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Air quality and health benefits of China's emission control policies on coal-fired power plants during 2005–2020

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Abstract

Coal-fired power plants (CPPs) dominate China's energy supply systems. Over the past two decades, the explosive growth of CPPs has led to negative air quality and health impacts in China, and a series of control policies have been implemented to alleviate those impacts. In this work, by combining a CPPs emission database over China (CPED), a regional chemical transport model (WRF-CMAQ), and the integrated exposure-response model, we summarized historical and ongoing emission control policies on CPPs over China, investigated the air quality and health impacts of China's CPPs during 2005–2020, and quantified the benefits of each policy. We found that despite the 97.4% growth of coal-fired power generation during 2005–2015, PM2.5 exposures caused by emissions from China's CPPs decreased from 9.0 μ g m⁻³ in 2005 to 3.6 μ g m⁻³ in 2015. The active emission control policies have decreased CPPs-induced PM_{2.5} exposures by 10.0 μ g m⁻³ during 2005–2015. We estimated that upgrading end-of-pipe control facilities and early retirement of small and low-efficiency units could respectively reduce PM_{2.5} exposures by 7.9 and 2.1 μ g m⁻³ during 2005–2015 and avoid 111 900 and 31 400 annual premature deaths. Since 2015, China's government has further required all CPPs to comply with the so-called 'ultra-low emission standards' before 2020 as a major component of China's clean air actions. If the policy is fully deployed, CPPs-induced PM2.5 exposures could further decrease by 2.5 μ g m⁻³ and avoid 43 500 premature deaths annually. Our study confirms the effectiveness of tailored control policies for China's CPPs and reveals that those policies have played important roles in air quality improvement in China.

1. Introduction

Coal-fired power plants (CPPs) are one of the largest contributors to air pollutant emissions in China. The sulfur dioxide (SO₂), nitrogen oxide (NO_x) and fine particulate matter less than 2.5 μ m in diameter

 $(PM_{2.5})$ emissions of CPPs accounted for 33%, 33% and 6% of national total emissions in 2010, respectively [1]. The large amount of air pollutant emissions from CPPs causes fine particulate air pollution, which contributed 26% of the fine particulate nitrate (NO3⁻) and 22% of the fine particulate sulfate (SO4²⁻)



Table 1. Scenario summary.					
Scenario	Description				
REF05 REF15	Actual emissions of CPPs in China in 2005 and 2015				
HIS-SAU15	Unchanged power plant fleet structure is assumed, and thus, the distribution of unit capacity is the same as in 2005. Total power generation is equal to that in REF15				
HIS-EOP15	Based on the HIS-SAU15 scenario, the end-of-pipe control level is assumed to be same as that in 2005. Total power generation is equal to that in REF15				
PRE-ULE20	All power units are assumed to have reached ultra-low emission standards. The removal efficiencies of FGD, de-NO _x devices and dust-removal are expected to reach as high as 95.0%, 85.0% and 99.3%, respectively				
PRE-GEN20	Based on the PRE-ULE20 scenario, the provincial power generation is set to be equal to the projected power generation in 2020.				

ambient concentration in 2012 [2]. CPPs have been vital target for emission control in recent decades and play an important role in air quality management in China. In addition, as the pioneer of the emission control sector, CPPs can provide a valuable reference for air quality management in other sectors.

A series of control measures at CPPs have been taken to improve energy efficiency and air quality in China over the last two decades [3, 4]. China has made a great effort to construct large units and phase out small units since 2005 to improve CPPs energy efficiency [5]. The percentage of large units (>600 MW) has increased significantly from 9.9% to 40.7% from 2005 to 2015, whereas the percentage of small units (<100 MW) decreased from 25.5% to 9.6% (see in table 1). Two sequential emission standards for CPPs were carried out in 2004 (SEPA, 2003 [6]) and 2011 (SEPA, 2011 [7]) to be in line with the national emissions caps. China set the cap of reducing national total emissions of SO₂ by 10.0% during the 11th Five-Year-Plan period (2005-2010) and the 12th Five-Year-Plan period (2010–2015), respectively [8, 9]. Additionally, NO_x emissions were required to decrease by 8% during the 12th Five-Year-Plan Period. Accordingly, CPPs started to install flue gas desulfurization (FGD) devices in 2005 and de-NO_x devices using selective non-catalytic reduction or selective catalytic reduction technology in 2011 [10]. By 2015, the ratio of CPPs equipped with FGD and de-NOx devices reached up to 95.6% and 84.2%, respectively [11]. The emission standard for CPPs has been strengthened more recently. China released the 'Full Implementation of Ultra-Low Emission and Energy-saving Transformation of CPPs (2014-2020) Work Plan [12]' (hereafter, ultra-low emission standards) in 2015 as a major component of China's clean air action [13]. The ultralow emission standard is attempting to decrease the average coal consumption per unit electricity supplied from 315 gce/kWh in 2015 to 310 gce/kWh by 2020. The concentrations of particulate matter (PM) including PM_{2.5} and PM₁₀, SO₂ and NO_x from CPPs plumes are required to decline to less than 10 mg m^{-3} , 35 mg m^{-3} and 50 mg m^{-3} by 2020, respectively, under the requirements of the ultra-low emission standards [12]. The implementation of the above

control measures is expected to bring about dramatic reductions in air pollutants emissions and concentration [10, 11, 14]. A good understanding of the air quality and health impacts associated with reduced emissions is essential for policy makers.

The impact of emissions from CPPs on air quality and health in China has been investigated in previous work [1, 2, 15–23]. Early studies (e.g. Zhao *et al* [1]) reported the historical contributions of CPPs to national total emissions of major air pollutants before implementation of the ultra-low emission standard in 2014. In a recent study (Liu et al [15]), emissions data from 17 CPPs showed that emission factors for NO_{xy} SO₂, and PM are up to 1–2 orders of magnitude lower than those of power units before the ultra-low control technology retrofitting to meet the requirement of the ultra-low emission standards. The contributions of emissions from CPPs to ambient concentrations of air pollutants have been quantified using air quality models. Huang et al [2] traced air pollutant concentrations from CPPs emissions by applying source apportionment techniques and assessed the impacts of power generation on air quality in China in 2012. The following studies compared emission scenario simulations based on a real-world situation and an assumption that emission levels from CPPs are comparable with those from natural gas-fired plants, which enabled prediction of the potential air quality benefits of the ultra-low emissions standard [19, 20]. Few studies have extended their analyses to health impacts [21–23]. To the best of our knowledge, premature mortality because of the power sector has only been quantified for the years prior to implementation of the ultra-low emission standard. Hu et al [21] estimated that 10% of PM_{2.5}-induced premature mortality in 2013 was attributable to the power sector. However, a comprehensive evaluation of air quality and health impacts of emissions from CPPs in China, which accounts for the influence of the historical and latest control measures during the last two decades, is missing.

In this paper, a comprehensive evaluation of the air quality and health impacts of China's CPPs during 2005–2020 is presented, and the benefits of each emission control policy are quantified. First, we develop



Table 2. Emissions and key parameters of China's CPPs during 2005–2020.

Category	Subcategory	2005	2010	2015	2020
	Coal consumption (million tons)	105 329.0	157 645.0	178 012.6	194 826.5
Activity data	Power generation (TWh)	2047.3	3474.9	4041.2	4448.7
	Coal consumption rate (gce/kWh)	356.4	335.6	315.4	312.8
	<100 MW	25.5%	11.5%	9.6%	10.0%
Capacity sizes	[100, 300] MW	31.1%	18.7%	12.5%	12.0%
	[300, 600] MW	33.4%	35.4%	37.1%	37.0%
	>600 MW	9.9%	34.4%	40.7%	41.0%
Average removal efficiency	De-SO ₂ devices	8.0%	78.0%	88.6%	95.0%
	$De-NO_x$ devices	0.0%	0.0%	62.0%	85.0%
	De-PM _{2.5} devices	86.0%	95.0%	97.0%	99.3%
	$SO_2(g/kWh)$	8.7	2.4	1.0	0.34
	$NO_x(g/kWh)$	3.4	2.5	1.1	0.31
	PM _{2.5} (g/kWh)	0.7	0.3	0.2	0.04
	PM10 (g/kWh)	1.3	0.4	0.2	0.1
Emission factor	$CO_2(g/kWh)$	986.9	851.7	795.2	791.3
	$SO_2(g/kg of coal)$	15.9	4.9	2.2	0.8
	$NO_x(g/kg of coal)$	6.2	5.3	2.5	0.7
	$PM_{2.5}$ (g/kg of coal)	1.3	0.5	0.4	0.1
	PM_{10} (g/kg of coal)	2.4	0.8	0.5	0.2
	CO_2 (g/kg of coal)	1801.2	1782.1	1796.2	1806.8
	$SO_2(Tg/yr)$	16.7	7.8	3.9	1.5
	$NO_x(Tg/yr)$	6.7	8.3	4.5	1.4
Emissions	PM _{2.5} (Tg/yr)	1.5	0.8	0.6	0.3
	PM ₁₀ (Tg/yr)	2.7	1.3	1.0	0.5
	$CO_2(Tg/yr)$	1.9	2.8	3.2	3.5

two retrospective emission scenarios based on the high-resolution coal-fired power plant (CPED) [10, 11] database at the unit level in China to quantify emission changes induced by the control strategy during 2005-2015. We also develop two prediction emission scenarios to predict the CPPs emission changes associated with the implementation of ultra-low emission standards and power generation increments during 2015–2020. Second, the air quality and health impacts associated with CPPs emission changes during 2005–2020 are evaluated by employing both the regional air quality model and the integrated exposure-response model (hereafter, 'IER') [24, 25], respectively. Finally, we compare the emission levels of CPPs in China with those in the United States and India, then provide guidelines for emission control of CPPs in India.

2. Methods and data

2.1. Emission reduction estimates

We establish two baseline scenarios and four hypothetical scenarios based on the CPED database [10, 11] to explore the air quality and health impacts of emission reductions from CPPs in China during 2005–2020. Table 1 shows the description of six emission scenarios and table 2 presents the evolution of technology and emissions of CPPs in China during 2005–2020. CPED is a unit-level database including dynamic information on boiler size, operation conditions, air pollutant emissions and locations for individual electricity generating units. Most previous studies applied the same scaling factor to all CPPs to represent the effectiveness of emission control policies, which ignores the variations among plants [18, 19]. The utilization of CPED for the first time allows for an estimate at the unit level for every time step and allocates the emission changes to exact locations. CPED has dynamic information for a given unit, including the commission time and decommission time of units, changes in technologies, and operating conditions of emission control facilities. The above information further improved the accuracy of emission estimates for every time step.

The historical emission reductions are calculated as the differences between the hypothetical emissions (HIS-SAU15, HIS-EOP15), assuming no control policy has been implemented, and the actual emissions in 2005 (REF05) and 2015 (REF15). Specifically, we follow our previous scenario design (Liu et al) [10] and quantify the impact of power plant fleet mix optimization using the HIS-SAU15 scenario by assuming that China did not adjust power plant fleet mixes during 2005-2015. This scenario shares the same total power generation with REF15 but has the same capacity distribution as REF05. The effect of the promotion of installing end-of-pipe control measures is further examined using the HIS-EOP15 scenario, which assumes that no new end-of-pipe control devices were installed during 2005-2015. Notably, the emissions associated with the power generation increment are suggested by the difference between HIS-EOP15 and

REF05. The effects of the ultra-low emission standards are assessed using the PRE-ULE20 scenario by assuming that all CPPs reach the standards in 2020. The projected provincial coal-fired electricity generation in 2020 derived from our latest work (Tong *et al*) [11] is further adopted in the PRE-GEN20 scenario to explore the future impact of power generation change. We did not include the impacts on emissions of further power plant fleet structure optimization during 2015–2020 due to the uncertainty in the spatial location predictions of newly built units. The details about scenario development are shown in text S1 and table S1 is available online at stacks.iop.org/ERL/14/ 094016/mmedia.

2.2. Chemical transport model

We examine the PM2.5 air quality impacts induced by reduced emissions from the CPPs during 2005-2020 using the Weather Research and Forecasting model (WRF) version 3.5.1 [26] and Models-3 CMAQ version 5.0.1 [24]. The WRF model is driven by the National Centers for Environmental Prediction Final Analysis (NCEP-FNL) [27] reanalysis data as initial and boundary conditions. The meteorological fields from the WRF model together with the anthropogenic emissions are used to drive the CMAQ model. Anthropogenic emissions, except for the power sector, are derived from the Multi-resolution Emission Inventory of China (MEIC) model [28] for mainland China and from the 2010 MIX Asian inventory [29] for other regions. Model configurations are documented in Zheng et al [30] and more details on configurations and evaluations are provided in Text S2.

We perform seven full year runs for 2015 at a horizontal resolution of 36 km by 36 km. We conduct the simulation for each emission scenario developed in section 2.1, including one base simulation and five referenced simulations. We also set up zero-out simulations by subtracting the emissions from the CPPs to calculate CPPs contributions to $PM_{2.5}$ concentrations. In all simulations, except for CPPs emissions, emissions from other emission sectors remained unchanged using the emissions in MEIC 2015 estimates.

2.3. Health impact assessments

We assessed the health impacts of long-term exposure to CPPs-related $PM_{2.5}$, which is the air pollutant with the largest impact on human health. $PM_{2.5}$ -related premature mortality can be determined using IER model, which was developed by Burnett *et al* [25] and has been used in the Global Burden of Disease (GBD) 2015 study [31].

Following the GBD2015 study, five health endpoints relevant to $PM_{2.5}$ exposure, including lung cancer (LC), ischemic heart disease (IHD), chronic obstructive pulmonary disease and stroke for adults age 25 and above, and acute lower respiratory infection for children age 5 and below were considered.



Premature mortality related to each health endpoint was calculated separately and then added up. In the IER function, mortality is determined by cause-specific mortality incidence rate, population, and attributable fraction (AF) [25] of total premature mortality to PM_{2.5}. We derived the national cause-specific mortality incidence rate and population by age and by sex from the GBD2015 study [32, 33]. The population distribution of 2015 was derived from the Gridded Population of World Version 4 [34]. The AF was determined by the IER model with the PM_{2.5} concentration from the CMAQ results. For the calculations of PM2.5-relevant premature mortality induced by CPPs, we multiplied the proportion of the total PM_{2.5} concentrations contributed by CPPs by the total premature mortality related to PM_{2.5} exposure. For the estimation of avoided premature mortality caused by emission control strategies, we calculated the changes in AF attributable to policy-induced PM2.5 changes, which were then multiplied by population and cause-specific mortality incidence rate. The details on the premature mortality estimation are provided in Text S3.

3. Results

3.1. Attribution of emission reduction to control measures

We evaluate the effects of the major emission control measures on reducing SO₂, NO_x, and PM_{2.5} emissions over the last two decades. As described in section 1, China has implemented three primary policies for CPPs during 2005–2020, including energy efficiency improvement by promoting large CPPs and decommissioning small plants during 2005-2020, national emission cap requirements by installing end-of-pipe control devices during 2005-2015, and ultra-low emission standards during 2014-2020. Figure 1 illustrates the contributions of those three policies to reduce the SO₂, NO_x and PM_{2.5} emissions of CPPs in China from 2005 to 2020. The power generation in China increased by 117.3% from 2047.3 TWh to 4448.7 TWh during 2005 to 2020, while a remarkable decline in emissions from CPPs was observed. The SO₂ emissions decreased by 91.0% from 16.7 Tg in 2005 to 1.5 Tg in 2020. The NO_x and PM_{2.5} emissions decreased by 79.1% from 6.7 Tg to 1.4 Tg and by 80.0% from 1.5 Tg to 0.3 Tg, respectively.

The substantial reductions during 2005–2015 resulted from energy efficiency improvements and the installation of FGD and de-NO_x devices. Figure 2 displays the evolution of unit fleets. From 2005 to 2015, the ratio of the most polluting units smaller than 100 MW decreased from 25.5% to 9.6%, while the share of larger units with capacities above 600 MW increased from 9.9% to 40.7%. The great effort to optimize unit fleets significantly improved China's CPPs energy efficiency, with the coal consumption rates





decreasing from 356.4 gce/kWh to 315.4 gce/kWh, which avoids 4.9 Tg of SO₂, 2.2 Tg of NO_x and 0.1 Tg of PM_{2.5} (green bars in figure 1). The installation of end-of-pipe control devices contributes more significantly to emission reductions. Figure 2 also shows the shift in emission rates over time. The emission rates are defined as air pollutant emissions per unit capacity. The emission rates of CPPs decreased dramatically from 2005 to 2020. The average emission rates of SO₂, NO_x and PM_{2.5} decreased from 47.4 to 4.4, from 19.0 to 5.1 and from 4.3 to 0.7 (unit: tonnes per MW), respectively. Specifically, 20.1 Tg of SO2 was averted by the FGD installation. The application of de-NO_x devices resulted in 3.9 Tg of NO_x reductions, and 2.1 Tg of PM_{2.5} emission reductions were achieved due to the dust-removal upgrade along with the co-benefit of wet FGD aid during 2005-2015 (blue bars in figure 1). If these historical control measures on CPPs were not taken, 12.3 Tg SO₂, 3.9 Tg NO_x and 1.4 Tg PM_{2.5} emissions would be increased in CPPs in China mainly due to power generation increments (pink bars in figure 1).

The expected decline in air pollutant emissions after 2015 is driven by implementation of the ultralow emission standards. To meet the requirements of the ultra-low emission standards, the average removal efficiency of SO₂ NO_x and PM_{2.5} emissions from CPPs will increase from 88.6% to 95.0%, 51.2% to 85.0% and 96.7% to 99.3%, respectively. Figure 2 further depicts the dramatic decrease in emissions per unit capacity from 2015 to 2020, which decreased by 2.9, 3.6 and 0.5 (unit: tonnes per MW) for the SO₂, NO_x and PM_{2.5} emission rates, respectively. The growth of coal-fired power generation is projected to slow, increasing by a mere 10.1% because the share of coal-fired electricity generation to the total electricity generation is expected to decrease from 71% to 67% [11]. In 2020, the SO₂, NO_x and PM_{2.5} emissions from CPPs are expected to decline to 1.5 Tg, 1.4 Tg and 0.3 Tg, respectively, which are 38.5%, 31.1% and 50.0% of the 2015 emissions levels, respectively.

3.2. Air quality and health benefits

CPPs contribute significantly to air quality over China. Figure 3(a) displays the PM_{2.5} mass concentrations contributed by CPPs in 2015, which account for 7.6% of the national population-weighted PM2.5 concentration. Higher levels of CPPs-induced PM2.5 were observed in eastern, central and southwestern China. Regions with larger power generation tend to observe higher levels of CPPs-induced PM_{2.5}. The top two provinces in terms of power generation are Shandong province and Jiangsu province, and their CPPs contributions to population weighted PM2.5 are $6.2 \,\mu g \,\mathrm{m}^{-3}$ and $5.4 \,\mu g \,\mathrm{m}^{-3}$, respectively, ranking second and fourth, respectively (figure S4). The contributions in each province also depend on the emission control level of CPPs. For example, the Guangdong Province is fourth in terms of power generation and contributes a relatively small amount to population weighted PM2.5 with a value of 2.3 μ g m⁻³. The averaged SO₂ and NO_x emission factors in this province are 76.5% and 89.5% of the national average level, respectively. Except for the above two factors, atmospheric diffusion conditions together with population distribution all alter the





labeled in the panel.

provincial population weighted CPPs-induced PM_{2.5}. As a combined effect, the annual mean population weighted PM_{2.5} induced by CPPs in Henan Province was at the maximum, reaching 6.8 μ g m⁻³.

The contributions of CPPs to air quality in terms of PM_{2.5} concentrations decrease over time due to the substantial emission reductions resulting from air pollutant control measures. Figure 3(b) illustrates the drivers of the population weighted PM_{2.5} trend. The contributions from CPPs to the national mean population weighted PM_{2.5} concentration decreased from 9.1 μ g m⁻³ in 2005 to 3.7 μ g m⁻³ in 2015. Figure 3(c) illustrates the reduction in PM_{2.5} concentrations resulting from historical emission control measures during 2005–2015. Emissions reductions of 20.1 Tg SO₂, 3.9 Tg NO_x and 2.2 Tg PM_{2.5} due to upgrades in end-of-pipe control facilities, depicted in figure 1, are the primary contributors to the decline in PM_{2.5} concentrations during 2005–2015. Figure 3(d) presents the reduction in PM_{2.5} concentrations arising from implementation of the ultra-low emission standards. The contributions from CPPs are expected to substantially decrease during 2015–2020 because of the ultra-low emission standards. The population weighted PM_{2.5} concentrations will decrease by 2.6 μ g m⁻³ on average, ranging from 0.4 μ g m⁻³ in the Xinjiang Province to 4.6 μ g m⁻³ in the Henan Province (see figure S5).

The $PM_{2.5}$ exposure induced by CPPs is an important source of the total $PM_{2.5}$ -related premature mortality. This exposure was responsible for 93.1 thousand deaths in 2015, accounting for 7.6% of the total $PM_{2.5}$ -related premature mortality (see table S4). The more populous and higher $PM_{2.5}$ exposure regions usually have higher premature mortality attributable to CPPs-induced $PM_{2.5}$ exposures. The Henan





Province with a population of 94.8 million persons had the largest CPPs-relevant premature mortality of 9.8 thousand deaths in 2015, followed by the Shandong, Jiangsu, Guangdong, Hunan and Anhui Provinces (see figure S6, table S5).

The premature mortality associated with emissions from CPPs declined along with the reduction in CPPs-induced PM2.5 concentrations during 2005–2020, which significantly protected human health across China. The energy efficiency improvement of CPPs during 2005-2015 period prevents 31 400 annual premature deaths, while 111 900 deaths are averted by upgrading end-of-pipe control facilities. The implementation of ultra-low emission standards is expected to further avoid 43 500 annual premature deaths. In total, 186 800 annual premature deaths are avoided resulting from the implementation of control strategies on CPPs during 2005-2020, which is 2 times the PM_{2.5}-related mortality induced by CPPs in 2015. Eastern and southeastern China tend to obtain larger health benefits due to the larger PM2.5 reductions and population density. Due to control strategies on CPPs over the fifteen years, the Guangdong Province with a large population density and the Henan Province with the largest PM_{2.5} reductions are supposed to avoid mortalities of 22 100 and 13 700 annually, respectively, ranking as the top two of all provinces. Notably,

the Guangdong Province has the maximum avoided premature deaths (see figure 4, table S6) due to the nonlinear effect of the IER model. The IER model uses a nonlinear curve to describe the relationship between mortality risk and exposure concentration. For certain specific diseases, especially stroke and IHD, a larger change in mortality risk will be achieved along with a PM_{2.5} decline at lower concentration levels [25], which is the so-called nonlinear effect. Here, the PM_{2.5} concentrations in Guangdong province are relatively lower than other populous provinces. Therefore, along with a PM_{2.5} decline, larger reductions in mortality risk are observed in Guangdong province than other areas, which result in larger decline of premature deaths.

4. Discussions

Our results demonstrate the effectiveness of CPPs control policies on emission reductions, air quality improvement and human health protection during 2005–2020. In this study, we focused on the environmental and health benefits of emission control measures on CPPs in China. The influences of emissions changes from other sectors in China and the surrounding countries are not included in this study. We





Figure 4. Avoided annual premature mortainty attributable to major emission control strategies on CPPs during 2005–2020. Five causes of premature deaths relevant to long-term $PM_{2.5}$ exposure was calculated and the total is shown here, including lung cancer (LC), ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD) and stroke for adults age 25 and above, and acute lower respiratory infection (ALRI) for children age 5 and below. The provinces are ranked by the magnitude of avoided premature deaths in 2015 and the unit is one thousand incidences. The eleven provinces in eastern China whose CPPs reached ultra-low emission standards by 2017 are highlighted and marked in bold.

estimated that 12.5 μ g m⁻³ PM_{2.5} exposures will be reduced and 186 800 related premature deaths are expected to be avoided annually as the result of emission control measures on CPPs in China. Before 2015, upgrading the end-of-pipe control measures played a more important role in the mitigation process. Specifically, upgrading the end-of-pipe control facilities and retiring the low-efficient power units could respectively reduce 7.9 and 2.1 μ g m⁻³ of PM_{2.5} exposures and avoid 111 900 and 31 400 PM_{2.5}-related annual premature deaths. The implementation of ultra-low emission standards after 2015 could further decrease PM_{2.5} exposures by 2.5 μ g m⁻³ and avoid 43 500 annual premature deaths.

The mitigation of emissions from CPPs is the primary contributor to meeting the local air quality standard required by clean air action. By 2018, 75% of CPPs in China reached the ultra-low emission standards [35]. The deployment of ultra-low emission standards has different timelines for different provinces over China. The standards were initially implemented in provinces in eastern China and subsequently extended to central and western China, with the aim of requiring around 90% of CPPs to meet the ultra-low emission standards by 2020. The Beijing-Tianjin-Hebei area in eastern China enacted strict emission standards from 2014. All CPPs in the Beijing-Tianjin-Hebei area reached ultra-low emission standards by 2017. Thus, the projected reduction of 2.4 μ g m⁻³ PM_{2.5} concentrations from 2015 to 2020 as a result of the simultaneous decline of 0.05 Tg SO_2 ,

 0.1 Tg NO_x and $0.03 \text{ Tg PM}_{2.5}$ is expected to have been achieved by 2017. The significant drop in PM_{2.5} concentrations acted as an important component in the 'Action Plan for the Prevention and Control of Air Pollution (Action Plan)' [13]. Simultaneously, the majority of CPPs in the Yangtze River Delta and Pearl River Delta have upgraded their emission control devices to meet the ultra-low emission standards during this period and the upgrade is completed for all required CPPs in these regions as of 2018. We estimated that, the emission change caused by ultra-low control technology retrofitting on CPPs are supposed to result 2.7 μ g m⁻³ and 1.6 μ g m⁻³ PM_{2.5} reductions for the Yangtze River Delta and Pearl River Delta, respectively. The central and western provinces also started to carry out the policy in 2014 and were required to complete upgrades by 2018 and 2020, respectively. The estimated reduction of 2.1 μ g m⁻³ in PM_{2.5} concentrations during 2015-2020 will contribute significantly to achieving 'The Three-year Action Plan on Defending the Blue Sky' [36].

The contribution from CPPs to air pollutant emissions in China has gradually decreased. From 2005 to 2015, the proportion of national total SO₂ and NO_x emissions from CPPs decreased sharply from 50.5% to 22.9% and 33.9% to 19.1%, respectively. Due to effective emission control, despite the coal-fired power generation being elevated by 97.4%, the SO₂ and NO_x emissions of CPPs were reduced by 76.6% and 32.8%, respectively, in the past ten years. Consequently, the SO₂ and NO_x emissions per power generation for





CPPs in China has decreased to a comparable level as that in the United States in 2015 (see in figure 5). These emission rates are projected to continuously decline to a level of 0.3 g/kWh, if the ultra-low emission standards are fully deployed. Here, the emission factor data of CPPs in the United States and China was calculated based on Emissions and Generation Resource Integrated database [37] and CPED [10, 11], respectively. More details of SO₂ and NO_x emission factors is provided in Text S4.

The countermeasures on China's CPPs can provide valuable guidelines for emission control in the power sector in other developing countries. CPPs in another developing country, India, tell a different story. Due to the lack of strict emission control policies, the emission factors for CPPs in India are relatively steady [38, 39]. The NO_x emission factor decreased slightly from 3.4 g/kWh in 2005 to 2.9 g/kWh in 2015 and the SO2 emission factor increased slightly from 8.9 g/kWh in 2005 to 9.8 g/kWh in 2011 due to the newly built power units located in a high sulfur content region, then dropped down to 9.0 g/kWh in 2015. The coal power generation in India is projected to increase by 49.3% from 1032.1 TWh in 2015 to 1541.2 TWh in 2025 under the current existing policies [40]. The dramatic growth in energy demand will cause substantial air pollution and result in damage to people's health without effective control. The Chinese control experience on CPPs demonstrates that upgrading end-of-pipe facilities has successfully decreased CPPs emissions over a relatively short-term period without fundamental adjustments to energy structures. This strong decrease in air pollutant emissions suggests that measures can be taken in other developing countries such as India that will reduce emissions alongside rapid economic development.

Our study is subject to some limitations and uncertainties. First, we developed emission scenarios based on the CPED database, which is established using an annual averaged unit-specific emission factor. These emission factors are determined by the coal quality and combustion equipment type of each unit, which could not reflect the variation in emission rates arising from operating status changes. Liu et al [15] reported that the actual operation status and adoption of different end-of-pipe control technologies alters the emission factors of ultra-low power units based on Continuous Emission Monitoring System data. Their estimated emission factors for ultra-low units are lower by 66.3%-97.5% for SO2 and 31.4% for NOx than in our study. Second, the contributions of emissions from CPPs to PM_{2.5} exposure were calculated using the zero-out method by extracting the CPPs emissions. Additional bias was introduced due to the nonlinear relationship between the changes in emissions and that in the simulated PM_{2.5} concentrations. A sensitivity analysis shows that the nonlinear effects of the zero-out method could be relatively small with relative biases ranging from -12.0% to +1.4% [41], therefore, such effects were not discussed in detail in this study. The estimated air quality and health benefits from emissions reductions from CPPs are subject to uncertainties due to the deployment of 2015 data for year 2020. The projected PM_{2.5} concentrations were simulated based on the meteorological condition and population of 2015, which may differ from the actual conditions. Third, to date, the estimation of premature mortality attributable to PM_{2.5} exposure contains large uncertainties, particularly in the higherexposure concentrations. A more recent global exposure mortality model (GEMM) was developed [42] to estimate the disease-specific hazard ratio to PM_{2.5} exposure, which predicted a 122% increase in excess deaths compared with the estimation in GBD study [31] using IER model. Different from the IER model, the GEMM model obtained the deaths risk of PM_{2.5} exposure using studies of out-door air pollution, which resulted in generally larger deaths risk, particularly at higher PM_{2.5} concentrations. We expect that the health benefits arising from the air quality improvements associated with emissions reductions from CPPs could be larger if the estimation is made using the GEMM model.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available for legal ethical reasons.

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