisms are in place to ensure adequate grid connection and

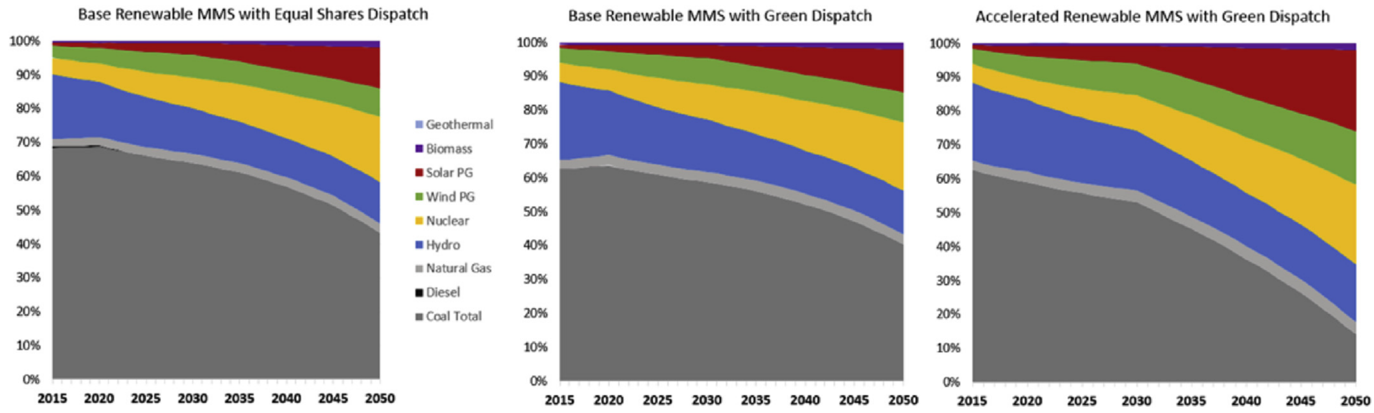

Fig. 3. Electricity generation by fuel shares for renewable MMS and green dispatch scenarios.

intermittency balancing, particularly in later years as solar and wind resources provide a much larger share of generation. For example, a two-part wholesale pricing reform in which generators receive a capacity payment for operational availability plus a payment based on the marginal cost of production for their electricity output, could help avoid some of the financial burdens on providers whose fossil-based generation would be reduced under green dispatch. This reform could also help ensure that peaking fossil-fuel generators, which are used rarely but are nonetheless needed at certain peak times, can survive financially under the new dispatch order.

3.2. *Carbon capture and sequestration in coal-fired generation*

By 2050, the base CCS policy scenario requires 25 Mtce more primary energy per year than the baseline scenario without CCS because of the energy required for carbon separation, compression, and pumping, as seen in Fig. 6. The accelerated CCS policy scenario requires 50 Mtce in 2050, or 2% more primary energy than the baseline scenario without CCS, as a result of greater CCS energy requirements to sequester doubled the CO_2 by 2050. On a cumulative basis, from 2030 to 2050, as much as 182 Mtce of primary energy are needed to meet the energy requirements of installing the base CCS capacity to sequester 500 Mt CO2 by 2050. To meet the 2050 electricity demand, the base and accelerated CCS policy scenarios also require 14 GW and 28 GW more coal-fired capacity, respectively, to compensate for the parasitic load.

In 2050, the energy penalty for CCS translates into 70 Mt CO_2 emissions for the base CCS policy scenario and 140 Mt CO_2 for the accelerated CCS policy scenario, which offsets some of the total CO_2 sequestered. Fig. 7 shows the net CO_2 emissions of the power sector after considering the total CO_2 sequestered and the offset by increased CO_2 emissions from the CCS energy penalty. Based on our assumption that large-scale CCS deployment will not start until after 2030, installing the base CCS capacity will allow power sector CO_2 emissions to peak two years earlier with 5.3 Gt CO_2 in 2036, while doubling the CCS capacity will further lower the peak CO_2 emissions by 50 Mt CO_2 but will not change the peak year. These results suggest that installing CCS could reduce power sector CO_2 emissions and lead to a slightly earlier peak, although it does not significantly change the emissions trajectory.

3.3. *Improving efficiency in coal-fired power generation*

Fig. 8 shows the breakout of coal-fired generation output under the Baseline and Accelerated Coal Efficiency scenarios. With accelerated coal efficiency policies, the share of ultra-supercritical coal-fired units with greater than 1000 MW installed capacity

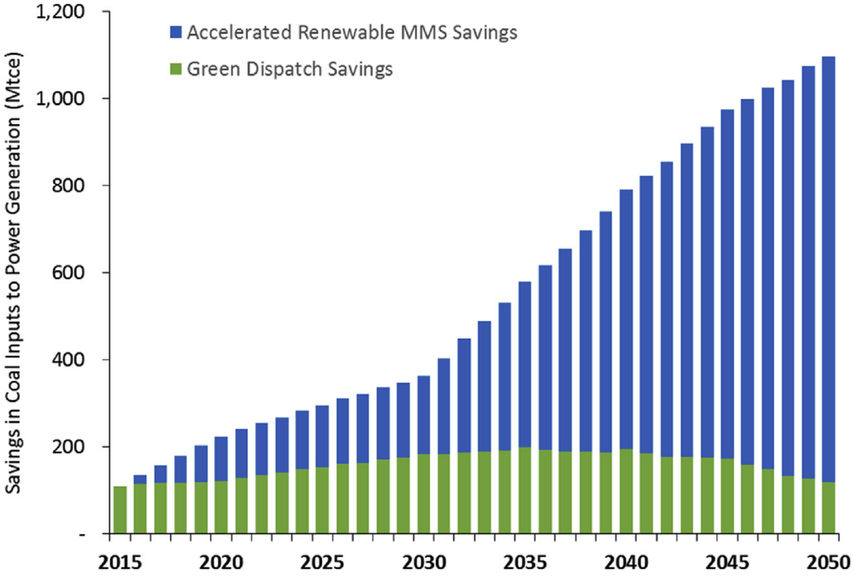

Fig. 4. Savings in coal input to power sector resulting from mandatory market share for renewables.

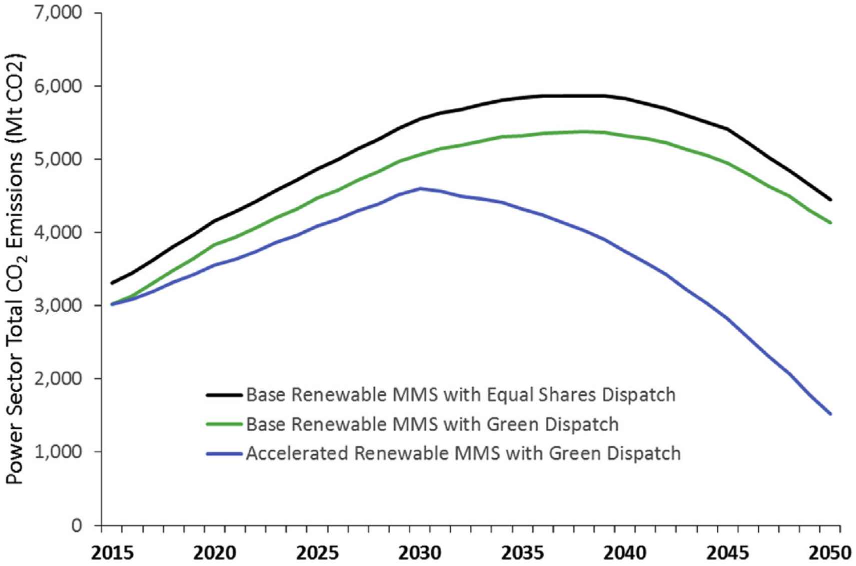

Fig. 5. Comparison of power sector CO_2 emissions from mandatory market share for renewables scenarios.

will increase rapidly after 2030 to reach 50% of total electricity generation by 2040. Subcritical coal-fired units (300–600 MW) are phased-out twenty years earlier (in 2030) and supercritical (600–1000 MW) are virtually phased-out ten years earlier (by 2040).

Improvements in coal-fired generation efficiency as a result of coal transformation policies and new heat-rate targets reduce the total energy input needed to meet electricity demand. Annual energy savings on the order of 11–24 Mtce and cumulative savings of 694 Mtce from 2015 to 2050 can be achieved as a result of accelerated efficiency improvements beyond the current baseline levels of efficiency improvement. Despite the earlier phase-outs of supercritical and subcritical coal-fired units under the Accelerated Coal Efficiency scenario, the relatively small savings from accelerated coal efficiency improvements reflect the relatively high efficiencies for coal-fired units captured in the baseline efficiency scenario. Significant improvements in the coal-fired generation efficiency were achieved from 2000 to 2010 and the fewer small plants remaining have a shrinking share of total coal-fired capacity (Xu et al., 2013). As illustrated in Fig. 9, accelerated coal-generation efficiency will achieve relatively small annual CO_2 emissions reductions, on the order of 28–55 Mt CO_2, but can shift power sector CO_2 emissions peak two years earlier (to 2037) compared to the baseline scenario.

3.4. Contextualizing supply-side power sector policy savings

Table 4 summarizes the 2030 and 2050 annual and cumulative CO_2 emissions reduction associated with the four power-sector policies. Prior to 2030, successful implementation of green dispatch and accelerated renewable MMS will result in similar reductions of CO_2 emissions. However, the emissions reduction from

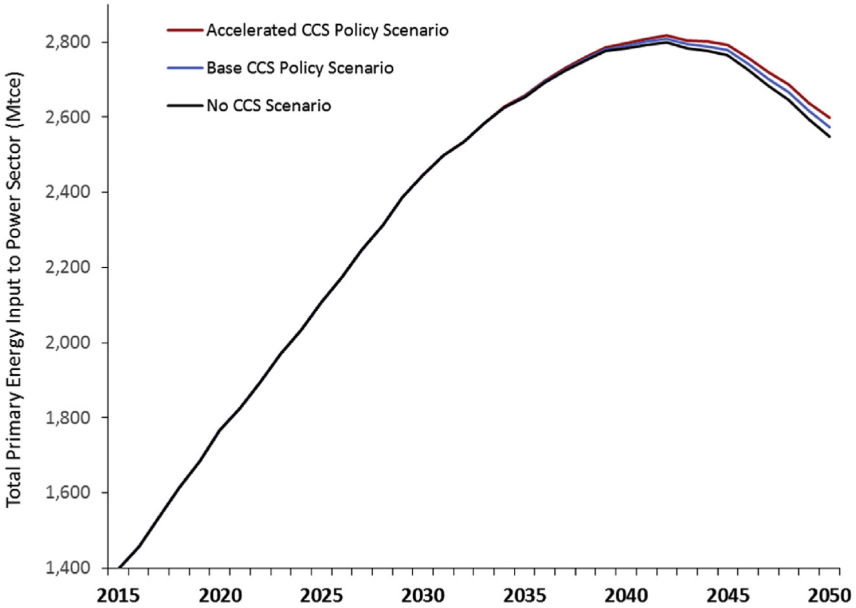

Fig. 6. Total primary energy input to power sector by CCS scenario. Note: Y-axis does not start at zero.

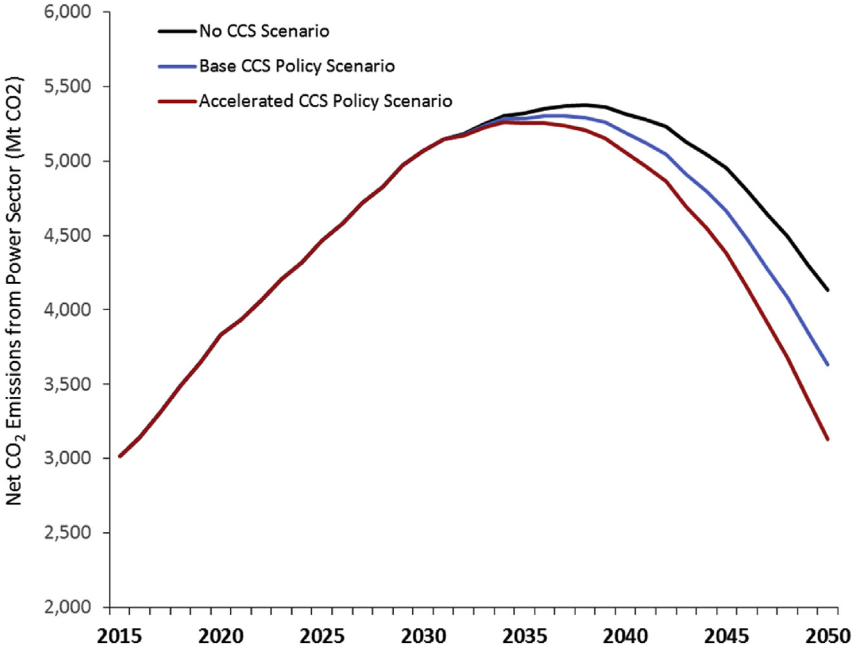

Fig. 7. Net Power Sector CO_2 emissions by CCS policy scenario. Note: Y-axis not does not start at zero. Net CO_2 refers to net CO_2 from generation and CO_2 sequestered.

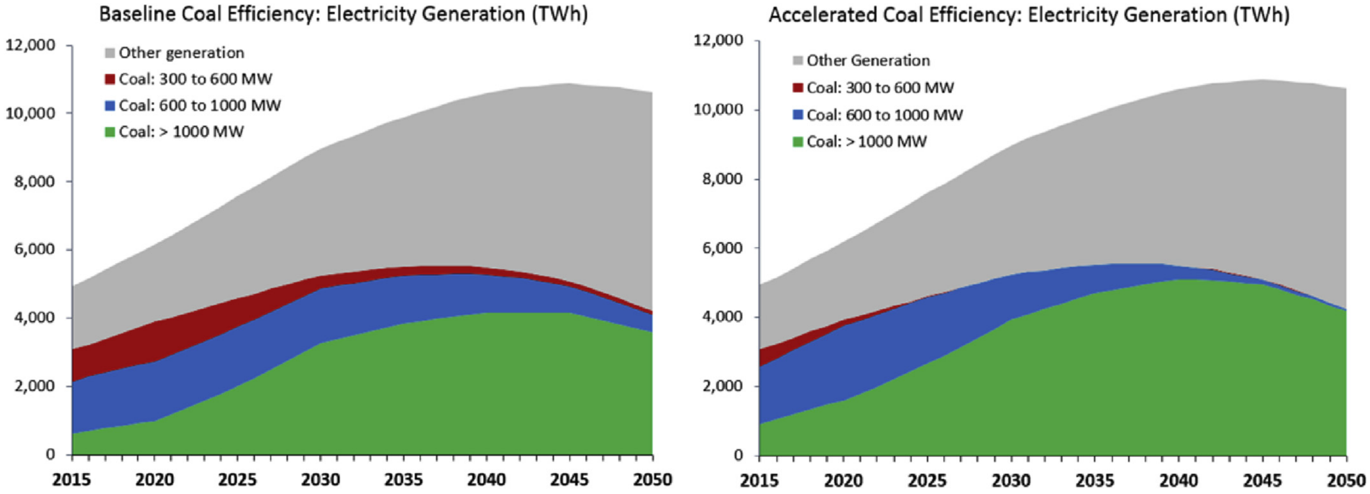

Fig. 8. Power generation output by coal-fired power plant sizes for baseline and accelerated coal efficiency scenarios.

accelerated renewable MMS will far exceed green dispatch reductions after 2030. Accelerated coal-efficiency improvements have the lowest annual and cumulative CO_2 emissions reduction potential of all four policies.

While the power-sector policies evaluated in this paper contribute to national energy and CO_2 emissions reductions, it is also important to contextualize these savings in light of the demand-side energy efficiency efforts underway in China. Ke et al. (2012) found that the Top 1000 Program focused on improving the efficiency of nine major energy-intensive industrial subsectors achieved annual savings of 20, 50, and 35 Mtce in 2006, 2007, and 2008, respectively. These savings are comparable to the potential savings from accelerated coal efficiency (13–23 Mtce/year) and accelerated renewable MMS (14–69 Mtce/year), and slightly lower than the green dispatch savings (75–78 Mtce/year) projected for 2016 to 2020. On a cumulative basis, the 1600 Mt CO_2 reduction in power sector CO_2 emissions from 2016 to 2020 from fully implementing green dispatch could equal twice the estimated 760 to 806 Mt CO_2 reduced cumulatively from 2011 to 2015 based on industrial energy efficiency improvements (Yu et al., 2015).

By 2020, projected annual reductions of 8% and 7% in power sector CO_2 emissions from green dispatch and accelerated renewable MMS policies, respectively, are also comparable to the projected 10% reduction in Guangdong's power sector CO_2 emissions from its pilot carbon-emissions trading system (ETS) (Cheng et al., 2015). Similar to green dispatch and accelerated renewable MMS, CO_2 emissions reductions from the ETS can only be achieved with successful market reforms that allow electricity prices to reflect the carbon costs. An effective ETS for the power sector will also require a shift away from equal-shares dispatch to a more flexible dispatch system that allows operators to adjust electricity production based on the cost of carbon (Teng et al., 2015).

Demand-side efficiency can also contribute to power sector CO_2 emissions reduction by reducing total electricity demand. Zhou

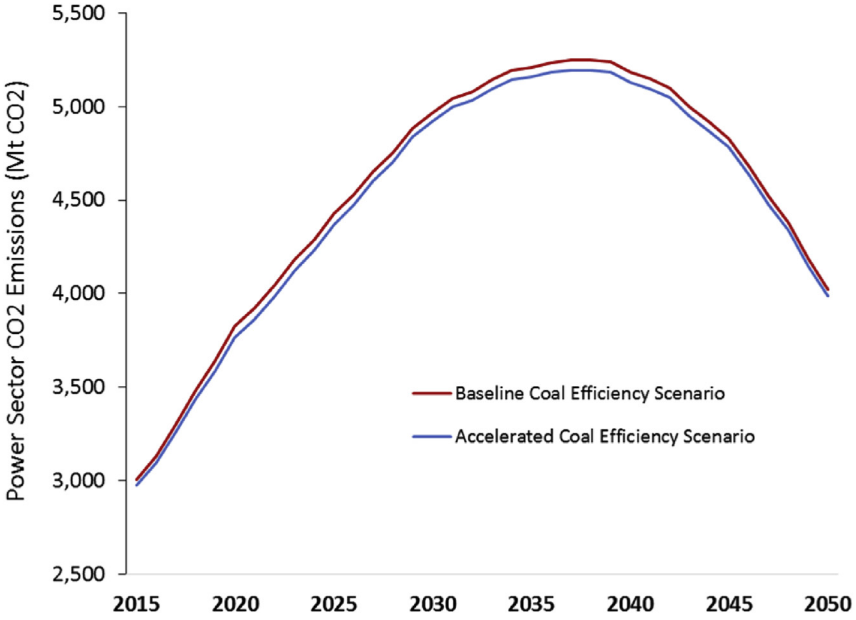

Fig. 9. Power-sector CO_2 emissions by coal efficiency scenarios. Note: Y-axis does not start at zero.

Table 4
Summary of annual and cumulative CO_2 emissions reduction of power sector policies.

Unit: Mt CO_2	Annual CO_2 emission reduction		Cumulative CO_2 emission reduction	
	2030	2050	2015–2030	2031–2050
Green dispatch	481	313	6021	9146
Accelerated renewable MMS	472	2611	4711	32,357
Base CCS	–	500	–	3649
Accelerated CCS	–	1000	–	7298
Accelerated coal efficiency improvement	44	35	796	961

et al. (2014) found that accelerated demand-side management and efficiency improvements beyond the current pace of improvement can reduce total electricity demand by 10% by 2030. This reduction is particularly important in the short-term because it can mitigate the need for building new coal-fired power plants, particularly if renewable capacities and existing coal-fired capacities are more fully utilized under the green-dispatch system.

4. Conclusions

China's power sector has grown by leaps and bounds in recent years, keeping pace with unprecedented continuous economic growth. This rapid power-sector growth has led to the adoption of numerous policies emphasizing generation efficiency and aggressive non-fossil energy targets. Although China has set aggressive targets for renewable and non-fossil generation, policy impacts have been constrained by solar and wind power curtailment, grid connection barriers, and challenges related to full implementation of green dispatch. We contributed to the existing literature by quantitatively evaluating four sets of power-sector efficiency and low-carbon policies to illustrate the wide-ranging and interlinked impacts of these policies on energy savings, particularly in terms of displacing coal input and reducing CO_2 emissions. This analysis focused on supply-side policies for the power sector and did not attempt to quantify the linkages between the supply and demand sides, including the effects of increased electrification and changes in electricity usage and efficiency.

Despite this limitation, broad comparisons across the recent power-sector policies implemented in China show that the two sets of policies that help expand renewable generation – green dispatch along with accelerated MMS for renewables – can displace significant amounts of coal, reducing total power-sector CO_2 emissions with a peak as early as 2030. Successful implementation of a green-dispatch policy would have a large impact in terms of reducing power sector CO_2 emissions before 2030, when renewable capacity grows at a slower rate than the period after 2030. Absent a MMS policy, the power-sector CO_2 emissions peak would be delayed to 2038, making it more difficult for China to achieve its national CO_2 emissions peak of 2030 or earlier. These results highlight the urgent need for improving grid connection and resolving curtailment issues to help China implement national green dispatch and accelerate renewable MMS policies, as it is difficult to effectively implement one policy without the other. Although specific policy recommendations for resolving the remaining issues associated with renewable curtailment are beyond the scope of this paper, our findings suggest that broader power sector reforms and more supportive policies, such as those recently adopted for limiting wind development in high-curtailment regions, are needed to facilitate grid connection and intermittency balancing.

In contrast, although policies to improve coal-generation efficiency are important, their effect on coal input and CO_2 emissions in the long run is limited because recent policies have already greatly improved the average thermal efficiency of coal-fired generation. Coal generation is also expected to decline significantly as construction of new coal power plants has been halted by the national government through 2018 and replaced by growing renewable energy and nuclear generation. Policies promoting CCS in coal-fired generation can sizably reduce power-sector CO_2 emissions in the later years of the planning horizon, but will increase primary energy requirements due to the energy penalty and will shift the power-sector CO_2 emissions peak to slightly earlier. This finding underscores the relevance of power-decarbonization policies aimed at reducing the CO_2 emissions associated with electricity consumption from the expansion of residential and commercial buildings as well as transport and industrial electrification.

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