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Current Emissions and Future Mitigation Pathways of Coal-Fired Power Plants in China from 2010 to 2030

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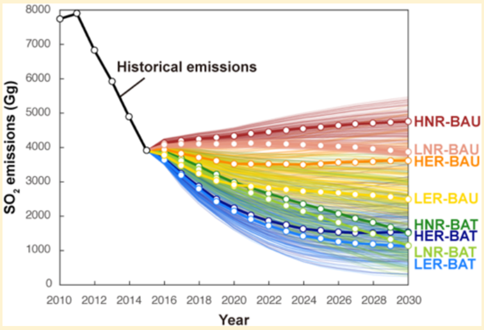
Supporting Information

ABSTRACT: As the largest energy infrastructure in China, the power sector consumed approximately half of China's coal over the past decade and threatened air quality and greenhouse gas (GHG) abatement targets. In this work, we assessed the evolution of coal-fired power plants and associated emissions in China during 2010−2030 by using a unit-based emission projection model, which integrated the historical power plant information, turnover of the future power plant fleet, and evolution of end-of-pipe control technologies. We found that, driven by stringent environmental legislation, SO_2, NO_x, and $PM_{2.5}$ (particulate matter less than 2.5 μm in diameter) emissions from coal-fired power plants decreased by 49%, 45%, and 24%, respectively, during 2010−2015, compared to 15% increase in CO_2 emissions. In contrast to ever-increasing CO_2 emissions until 2030 under current energy development planning, we found that aggressive energy development planning could curb CO_2 emissions from the peak before 2030. Owing to the implementation of a "near zero" emission control policy, we projected emissions of air pollutants will significantly decrease during 2016−2030. Early retirement of small and low-efficiency power plants would further reduce air pollutants and CO_2 emissions. Our study explored various mitigation pathways for China's coal-fired power plants, which could reduce coal consumption, air pollutants, and CO_2 emissions and improve energy efficiency.



INTRODUCTION

Among the major anthropogenic emitting sources, power plants contribute significantly to emissions of greenhouse gases and air pollutants in China (32% CO_2, 33% SO_2, 33% NO_x, and 6% $PM_{2.5}$ (particulate matter less than 2.5 μm in diameter) in 2010[1]) and play important roles in regional air quality, ecosystem acidification, and climate change.[2,3] During 2006−2010, a 54% decrease was obtained from coal-fired power plants for SO_2 emissions through the widespread installation of flue gas desulfurization (FGD) systems and the substitution of lower sulfur fuels.[4] This is the most important step to reduce national SO_2 emissions by 10% during the "11th Five-Year-Plan (2006−2010)" (11th FYP).[5] In the 12th FYP, China set a target to reduce national NO_x emissions by 10% for the first time, thus, fewer actions were taken to diminish NO_x emissions until 2010.[6,7] To mitigate the heavy haze pollution in China, the Chinese government released the Air Pollution Prevention and Control Action Plan (the "Action Plan") in 2013.[8] In addition, China announced its intention to achieve a peak in CO_2 emissions by 2030 and make every effort to achieve this peak earlier to tackle global climate change.[9,10]

A series of emission control measures for various sectors have been taken in support of the Action Plan by national and local governments. In view of the coal-dominated energy structure in the power sector, the development of clean coal-fired power generation has been promoted by issuing "Full Implementation of Ultra-low Emission and Energy-saving Transformation of Coal-fired Power Plants" (the "Power Plan") in December 2015.[11] The Power Plan announced that all coal-fired units in China should strive to implement an ultralow emission standard (also called "near zero" emissions) before 2020 by accelerating the retirement of outdated units, transforming the remaining units to achieve ultralow emission levels, and applying the most advanced combustion technologies for new generation units to improve energy efficiency. Emission reductions from the power sector play an important role in future air quality improvement and climate change alleviation. Therefore, quantifying historical emissions and exploring future mitigation pathways from coal-fired power plants is valuable for policy making.

Historical trends and future projections of coal-fired power sector emissions have been estimated in many national, regional, and global emissions inventories and for individual

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sectors.[1,2,4,12−21] With the development of technology-based methodologies and unit-level power plant emissions databases, the accuracy of the historical emission magnitudes and spatial resolutions have been significantly improved.[2,4,6,16] In previous work, we developed a unit-based database named the China coal-fired Power plant Emissions Database (CPED),[4] and it includes detailed information on individual units for the period 1990−2010. In addition, future emissions of the power sector in previous works are explored under different penetration assumptions of combustion technologies and end-of-pipe control measures in 5 or 10 year steps.[2,6,12,14,15,17] Those studies treated power plants as one single sector, ignoring the differences of combustion technologies and control technologies among current power units and the integration of latest historical unit-based information, which could not track the future evolution of power plant fleet accurately, reflect the latest policy, and provide possible emissions mitigation pathways in the power sector.

This paper presents the evolution of the coal-fired power plant fleet in China and the evolution of SO_2, NO_x, $PM_{2.5}$, PM_{10}, and CO_2 emissions from coal-fired power plants for the period 2010−2030 by using a unit-based emission projection model. We first developed a high-resolution coal-fired power plant emission inventory during 2010−2015 that contains the latest unit-specific data and provided an overall understanding of major policies for emissions mitigation and power plant fleet optimization during the 12th FYP. We then explored future mitigation pathways from coal-fired power plants over China through the year 2030 under various coal-fired electricity demand, power supply, and end-of-pipe control scenarios, which could reduce air pollutants and CO_2 emissions, save energy, and optimize the power plant fleet.

■ MATERIALS AND METHODS

Unit-Based Power Plant Emission Inventory from 2010 to 2015. A power plant emission inventory for 2010−2015 was developed in this study by integrating the latest unit-based information from the Ministry of Ecology and Environment (MEE; unpublished data, referred to hereafter as the MEE database). The annual SO_2, NO_x, $PM_{2.5}$, PM_{10}, and CO_2 emissions for specific units from 2010 to 2015 are estimated using the following equation:[4]

$$E_{s,i,y} = \sum_{m=1}^{12} \left[U_i P_{i,y} (H_0/H_{i,y}) T_{i,y} f_{m,y} \mathrm{EF}_{s,i,y} \prod_{n} (1 - \eta_{s,n,i,y} \tau_{n,m,y}) \right] \quad (1)$$

where s, i, y, m, and n represent the emission species, power unit, year, month, and emission abatement technology type, respectively. U is the unit capacity in MW; P is the coal consumption rate presented in grams coal equivalent per kWh supplied (gce kWh^{-1}); H is the heating value of coal used for each unit in kJ g^{-1}; H_0 is the heating value of standard coal, which is 29.27 kJ gce^{-1} (the ratio of H_0 to H converts the coal equivalent (gce) to the physical quality of coal (g)); T is the annual operation in hours (the product of U and T is the annual electricity generation); f is the monthly fraction of annual electricity generation; EF is the unabated emission factor, in g kg^{-1} of coal; η is a parameter representing the removal efficiency of the abatement equipment; and τ is the state factor for the abatement equipment. When the equipment is present and running, $\tau = 1$; otherwise, $\tau = 0$.

The description of the MEE database and the method for obtaining activity rates and emission factors can been found in Supporting Information (SI).

Future Projections. A unit-based emission projection model was developed for this study to estimate future power plant emissions over China through 2030. As shown in Figure 1, the model was designed to simulate power plant fleet turnover by tracking the lifespan of each power generation unit. For a given future year, the model first estimates the power supply capability of in-fleet units, which is determined by the capacity and annual operating hours. The model then estimates the coal-fired power supply gap under the total predicted electricity demand and the share of coal-fired power generation and fills the gap using new generation units. By assuming different lifetimes and retirement policies for each unit in different scenarios, the power plant fleet structure then changes as a result of the retirement of old units and construction of new units. We then modeled the changes in emission factors at the unit level by considering the evolution of end-of-pipe control technologies under different environmental regulation scenarios. Future emissions for each unit were then estimated using eq 1. Note that our model was carried out under a fixed coal-fired power generation demand to simulate how the coal-fired power generation demand drives the power plant fleet turnover. Therefore, the change of coal-fired power generation demand by new technological innovations or expanded transmission in renewable or clean energy is out of the boundary of our model.

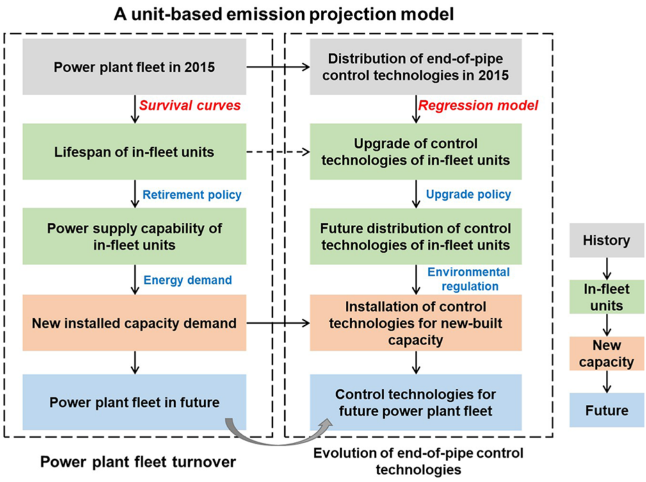

Figure 1. Framework of projections model.

In this work, we designed two coal-fired electricity demand scenarios under different development plans. The first scenario assumes a moderate decrease of coal-fired electricity share in future based on development planning for renewable energy in the power sector (high demand, H), and an aggressive action for developing renewable energy in future was designed in the second scenario (low demand, L). We then designed two power supply scenarios. The baseline scenario assumes that all current units will be retired with 40-year life times, and additional power demand is then supplied by new power plants (natural retirement, NR). The second scenario then assumes that small, old, or inefficient power units (called "outdated" power units) will be retired early and replaced with new power plants (early retirement, ER). We finally designed two end-of-pipe control scenarios. The first scenario assumes that the end-of-pipe control technologies will follow current legislation and maintain the average control levels in the year of 2015 (business as usual, BAU), and the second scenario assumes that the best available technologies will be fully applied to all power plants before 2030 (best available technology, BAT). We therefore created two sets of four different emission scenarios, totally eight scenarios (HNR-BAU, HNR-BAT, HER-BAU, and HER-BAT scenarios; and LNR-BAU, LNR-BAT, LER-BAU, and LER-BAT scenarios) made from two coal-fired electricity demand scenarios, two power supply scenarios, and two end-of-pipe control scenarios (Table S1). In addition, carbon capture and storage (CCS) technology is considered as a promising technology to fight climate change.[22,23] As reported, more than 10 CCS projects are in operation, planned, or under construction in coal-fired power plants, indicating broad prospects for CCS development supported by governments.[24,25] Although CCS technology could significantly reduce CO_2 emissions, additionally 25−40% electricity consumed when operating would increase air pollutants and CO_2 emissions.[23] Therefore, a set of sensitivity test scenarios (CHER-BAT and CLER-BAT scenarios) is designed to quantify the trade-off between air pollutants and CO_2 emissions.

Estimation of Future Coal-Fired Electricity Demand. We followed the predictions of future total electricity demand under a planning scenario from the Research on the Energy Development Strategy of China in Mid and Long-term (the "Energy Strategy").[26] According to the Energy Strategy, the total power generation will increase to 9020 TWh by 2030 with an average annual growth rate of 3.0% from 2015 to 2030. A range of models and previous studies provide important perspectives on the coal-fired electricity demand under current legislation and climate goals[27−31](Table S2). It is projected that the share of coal-fired electricity ranges from 33.1% to 85.4% in 2030; the large range in the share of coal-fired electricity indicates the uncertainty of energy pathways and long-term carbon mitigations. In view that the share of coal-fired electricity is 70.8% in 2015, decreases to 57.0% (H scenario) and 43.0% (L scenario) in 2030 are chosen as two demand scenarios based on current and aggressive development planning for renewable energy and different carbon budgets in the power sector (Table S3),[15,27−33] respectively. Two demand scenarios are designed to explore the emission mitigation benefits from low-carbon energy transitions. Detailed description on choosing two shares of coal-fired electricity is shown in the SI. In addition, additional energy consumptions by CCS technologies (C scenarios) are also evaluated in the SI.

Modeling Future Power Plant Fleet. The NR scenario assumes that the annual supplied electricity for in-fleet units during their lifespan remains at the 2015 level. Historically, statistical results show that coal-fired units generally operate for ∼40 years globally, which reflects the decision to retire a unit or power plant with the economic consideration of operating costs, replacement costs, and revenues.[34] Therefore, a single reference lifetime of 40 years for all units was assumed in the NR scenario. We assumed that the annual operating hours for all the units remain at the average level of 2015, and the power supply gap was then filled up by new generation units. More details of new generation units are given in SI text.

The ER scenario shares the same assumptions as the NR scenario with the exception of the life spans of the in-fleet units. In fact, the average lifetime of China's coal-fired units is ∼28 years by summarizing the retired units from the CPED. Unlike the decision to retire a generator driven by economic considerations worldwide, in China, the decision is mainly driven by policies at present. In recent years, the government has constantly optimized the generation unit fleet by promoting large units and decommissioning small units,[4] and mandatory retirement in China is much faster than natural retirement compared to other countries.[35] That is why the average lifetime of China's coal-fired power units is much shorter than that of global coal-fired generators. Our study modeled the historical survival of all the generators by considering their ages, installed capacities, and coal consumption rates (Figures S1 and S2). And we then predicted the survival curves of in-fleet units and determined their retirement orders by their median retirement ages (see the SI). The aim of our designed power supply scenarios (NR vs ER scenarios) was to explore the environmental benefits of optimizing the power plant fleet.

Evolution of End-of-Pipe Control Technologies. We modeled the changes in unit-based emission factors by considering the evolution of the end-of-pipe control technologies. The BAU scenario assumes that all current environmental regulations and development plans (until the end of 2014) would be implemented without any additional environmental policy from 2016 to 2030. We assumed that the removal efficiencies of all FGD facilities and de-NO_x devices for in-fleet units will be the same as the control levels of 2015 by 2030 (Figure S3), respectively. The removal efficiencies of FGD and de-NO_x devices for new generation units maintain the average control levels in the year 2015. We also consider that all units should be at least equipped with electrostatic precipitators (ESPs)[36] until 2030. For removing CO_2 emissions, in view of pretty small share of planned coal-CCS capacity in coal-fired power plants (∼0.7%), we assumed control measures to remove CO_2 until 2030 were not implemented under both BAU and BAT scenarios, but a sensitivity test of coal-CCS penetration of 10% by 2030 is added to quantify the trade-off between air pollutants and CO_2 emissions.[27−31]

Under the BAT scenario, we assumed that the maximum technically feasible control technologies would be fully applied by 2030 to realize "near zero" emissions for all units under the Power Plan. The removal efficiencies of the FGD and de-NO_x devices for all units were considered to be at least 95% and 85%, respectively.[37,38] Wet electrostatic precipitators (WESPs) are expected to be widely placed into commercial use in the near future,[39,40] and they are usually installed after all regular control devices. Under the BAT scenario, all units were assumed to be equipped with additional WESPs after fabric baghouses (FABs). De-SO_2, de-NO_x, and de-PM devices should be upgraded in order when their removal efficiencies do not meet the minimum assumptions in the BAT scenario; otherwise, they will remain at the same level as in 2015. A generalized linear regression model was developed to determine the upgrade order for de-SO_2, de-NO_x, and de-PM devices, respectively. More details of the upgrade model are given in SI text.

In fact, projections intended to represent plausible emissions pathways, and future projections are subject to large uncertainties due to policy implementation and technology development. In this study, we used scenario analysis (developing "plausible" scenarios that span an interesting range of possible outcomes) to approach the problem of pathways[41] (see SI; Table S4).

■ RESULTS

Operating Capacity, Coal Consumption, and Emissions from 2010 to 2015. Figure 2 and Table 1 summarize the

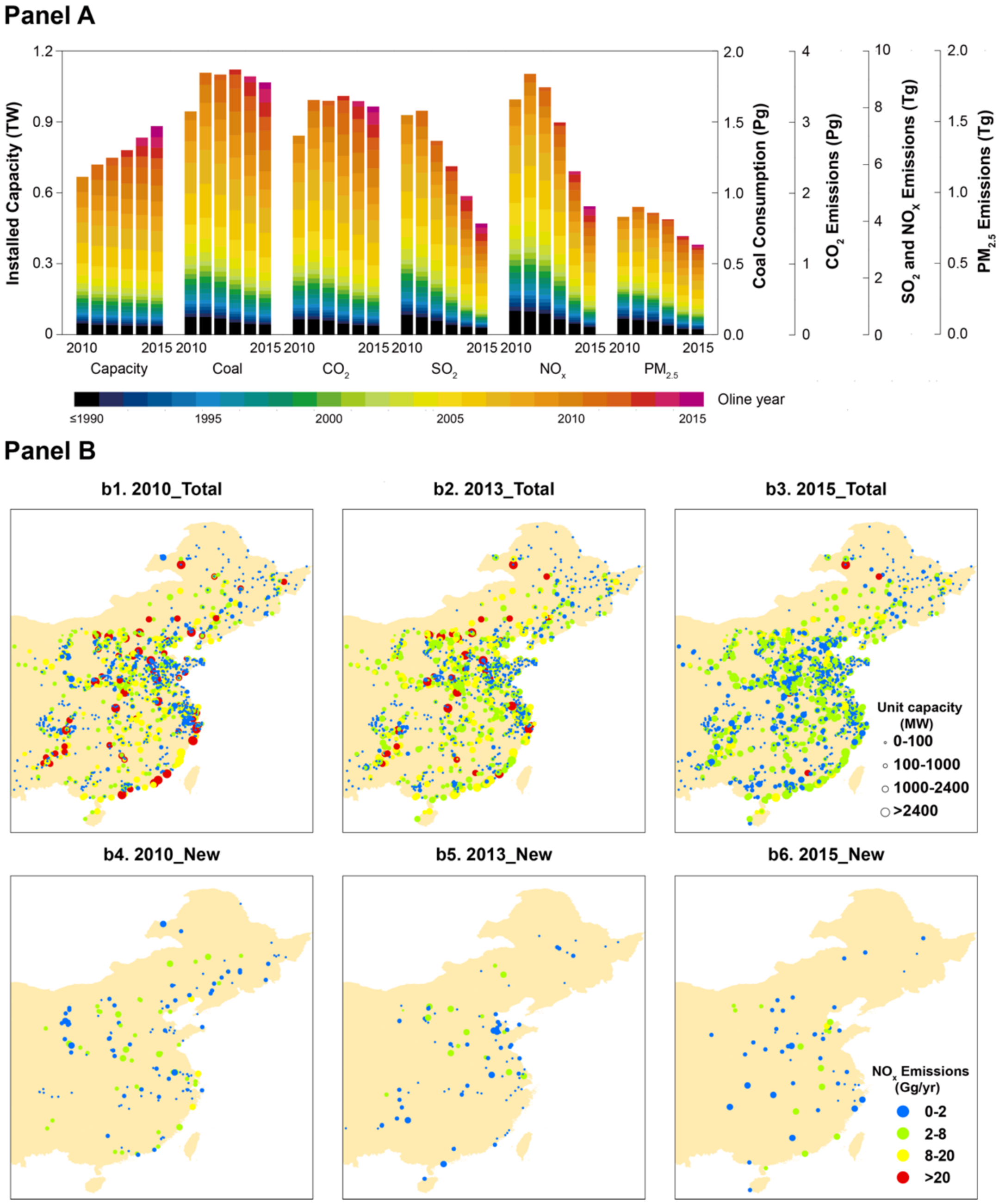

Figure 2. (A) Total operating capacities, coal consumption, and CO_2, SO_2, NO_x, and $PM_{2.5}$ emissions of coal-fired power plants in China by online year (year generator began operating) from 2010 to 2015. (B) Evolution of NO_x emissions from China's coal-fired power plants in the years 2010, 2013, and 2015 for all operating units and newly built power units in the corresponding year. Units: Gg/yr.

annual total operating capacity, coal consumption, and emissions of each species from China's coal-fired power plants for the period 2010−2015. In Figure 2A, with an ever-increasing demand for power generation, coal-fired operating capacity increased at an annual rate of 5.7%, and almost 2000 coal-fired units with a total installed capacity of 319 GW were established after 2010 in China. The total coal consumption in China's coal-fired power plants increased from 1.6 Pg in 2010 to 1.8 Pg in 2015, a 13% increase, with two fluctuating peaks occurring in 2011 and 2013. This variation trend could be attributed to the share decrease of coal-fired power generation and the energy efficiency improvement. The average coal consumption per unit electricity supplied decreased from 336 gce kWh^{-1} in 2010 to 315 gce kWh^{-1} in 2015, representing an improvement of 6% in energy efficiency over past 5 years. CO_2 emissions, which increased by 15%, were relatively stable and exhibited time-wise trends similar to that of coal consumption because control measures were not applied until 2015. Overall, emissions of air pollutants have a significant decrease compared to CO_2 emissions, SO_2, NO_x, and $PM_{2.5}$ emissions were decreased by 3.9 Tg, 3.8 Tg, and 0.2 Tg, with a reduction of 49%, 45%, and 24% during 2010−2015, respectively. Especially after 2013, the Action Plan drove synergistic co-reductions in SO_2, NO_x, and $PM_{2.5}$ emissions, indicating that significant technological improvement occurred in the power sector. As shown in Table 1, the coal-consumption weighted mean SO_2 removal efficiency of all FGD facilities was further improved from 78% in 2010 to 89% in 2015. And the coal-consumption weighted mean NO_x

Table 1. Capacity Size, Average Removal Efficiency, Technology Penetration, Fuel Quality, Emission Factors, and Emissions of Coal-Fired Power Plants in China in 2010, 2015, and 2030 under All Scenarios

		history		2030 projection							
category	subcategory	2010	2015	HNR-BAU	HNR-BAT	HER-BAU	HER-BAT	LNR-BAU	LNR-BAT	LER-BAU	LER-BAT
capacity size[a] (%)	<100 MW	11.5	9.6	7.5	7.5	0.2	0.2	8.9	8.9	0.2	0.2
	[100,300) MW	18.7	12.5	9.2	9.2	0.9	0.9	10.7	10.7	1.2	1.2
	[300,600) MW	35.4	37.1	29.7	29.7	15.5	15.5	34.6	34.6	20.4	20.4
	≥600 MW	34.4	40.7	53.6	53.6	83.4	83.4	45.8	45.8	78.1	78.1
average removal efficiency[a] (%)	de-SO_2 devices	78.0	88.6	89.0	95.1	92.5	95.1	88.4	95.1	89.6	95.1
	de-NO_x devices	0.0	62.0	63.5	85.0	72.5	85.0	62.2	85.1	62.6	85.1
technology penetration of de-PM devices (%)	ESP	92.8	79.0	84.7	0.0	87.0	0.0	82.1	0.0	82.8	0.0
	FAB	4.4	17.2	15.3	0.0	13.0	0.0	17.9	0.0	17.2	0.0
	WESP	0.0	0.0	0.0	100.0	0.0	100.0	0.0	100.0	0.0	100.0
fuel quality	coal consumption rate (gce kWh^{-1})	335.6	315.4	308.9	308.9	296.5	296.5	312.2	312.2	297.1	297.1
	sulfur content (%)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
emission factors	SO_2 (g kWh^{-1})	2.4	1.0	0.9	0.3	0.7	0.3	1.0	0.3	0.6	0.3
	NO_x (g kWh^{-1})	2.5	1.1	1.0	0.3	0.7	0.3	1.1	0.3	0.7	0.3
	$PM_{2.5}$ (g kWh^{-1})	0.3	0.2	0.1	0.0	0.1	0.0	0.2	0.0	0.1	0.0
	PM_{10} (g kWh^{-1})	0.4	0.2	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.1
	CO_2 (g kWh^{-1})	851.7	795.2	797.1	797.1	768.0	768.0	830.4	830.4	773.8	773.8
	SO_2 (g kg^{-1} of coal)	4.9	2.2	2.1	0.7	1.7	0.7	2.2	0.7	1.5	0.7
	NO_x (g kg^{-1} of coal)	5.3	2.5	2.3	0.7	1.6	0.6	2.4	0.7	1.7	0.6
	$PM_{2.5}$ (g kg^{-1} of coal)	0.5	0.4	0.3	0.1	0.2	0.1	0.3	0.1	0.2	0.1
	PM_{10} (g kg^{-1} of coal)	0.8	0.5	0.5	0.2	0.4	0.2	0.5	0.2	0.4	0.2
	CO_2 (g kg^{-1} of coal)	1782.1	1796.2	1811.4	1811.4	1818.3	1818.3	1810.9	1810.9	1819.7	1819.7
emissions	SO_2 (Tg yr^{-1})	7.8	3.9	4.8	1.5	3.6	1.6	3.9	1.2	2.5	1.1
	NO_x (Tg yr^{-1})	8.3	4.5	5.1	1.6	3.5	1.3	4.3	1.3	2.7	1.0
	$PM_{2.5}$ (Tg yr^{-1})	0.8	0.6	0.7	0.2	0.5	0.1	0.6	0.1	0.4	0.1
	PM_{10} (Tg yr^{-1})	1.3	1.0	1.1	0.5	0.8	0.4	1.0	0.4	0.7	0.3
	CO_2 (Pg yr^{-1})	2.8	3.2	4.1	4.1	3.9	3.9	3.2	3.2	3.0	3.0

[a] Shares of coal consumption for each capacity size and technology.

removal efficiency was greatly improved to 62% in 2015 and represented the most important step undertaken to reduce national NO_x emissions in the 12th FYP.

Figure 2A also presents the capacity, coal consumption, and emissions variation trends in the share of units with different online years (year generator began operating) from 2010 to 2015. We can see the share of capacity built before 2000 decreased with the phase-out of old units and the newly built of young units, the coal consumption of those units decreased from 27% in 2010 to 16% in 2015. As of 2015, the operating units constructed after 2005 accounted for 76% of the total installed capacity, indicating the predominance of younger coal-fired power units in China. The coal consumptions and CO_2, SO_2, NO_x, and $PM_{2.5}$ emissions of those units contributed to 75%, 75%, 72%, 69%, and 67% of the respective totals for units in 2015, indicating the better combustion technologies of boilers and control levels of air pollutant emissions for those units, and also validating the retirement priority of relatively old units.

Figure 2B depicts the evolution in NO_x emissions from China's coal-fired power plants for the year 2010, 2013, and 2015 at the unit level (only eastern China is shown on the map), and it provides a visual indicator of the rapid change in NO_x emissions. Under the constraints of the 12th FYP and the Action Plan, de-NO_x devices have been gradually installed nationwide since 2010. Most of the hot spots disappeared from year to year with the installation of de-NO_x devices. Effective equipped de-NO_x devices were not in operation until 2011 (Figure 2A), and the NO_x emissions from large units declined significantly after 2013, which is also verified by satellite measurements.[42−44] The maps also show the differences in the progress of controlling NO_x emissions among regions. The control policy initially became effective and achieved obvious emission reduction in relatively developed regions (e.g., the southeast coastal region), followed by less developed regions (e.g., the middle of China), and emission reduction in all regions were eventually realized in a manner, similar to the progress observed in the control of SO_2 emissions (Figure S4). Figure 2B also shows the distributions of the newly built units in the corresponding years. Most of the new generation units were large and usually equipped with high-efficiency de-NO_x devices when placed into operation; thus, they emit fewer NO_x emissions.

Evolution of Emissions and Coal Consumption from 2010 to 2030. Figure 3a−c shows the evolution of air pollutant emissions from 2010 to 2030 under eight scenario groups, and each scenario group represents different emission mitigation pathways. Under high coal-fired electricity demand, we found emissions of air pollutants slightly change under two BAU scenarios (HNR-BAU and HER-BAU) during 2015−2030 because the optimization of power plant fleet and the upgrade of control measures were not or were partially offset by the increasing coal-fired electricity demand. The differences of emission trends between HNR-BAU and HER-BAU scenarios represent the effects of new-built power units, which have higher combustion efficiencies and better control devices

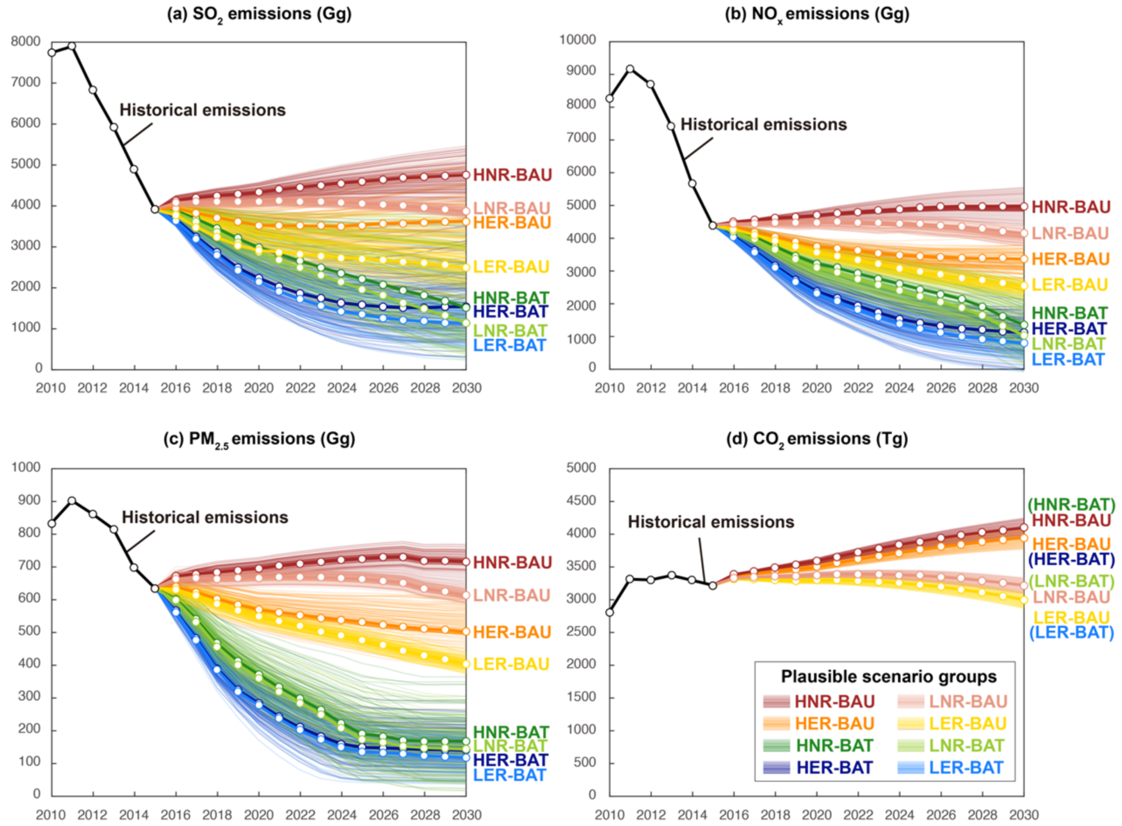

Figure 3. Emissions of air pollutants and CO$_2$ of coal-fired power plants in China from 2010 to 2030 based on historical data and two sets of emission scenario groups (HNR-BAU, HNR-BAT, HER-BAU, and HER-BAT scenarios; LNR-BAU, LNR-BAT, LER-BAU, and LER-BAT scenarios): (a) SO$_2$; (b) NO$_x$; (c) PM$_{2.5}$; (d) CO$_2$ emissions. The narrow lines with transparency in each scenario represent the plausible emission mitigation pathways under 100 runs.

compared to old power units. Figure 3a shows that SO$_2$ emissions increase by 21% (−3% to 40%; referred to the lower and upper bounds in each scenario group) and decrease by 7% (−33% to 55%) under the HNR-BAU and HER-BAU scenarios from 2015 to 2030, respectively. By 2030, SO$_2$ emissions in the HER-BAU are 24% lower than those in the HNR-BAU scenario. Figure 3b shows NO$_x$ emissions also decrease by 22% (7% to 50%) and increase by 13% (0% to 24%) under the HER-BAU and HNR-BAU scenarios, respectively. Similar, PM$_{2.5}$ emissions decrease by 22% (4% to 39%) and increase by 12% (0% to 21%) under the HER-BAU and HNR-BAU scenarios (Figure 3c), respectively. Emissions of PM$_{10}$ have the same trend as PM$_{2.5}$ emissions under each scenario (Figure S5). The results indicate the benefits from early retirement of outdated power units.

Although significant emission reductions were obtained from 2010 to 2015 for air pollutants, the coal-fired power sector still has large potential for emission mitigations in the future. Under BAT scenarios, our estimates show that SO$_2$, NO$_x$, and PM$_{2.5}$ emissions will decrease rapidly during 2016−2020 because of control technologies upgrade whether under high or low coal-fired electricity demands, especially for the HER-BAT and LER-BAT scenarios, which first occurred to control measures under poor operating conditions in 2015 to meet the compulsory standards. For example, SO$_2$ emissions decrease by 43% (15% to 59%) and 24% (1% to 41%) under the HER-BAT and HNR-BAT scenarios during 2015−2020, respectively. An additional SO$_2$ emission reduction by ∼25% is obtained under HER-BAT scenario in the year 2020 compared to HNR-BAT scenario due to the mandatory power plant fleet turnover, which is similar to NO$_x$ and PM$_{2.5}$ emission reductions. After 2020, the rates of decrease in SO$_2$, NO$_x$, and PM$_{2.5}$ emissions slow down because most of the potential for reductions was exhausted in the early period, and additional strict policies were not added. We can see that the air pollutant emissions under the two sets of BAT scenarios (HNR-BAT vs HER-BAT and LNR-BAT vs LER-BAT) eventually would be pretty close by the end of 2030 because the most advanced end-of-pipe control measures have been applied to all the power units under our assumptions.

Comparing the BAT with the BAU scenarios, air pollutant emissions in the BAT scenario are greatly reduced because of enhanced end-of-pipe control measures. Taking NO$_x$ emissions under HER-BAU and HER-BAT scenarios as an example (Figure 3b), NO$_x$ emissions from coal-fired power plants decrease from 4.5 Tg in 2015 to 3.5 Tg (2.3 to 4.2 Tg) and 1.3 Tg (0.3 to 2.3 Tg) in 2030 under the HER-BAU and HER-BAT scenarios, respectively. A decrease of more than 50% will occur by 2030 under HER-BAT scenario in comparison to HER-BAU scenario. By 2030, under the BAT scenarios, the air pollutant emissions from coal-fired power units could remain at a low level.

Meanwhile, the decrease of coal-fired electricity demand could fundamentally decrease air pollutants and CO$_2$ emissions by reducing coal use (a set of H scenarios vs L scenarios). Taking HER-BAU and LER-BAU scenarios as an example, SO$_2$, NO$_x$, and PM$_{2.5}$ emissions significantly decrease by 31%, 23%, and 20% under the LER-BAU scenario with a decrease of

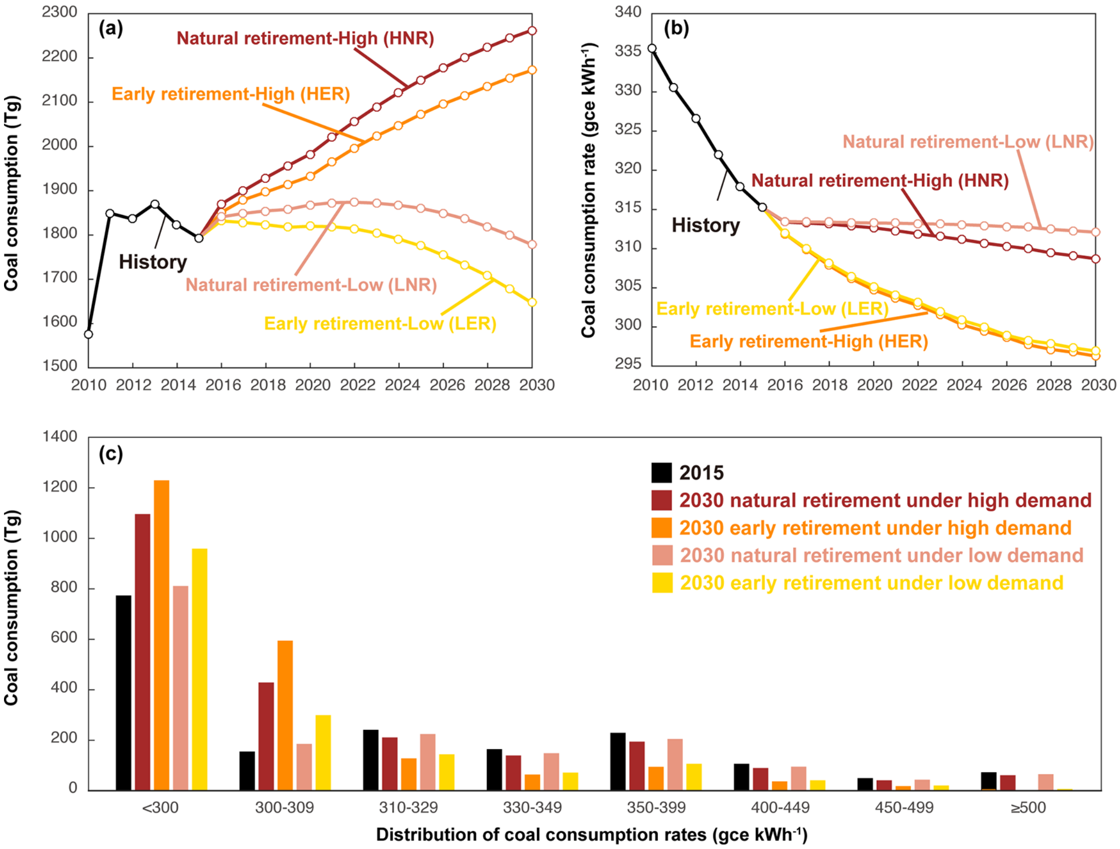

Figure 4. Coal consumption (a) and coal consumption rates (b) of coal-fired power plants in China from 2010 to 2030 under two of retirement scenarios (natural retirement and early retirement) and two of coal-fired electricity demand scenarios (high and low demand), and distribution of coal consumption rates in coal-fired power plants in 2015 and 2030 under four combined scenarios (c).

coal-fired electricity demand by 25% in 2030 compared to HER-BAU scenario, respectively.

Figure 3d shows the CO_2 emissions under two coal-fired electricity demand scenarios and two power supply scenarios because the power supply structures and CO_2 emissions are the same in the two end-of-pipe control scenarios. The CO_2 emissions shown in Figure 3d continue to increase because none of the CCS systems was implemented in our assumptions under high coal-fired electricity demand; CO_2 emissions increase by 23% (17% to 27%) and 27% (22% to 32%) under the HER-BAU (or HER-BAT) and HNR-BAU (or HNR-BAT) scenarios, respectively, during 2015−2030. And the CO_2 emissions in the set of high demand scenarios did not peak before 2030 because of increased demand for electricity and coal consumption despite the energy efficiency improvement. However, the decrease of coal-fired electricity demand could reverse the CO_2 emission trend and bring the peak before 2030 by reducing coal use in the power sector. Under low demand, CO_2 emissions peak at 3.3 Pg in 2021 and 3.4 Pg in 2022 under the HER-BAU (or HER-BAT) and HNR-BAU (or HNR-BAT) scenarios, respectively.

In addition, sensitivity test scenarios on CCS technologies indicate that although a decrease in CO_2 emissions is obtained by installing CCS systems, air pollutant emissions significantly increase with the increasing penetration of CCS systems (Figure S6). Taking CLER-BAT scenario as an example, CO_2 emissions could be reduced by 24% under the CLER-BAT scenario compared to LER-BAT scenarios in 2030. However, the SO_2, NO_x, and $PM_{2.5}$ emissions would increase by 10%, 9%, and 6% in 2030, respectively.

The comparison of these eight scenarios and additional sensitivity test scenarios shows the evolution of air pollutants and CO_2 emissions under the combination of clean and renewable energy development plans, power plant fleet turnover, and emission control policies, all of which significantly contribute to CO_2 and air pollutants emission reductions. In future, after all the power units are equipped with the most advanced combustion technologies and control measures, the potential emission reductions are basically exhausted in coal-fired power units. The further optimization of energy structure and power plant fleet can substantially reduce the air pollutants and CO_2 emissions.

In order to further compare the effects of natural retirement and early retirement on activity rates, as shown in Figure 4, we further compared the coal consumption (Figure 4a), coal consumption rate (Figure 4b), and distribution of coal consumption rates in the year of 2030 under two retirement modes (Figure 4c). The average coal consumption rate decreased remarkably from 336 gce kWh^{-1} in 2010 to 315 gce kWh^{-1} in 2015; the average coal consumption rates under natural retirement modes decreased slowly to 309 and 312 gce kWh^{-1} under high and low coal-fired electricity demand, which were much higher than those under early retirement modes. Decreases by 19 and 18 gce kWh^{-1} from 2015 to 2030 under early retirement modes represent improvements of 6.0% and 5.8% in energy efficiency after the mandatory optimization of power plant fleet under high and low demand, respectively. The estimated cumulative coal savings reach 0.9 and 1.0 Pg when comparing the natural retirement with early retirement modes under high and low demand during 2016−2030, respectively.

Saved coal almost equals half of coal consumption in the power sector in the year 2015. These results demonstrate that the most advanced combustion technologies will be deployed on a large scale by 2030 under the early retirement modes and indicate that optimizing the generation unit fleet mix will greatly reduce coal consumption and fundamentally reduce air pollutants and CO_2 emissions. Figure 4c compares the coal consumption of plants by coal consumption rate (gce kWh^{-1}) in 2015 and 2030 under two retirement modes. In 2015, 87% of coal consumed in power units in China had a coal consumption rate of 400 gce kWh^{-1} or lower. Generally, large units consume less coal than small units for the same amount of electricity generated because of the more advanced combustion technology used in larger units such as supercritical and ultra-supercritical technology. From 2015 to 2030, with the retirement of low-efficiency power units, almost all the units had a coal consumption rate of 400 gce kWh^{-1} or lower under early retirement mode. And 84% and 76% of coal consumed in power units had a coal consumption rate of 310 gce kWh^{-1} or lower in the year 2030 under early retirement modes of high and low demands, respectively.

DISCUSSION AND POLICY IMPLICATIONS

In this study, a unit-based emission projection model of coal-fired power plants was developed to estimate the evolution of air pollutants and CO_2 emissions, which also can be used in various future policy analyses and emission estimates for coal-fired power plants. A full understanding of emission mitigation pathways was achieved under current and aggressive energy development plans during 2010−2030. Our analyses identify a more feasible pathway for constructing an environmentally friendly power sector, which could provide clean electricity for the whole society. Here we analyzed the subsequent possible policy implications.

Our results show that the decrease of coal-fired electricity demand could save coal consumption and fundamentally reduce CO_2 and air pollutant emissions (a set of H scenarios vs L scenarios). The optimization of power plant fleet structure would improve the energy efficiency and then substantially reduce CO_2 and air pollutant emissions (NR vs ER scenarios), which could simultaneously provide air quality and climate benefits. The end-of-pipe control measures would further reduce air pollutant emission levels (BAU vs BAT scenarios). Despite coal being considered a "dirty energy",[45] the Power Plan and mature control technologies provide an impetus for the clean use of coal resources in the power sector in the case of air pollutant emissions.[46,47] However, widespread application of advanced control measures could reduce but not totally eliminate emissions of air pollutants and greenhouse gases in coal-fired power plants.[48] The comparison of different coal-fired electricity demand scenarios also indicates the competitiveness of clean and renewable energy sources.[29,49,50] By replacing coal burning with other clean energy and renewable energy sources (such as hydropower, wind power, and solar power) for power generation in medium and long-term future, the emissions of air pollutants, greenhouse gases, and heavy metals could be finally eliminated.[51,52] Meanwhile, the negative effect of CCS technologies on air pollutants and CO_2 emissions due to the additional energy consumptions further highlights the importance of accelerating energy transformation in the power sector.

In our study, we find that future coal-fired electricity demand and relevant coal consumption would dominate the CO_2 emission trend if CCS technology was not widely applied until 2030. Under current energy development planning, the decoupling trends of air pollutants and CO_2 emissions indicates that the trend of CO_2 emission from coal-fired power plants would deviate from the China's Intended Nationally Determined Contributions (INDCs) targets;[53] achieving the carbon peak before 2030 is a big challenge for policy making. In contrast, the CO_2 emission trend could be reversed with more aggressive CO_2 emission reduction policies (e.g., increasing the penetration of CCS technologies) and enhanced energy scenarios (e.g., decreasing coal-fired electricity demand).

Our study is subject to some limitations. First, this work explored emission mitigation pathways based on national strategies without the consideration of economic costs, such as replacement costs of new power units and costs of control device upgrades. Second, electric energy is consumed to make end-of-pipe control measures operate,[54−57] which is not included in the total coal-fired electricity demand in this work. A set of sensitivity test scenarios on conventional end-of-pipe controls (de-SO_2, de-NO_x, and de-PM devices) shows that additional 2% energy consumption from end-of-pipe controls have a minor effect on air pollutants and CO_2 emissions increasing by 0.5−2.3% during 2015−2030 (Figure S6). Third, we estimated the life spans of in-fleet units and their retirement order at the provincial level without considering their locations. Given the uneven distribution of industrial infrastructure and population, larger air quality and health benefits might be obtained when the location optimizations of in-fleet units are applied (e.g., set priority to the retirement of outdated power units near populous urban areas). However, it is more complicated to take the locations into consideration because additional evaluations (e.g., air quality and health evaluations) will be required to quantify their impacts. Fourth, we estimated the demand of new-built capacity without locating them due to the high uncertainty of proposed power plants. Development plans proposed by governments in China could affect the distribution of power plants in great part. For example, the proposed west-to-east long-distance electricity transmission lines would alter the spatial distribution of new-built capacity from energy-thirsty coastal regions to inland China.[58,59] The environmental effect of building new power units is worth evaluating in future. Balancing the construction of new coal-fired power plants and the current air quality situation is a challenge for policy makers with the political task to ensure the attainment of regional air quality to the national standard in 2030.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b02919.

> Details of unit-based power plant emission estimation method and future projections model, summary of retired units and in-fleet operating power units, distribution of FGD and de-NO_x devices installed, historical evolution of SO_2 emissions and future PM_{10} emissions, emissions of air pollutants and CO_2 for sensitivity test scenarios, definitions and parameters of scenarios, summary of shares of coal-fired electricity and estimates of coal-fired electricity demand, related parameters and their uncertainty ranges, and parameters of control technologies for particulate matter (PDF)

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REFERENCES

(1) Zhao, Y.; Zhang, J.; Nielsen, C. P. The effects of recent control policies on trends in emissions of anthropogenic atmospheric pollutants and CO_2 in China. *Atmos. Chem. Phys.* **2013**, *13* (2), 487−508.

(2) Zhao, Y.; Wang, S.; Duan, L.; Lei, Y.; Cao, P.; Hao, J. Primary air pollutant emissions of coal-fired power plants in China: Current status and future prediction. *Atmos. Environ.* **2008**, *42* (36), 8442−8452.

(3) Unger, N.; Shindell, D. T.; Wang, J. Climate forcing by the on-road transportation and power generation sectors. *Atmos. Environ.* **2009**, *43* (19), 3077−3085.

(4) Liu, F.; Zhang, Q.; Tong, D.; Zheng, B.; Li, M.; Huo, H.; He, K. High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010. *Atmos. Chem. Phys.* **2015**, *15* (23), 13299−13317.

(5) Zhang, Q.; He, K.; Huo, H. Policy: cleaning China's air. *Nature* **2012**, *484* (7393), 161−162.

(6) Tian, H.; Liu, K.; Hao, J.; Wang, Y.; Gao, J.; Qiu, P.; Zhu, C. Nitrogen oxides emissions from thermal power plants in china: current status and future predictions. *Environ. Sci. Technol.* **2013**, *47* (19), 11350−11357.

(7) Wang, S.; Zhang, Q.; Streets, D. G.; He, K.; Martin, R. V.; Lamsal, L. N.; Chen, D.; Lei, Y.; Lu, Z. Growth in NO_x emissions from power plants in China: bottom-up estimates and satellite observations. *Atmos. Chem. Phys.* **2012**, *12* (10), 4429−4447.

(8) The State Council of the People's Republic of China. http://english.mee.gov.cn/News_service/infocus/201309/t20130924_260707.htm (accessed date: August 21, 2018).

(9) The White House. http://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change (accessed date: May 26, 2018).

(10) Liu, Z.; et al. Steps to China's carbon peak. *Nature* **2015**, *522* (7556), 279−281.

(11) Ministry of Ecology and Environment of the People's Republic of China. http://www.mee.gov.cn/gkml/hbb/bwj/201512/t20151215_319170.htm?_sm_au_=iVVR2PCFSksVLj6H (accessed date: August 21, 2018) (in Chinese).

(12) Ohara, T.; Akimoto, H.; Kurokawa, J.-I.; Horii, N.; Yamaji, K.; Yan, X.; Hayasaka, T. An Asian emission inventory of anthropogenic emission sources for the period 1980−2020. *Atmos. Chem. Phys.* **2007**, 7 (16), 4419−4444.

(13) Zhang, Q.; Streets, D. G.; Carmichael, G. R.; He, K.; Huo, H.; Kannari, A.; Klimont, Z.; Park, I.; Reddy, S.; Fu, J.; et al. Asian emissions in 2006 for the NASA INTEX-B mission. *Atmos. Chem. Phys.* **2009**, *9* (14), 5131−5153.

(14) Xing, J.; Wang, S.; Chatani, S.; Zhang, C.; Wei, W.; Hao, J.; Klimont, Z.; Cofala, J.; Amann, M. Projections of air pollutant emissions and its impacts on regional air quality in China in 2020. *Atmos. Chem. Phys.* **2011**, *11* (7), 3119−3136.

(15) Zhao, B.; Wang, S.; Liu, H.; Xu, J. Y.; Fu, K.; Klimont, Z.; Hao, J.; He, K.; Cofala, J.; Amann, M. NO_x emissions in China: historical trends and future perspectives. *Atmos. Chem. Phys.* **2013**, *13* (19), 9869−9897.

(16) Chen, L.; Sun, Y.; Wu, X.; Zhang, Y.; Zheng, C.; Gao, X.; Cen, K. Unit-based emission inventory and uncertainty assessment of coal-fired power plants. *Atmos. Environ.* **2014**, *99*, 527−535.

(17) Wang, S.; Zhao, B.; Cai, S.; Klimont, Z.; Nielsen, C. P.; Morikawa, T.; Woo, J. H.; Kim, Y.; Fu, X.; Xu, J.; Hao, J.; He, K. Emission trends and mitigation options for air pollutants in East Asia. *Atmos. Chem. Phys.* **2014**, *14* (13), 6571−6603.

(18) Janssens-Maenhout, G.; Crippa, M.; Guizzardi, D.; Dentener, F.; Muntean, M.; Pouliot, G.; Keating, T.; Zhang, Q.; Kurokawa, J.; Wankmüller, R.; Denier van der Gon, H.; Kuenen, J. J. P.; Klimont, Z.; Frost, G.; Darras, S.; Koffi, B.; Li, M. HTAP_v2.2: a mosaic of regional and global emission grid maps for 2008 and 2010 to study hemispheric transport of air pollution. *Atmos. Chem. Phys.* **2015**, *15* (19), 11411−11432.

(19) Xia, Y.; Zhao, Y.; Nielsen, C. P. Benefits of China's efforts in gaseous pollutant control indicated by the bottom-up emissions and satellite observations 2000−2014. *Atmos. Environ.* **2016**, *136*, 43−53.

(20) Li, M.; Zhang, Q.; Kurokawa, J. I.; Woo, J. H.; He, K.; Lu, Z.; Ohara, T.; Song, Y.; Streets, D. G.; Carmichael, G. R.; Cheng, Y.; Hong, C.; Huo, H.; Jiang, X.; Kang, S.; Liu, F.; Su, H.; Zheng, B. MIX: a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP. *Atmos. Chem. Phys.* **2017**, *17* (2), 935−963.

(21) Wang, J.; Zhao, B.; Wang, S.; Yang, F.; Xing, J.; Morawska, L.; Ding, A.; Kulmala, M.; Kerminen, V. M.; Kujansuu, J.; et al. Particulate matter pollution over China and the effects of control policies. *Sci. Total Environ.* **2017**, *584*, 426−447.

(22) Szulczewski, M. L.; MacMinn, C. W.; Herzog, H. J.; Juanes, R. Lifetime of carbon capture and storage as a climate-change mitigation technology. *Proc. Natl. Acad. Sci. U. S. A.* **2012**, *109* (14), 5185−5189.

(23) Working group III of the Intergovernmental Panel on Climate Change. IPCC special report on Carbon Dioxide Capture and Storage. http://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf (accessed date: August 20, 2018).

(24) Power Plant Carbon Dioxide Capture and Storage Projects. http://sequestration.mit.edu/tools/projects/index_capture.html (accessed date: August 20, 2018).

(25) Global CCS Institute. https://www.globalccsinstitute.com/projects/large-scale-ccs-projects (accessed date: August 20, 2018).

(26) Chinese Academy of Engineering, The Energy Development Strategy of China in Mid and Long-term (2030, 2050), 2011.

(27) National Development and Reform Commission. China's Low Carbon Development Pathways by 2050. Science Press: China, 2009.

(28) GCAM RCP Scenario Results. http://www.globalchange.umd.edu/gcamrcp (accessed date: August 20, 2018).

(29) He, G.; Avrin, A. P.; Nelson, J. H.; Johnston, J.; Mileva, A.; Tian, J.; Kammen, D. M. SWITCH-China: A Systems Approach to Decarbonizing China's Power System. *Environ. Sci. Technol.* **2016**, *50* (11), 5467−5473.

(30) International Energy Agency. World Energy Outlook 2016, 2016.

(31) U.S. Energy Information Administration. International Energy Outlook 2017, 2017.

(32) National Energy Administration. http://www.nea.gov.cn/2013-02/20/c_132180424.htm (accessed date: May 26, 2018) (in Chinese).

(33) National Development and Reform Commission. http://www.ndrc.gov.cn/zcfb/zcfbtz/201612/t20161216_830264.html (accessed date: May 26, 2018) (in Chinese).

(34) Davis, S. J.; Socolow, R. H. Commitment accounting of CO_2 emissions. *Environ. Res. Lett.* **2014**, *9* (8), No. 084018.

(35) Tong, D.; Zhang, Q.; Davis, S. J.; Liu, F.; Zheng, B.; Geng, G.; Xue, T.; Li, M.; Hong, C.; Lu, Z.; Streets, D. G.; Guan, D.; He, K. Targeted emission reductions from global super-polluting power plant units. *Nat. Sustainability* **2018**, *1* (1), 59−68.

(36) Ministry of Ecology and Environment of the People's Republic of China. GB 13223-2011, http://permit.mep.gov.cn/permitExt/images/20161123122226213.pdf (accessed date: August 20, 2018).

(37) U.S. Environmental Protection Agency. Compilation of Air Pollutant Emission Factors (AP-42), http://www.epa.gov/chief/ (accessed date: May 10, 2018).

(38) Graus, W. H. J.; Worrell, E. Effects of SO_2 and NOx control on energy-efficiency power generation. *Energy Policy* **2007**, *35* (7), 3898−3908.

(39) Li, K.; Wang, W.; Mo, J. M. The Application Prospects of Wet-Electrostatic Precipitation in Coal-fired Power Plant. *Guangdong Chemical Industry* **2013**, *40* (11), 54−55.

(40) Yang, Z.; Zheng, C.; Liu, S.; Guo, Y.; Liang, C.; Wang, Y.; Hu, D.; Gao, X. A combined wet electrostatic precipitator for efficiently eliminating fine particle penetration. *Fuel Process. Technol.* **2018**, *180*, 122−129.

(41) Webster, M. D.; Babiker, M.; Mayer, M.; Reilly, J. M.; Harnisch, J.; Hyman, R.; Sarofim, M. C.; Wang, C. Uncertainty in emissions projections for climate models. *Atmos. Environ.* **2002**, *36* (22), 3659−3670.

(42) Liu, F.; Zhang, Q.; Zheng, B.; Tong, D.; Yan, L.; Zheng, Y.; He, K.; van der A, R. J. Recent reduction in NOx emissions over China: synthesis of satellite observations and emission inventories. *Environ. Res. Lett.* **2016**, *11* (11), 114002.

(43) Krotkov, N. A.; McLinden, C. A.; Li, C.; Lamsal, L. N.; Celarier, E. A.; Marchenko, S. V.; Swartz, W. H.; Bucsela, E. J.; Joiner, J.; Duncan, B. N.; Boersma, K. F.; et al. Aura OMI observations of regional SO_2 and NO_2 pollution changes from 2005 to 2015. *Atmos. Chem. Phys.* **2016**, *16* (7), 4605−4629.

(44) van der A, R. J.; Ding, J.; Koukouli, M. E.; Liu, F.; Li, Q.; Mao, H.; Theys, N.; Mijling, B. Cleaning up the air: effectiveness of air quality policy for SO_2 and NOx emissions in China. *Atmos. Chem. Phys.* **2017**, *17* (3), 1775−1789.

(45) Chen, W.; Xu, R. Clean coal technology development in China. *Energy Policy* **2010**, *38* (5), 2123−2130.

(46) National Energy Administration. http://zfxxgk.nea.gov.cn/auto85/201505/t20150505_1917.htm (accessed date: May 10 2018) (in Chinese).

(47) Franco, A.; Diaz, A. R. The future challenges for "clean coal technologies": joining efficiency increase and pollutant emission control. *Energy* **2009**, *34* (3), 348−354.

(48) Zhu, C.; Tian, H.; Cheng, K.; Liu, K.; Wang, K.; Hua, S.; Gao, J.; Zhou, J. Potentials of whole process control of heavy metals emissions from coal-fired power plants in China. *J. Cleaner Prod.* **2016**, *114*, 343−351.

(49) Yang, J.; Li, X.; Peng, W.; Wagner, F.; Mauzerall, D. L. Climate, air quality and human health benefits of various solar photovoltaic deployment scenarios in China in 2030. *Environ. Res. Lett.* **2018**, *13* (6), No. 064002.

(50) Peng, W.; Yang, J.; Lu, X.; Mauzerall, D. L. Potential co-benefits of electrification for air quality, health, and CO_2 mitigation in 2030 China. *Appl. Energy* **2018**, *218*, 511−519.

(51) Pacyna, J. M. Atmospheric Emissions of Arsenic, Cadmium, Lead and Mercury from High Temperature Processes in Power Generation and Industry. 1987.

(52) Fu, J.; Liu, G.; Xue, Z.; Zhi, G.; Zhao, K. Configuration distribution and emissions characteristics of arsenic from coal-fired power plants. *Chinese Power* **2013**, *3*, 95−99.

(53) Intended Nationally Determined Contributions (INDCs): http://www4.unfccc.int/submissions/INDC/Submission%20Pages/submissions.aspx (accessed date: February 12, 2018).

(54) Xu, G.; Yang, Y.; Wang, N.; Yuan, X.; Li, J.; Song, X.Analysis on energy consumption and optimal operation of FGD system in power plant. Presented at the Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific (1−4). IEEE.

(55) Lu, H.; Hou, S. Optimized operation and energy reduction of electrostatic precipitators for 600MW supercritical boiler. *Anhui Power* **2012**, *3*, 24−25 (in Chinese).

(56) Du, Z.; Qian, X.; He, S.; Zhu, Y. Cost analysis and optimization of SCR denitration in coal-fired Power Plants. *Chinese Power* **2013**, *10*, 124−128 (in Chinese).

(57) Ding, H. Retrofit on high-frequency power sources of the electrostatic precipitator. *Technological pioneers* **2012**, *17*, 83 (in Chinese).

(58) Liu, Z.; Zhang, Q. Study on the development mode of national power grid of China. *Proceedings of the CSEE* **2013**, *33* (7), 1−10.

(59) Peng, W.; Yuan, J.; Zhao, Y.; Lin, M.; Zhang, Q.; Victor, D. G.; Mauzerall, D. L. Air quality and climate benefits of long-distance electricity transmission in China. *Environ. Res. Lett.* **2017**, *12* (6), No. 064012.

DOI: 10.1021/acs.est.8b02919
Environ. Sci. Technol. 2018, 52, 12905−12914