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Benefits of current and future policies on emissions of China's coal-fired power sector indicated by continuous emission monitoring★

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A B S T R A C T

Emission inventories are critical to understanding the sources of air pollutants, but have high uncertainties in China due in part to insufficient on-site measurements. In this study, we developed a method of examining, screening and applying online data from the country's improving continuous emission monitoring systems (CEMS) to reevaluate a “bottom-up” emission inventory of China's coal-fired power sector. The benefits of China's current national emission standards and ultra-low emission policy for the sector were quantified assuming their full implementation. The derived national average emission factors of SO_2, NO_x and particulate matter (PM) were 1.00, 1.00 and 0.25 kg/t-coal respectively for 2015 based on CEMS data, smaller than those of previous studies that may not fully recognize improved emission controls in recent years. The annual emissions of SO_2, NO_x and PM from the sector were recalculated at 1321, 1430 and 334 Gg respectively, 75%, 63% and 76% smaller than our estimates based on a previous approach without the benefit of CEMS data. The results imply that online measurement with proper data screening can better track the recent progress of emission controls. The emission intensity (the ratio of emissions to economic output) of Northwest China was larger than that of other regions, attributed mainly to its less intensive economy and industry. Transmission of electricity to more-developed eastern provinces raised the energy consumption and emissions of less-developed regions. Judged by 95 percentiles of flue-gas concentrations measured by CEMS, most power plants met the current national emission standards in 2015 except for those in Northwest and Northeast China, while plants that met the ultra-low emission policy were much scarcer. National SO_2, NO_x and PM emissions would further decline by 68%, 55% and 81% respectively if the ultra-low emission policy can be strictly implemented, implying the great potential of the policy for emission abatement.

1. Introduction

The power sector is considered one of the most important sources of air pollution in China (Fu et al., 2013; Tang et al., 2012; Zhang et al., 2012; Zhao et al., 2010; Zhao et al., 2013). The installed capacity of thermal power plants reached 1005 GW in 2015, accounting for 75% of the total generating capacity in the country (EBCEPY, 2016). Coal remains by far the dominant fossil fuel in the electricity sector, comprising 90% of thermal power installed capacity. Previous studies concluded that the power sector contributed 21%–33% and 28–33% of China's total emissions of SO_2 and NO_x in 2010, respectively (Li et al., 2017; Lu et al., 2011; Zhao et al., 2013; Zhao et al., 2013). These pollutants are especially harmful to human health due to their roles in the formation of secondary fine particles through reactions in the atmosphere (Gao et al., 2018; Zhang et al., 2012).

Air pollutant emissions from the power sector are commonly estimated through a “bottom-up” approach. Zhao et al. (2008, 2010) compiled a database of emission factors (emissions per unit

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coal consumption) for China's coal-fired power plants based on available field measurements and calculated the emissions of individual generation units throughout the country. With updated information at the unit level, the method has been modified and widely applied to improve emission estimation and to evaluate inter-annual changes (Lei et al., 2011; Lu et al., 2011; Zhao et al., 2013a; Tian et al., 2013; Wang et al., 2015). Liu et al. (2015) compiled comprehensive information on combustion technology, activity level, and fuel quality of each unit, and developed a power sector emission inventory for 1990–2010. Insufficient direct measurements of emission factors, however, contributed to uncertainties in the inventory, and data from continuous emission monitoring system (CEMS) were recommended to further improve emission estimation.

In recent years, a series of energy and environment policies has been implemented in China's power sector and was expected to effectively reduce the emissions of air pollutants. Klimont et al. (2013) estimated that SO_2 emissions in China reached a peak in 2006 and began to decline afterwards, primarily due to the increased use of flue gas desulfurization (FGD) systems. Liu et al. (2016) found that NO_x emissions in China declined continuously after 2011 despite increasing coal consumption, resulting mainly from the deployment of selective catalyst reduction (SCR) in the power sector. Based on the adjustment of the penetration rates and removal efficiencies of emission control devices in power sector, Tong et al. (2018) predicted that the emissions of air pollutants from power sector would significantly decline during 2016–2030 due to the ultra-low emission policy. Relying only on routine environmental statistics without the support of online measurement data, however, the effects of these swift changes in emission controls could not be quantified accurately or in a timely fashion at the unit level.

Since 2007, CEMS have been installed and operated in some (chiefly high-emitting) plants in China to track the real-time concentrations of selected air pollutants in the flue gas. Recently efforts have been made to estimate the emissions from power generation using CEMS data (Bo et al., 2015; Chen, 2016; Wu et al., 2017; Liu et al., 2019). For example, Zhang et al. (2018) calculated the emissions of coal-fired power plants in Jiangsu for 2012 incorporating CEMS data. Cui et al. (2018) developed an emission inventory of China's thermal power sector combining CEMS data, official environmental statistics compiled by the State Ministry of Environment Protection (MEP) and the information from pollutant emission permits issued for individual plants by the government. The main limitations of those studies were lack of assessment of data quality of and limited quantification of the effects of CEMS data on emission estimation. CEMS measurement has its own uncertainties, particularly in earlier years of deployment, resulting from both technical and management weaknesses. By examining the CEMS data from 38 power units of China Energy Group, Liu et al. (2019) found that the emission factors for SO_2, NO_x and PM were up to 1–2 orders of magnitude lower after ultra-low emission retrofitting. With expanded data samples, therefore, reliable online measurements are expected to help to better capture the benefit of emission control measures. Karplus et al. (2018) applied satellite observation and available CEMS data of power sector to detect the emission reduction due to implementation of ultra-low emission policy, and suggested more careful evaluation of CEMS data.

In this study, we developed a method for estimating emissions from power sector by examining, screening and applying the CEMS data. The annual emissions of selected species were calculated using different approaches, with and without the CEMS data, and the results were compared against each other to understand the effects of CEMS data on emission estimation of the sector. The benefits of national polices on emission abatement for the sector were then evaluated based on the CEMS measurement of individual plants.

2. Methodology and data

2.1. Study domain

The study domain includes 30 provinces/autonomous regions/municipalities in mainland China, including (noting there are no coal-fired power plants in Tibet). It included 1736 coal-fired power plants in total, distributed into six large interprovincial power grids named for the regions they serve: Northwest, Northeast, North, Central, East, and South China. The total capacity and coal consumption of coal-fired power sector were reported at 880 GW and 1830 Mt in 2015 (NBS, 2016). The distribution of total installed capacity by unit size is illustrated for each grid in Fig. 1. The total capacity shares of small units (<300 MW) ranged 8–23%, smaller than those of large (≥600 MW) and medium ones (300–600 MW) for all six grids. The total installed capacity and capacity share of large units were largest in East China, reaching 135 GW and 66%, respectively.

2.2. Emission estimations without and with CEMS data

A unit-based inventory of SO_2, NO_x and PM emissions from China's coal-fired power sector for 2015 was developed first without CEMS data (referred as base emission inventory, BEI). Details of the method can be found in the Supplementary material. With the emission factors and activity levels investigated and compiled for individual plants, the annual emissions of each species were generally calculated using Eq. (1), as described in Zhao et al. (2008, 2010):

$$E_i = \sum_{i,j,m} A_{j,m} \times EF_{i,j,m} \times (1 - \eta_{i,j,m}) \tag{1}$$

where i, j and m represent the pollutant species, individual plant, and fuel or technology type, respectively; A is the activity level, e.g., the annual coal consumption; EF is the emission factor without added controls; and η is the removal efficiency of any air pollutant control device (APCD).

CEMS data for 1039 electric generating units were obtained, including monitoring time, unit operational state, flue gas flow, and hourly concentrations of SO_2, NO_x and PM. Two estimations were made incorporating CEMS data, referred as updated emission inventories, UEI (A) and UEI (B), respectively. In UEI (A), the annual mean hourly concentrations of air pollutants obtained from CEMS and the annual total volume of flue gas taken from environmental statistics were applied to calculate the annual emissions of each individual plant (Eq. (2)), while in UEI (B) the theoretical annual flue gas volume of each plant was calculated and applied (Eq. (3)):

$$E_{i,j} = C_{i,j} \times V_j \tag{2}$$

$$E_{i,j} = C_{i,j} \times A_j \times V_m^0 \tag{3}$$

where C is the annual average concentration; V is the annual total flue gas volume; A is the annual coal consumption; and V^0 is the theoretical flue gas volume per unit of coal consumption. V^0 depends on the coal type and can be calculated following the method in Zhao et al. (2010).

The operational condition and resulting data quality of CEMS have been a concern since they were installed, likely contributing to measurement errors. We took steps to screen the CEMS data before

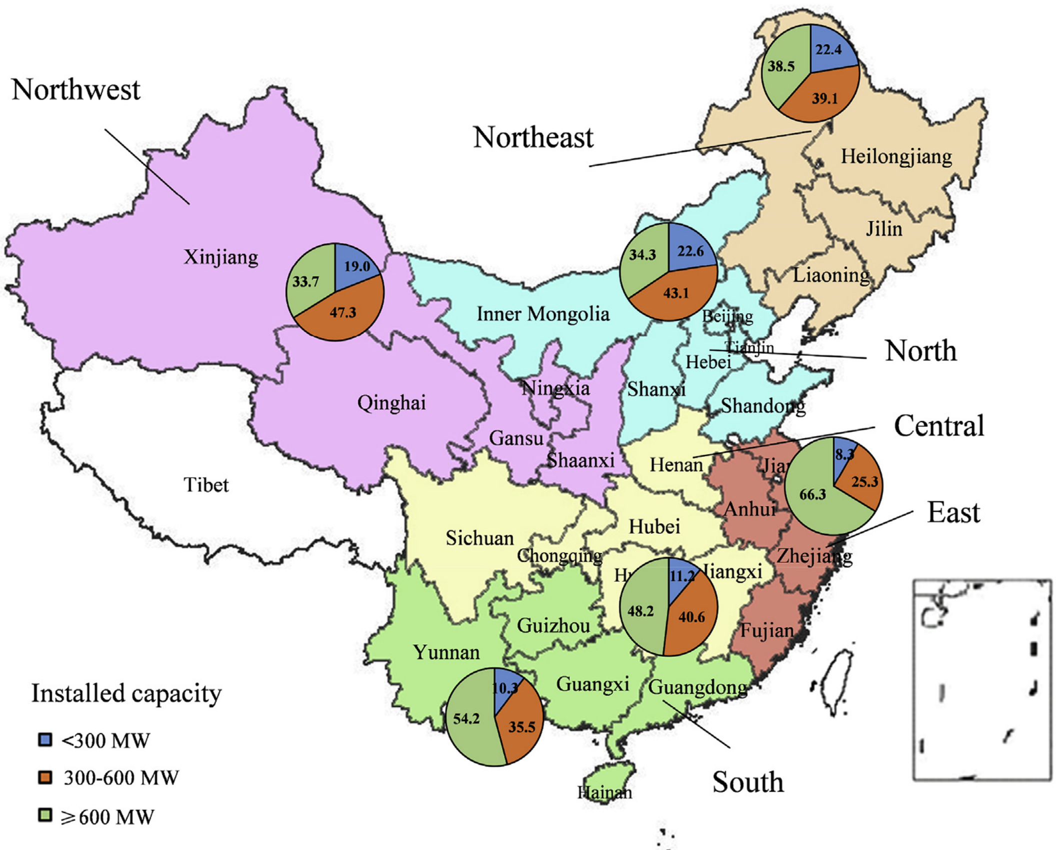

Fig. 1. The capacity distribution of coal-fired power plants in China's six interprovincial power grids in 2015.

they were applied to estimate emissions. First, negative concentrations and those detected when the power unit was shut down or undergoing maintenance were excluded. The 95% confidence intervals (CIs) of the hourly concentrations were then applied to filter out extremely low concentrations. Additional infeasible concentrations were further detected and excluded with the following approach. We calculated the abated emission factors using Eq. (1), by assuming the removal efficiencies of APCDs (η in Eq. (1)) for the extremely optimistic and pessimistic cases. The "reference concentration" (i.e., the expected lower and upper bounds of concentrations) was then calculated using Eq. (4):

$$Cs_{i,j} = \mu_{i,j} \times EF_{i,j} \times V^0_{j,m} \quad (4)$$

where Cs is the reference concentration and μ is a factor considering the uncertainty of emission factors. To calculate the theoretically highest concentration of SO_2, for example, we assumed that an FGD system was not installed or operated and an uncertainty of 100% for the emission factor, i.e., η was 0 in Eq. (1) and μ was 2 in Eq. (4). For the theoretically lowest concentration, the maximum removal efficiency of FGD for SO_2 was assumed to be 99%, which meant that η was 99% and μ was 1. Similarly for NO_x, η and μ were assumed to be 0 and 3 for the highest concentration, and at 90% and 1 for the lowest, respectively. A range of removal efficiencies was calculated by type of dust collector based on official environmental statistics, and the lower and upper bounds of the reference removal efficiency were set at the 2.5 and 97.5 percentiles of the range respectively. The lowest and highest reference PM concentrations of individual plants could then be determined according to their dust collector types. For example, the maximum and minimum removal efficiency of an electrostatic precipitator (ESP) were calculated at 99.95% and 89.85%, respectively.

As illustrated in Fig. S1 in the Supplementary material, the fractions of detected abnormal online monitoring data of coal-fired power plants varied by province due to different operation conditions, data qualities and sources of CEMS. The systematic abnormal concentration values include negative concentrations and those detected under abnormal operation conditions, while the evaluated abnormal concentration values indicate those detected based on the statistical method with the mass balance principle as described above. The fractions of abnormal SO_2, NO_x and PM concentrations in most provinces were between 4% and 40%, and the largest were found for Yunnan at 32%, 38% and 66%, respectively. The numbers indicate relatively poor operation or management condition of CEMS in this province. The fractions of abnormal SO_2, NO_x and PM concentrations in Heilongjiang were the smallest at 2%, 1% and 2% respectively, implying relatively stable operation conditions of power units. The fractions of systematic abnormal values were larger than evaluated ones in all the provinces. The largest fraction of systematic abnormal values reached 60% for PM concentrations in Yunnan, followed by those of SO_2 and NO_x in Hubei (both 37%). The results indicate that there are unexpected errors in the measurement technology or abnormal conditions in management and operation of CEMS, and the resulting abnormal concentrations should be excluded from emission estimation.

The online monitoring data did not cover all the plants. The fractions of the units with CEMS data in installed capacities were calculated by province and summarized in a new Table S1 in the Supplementary material. The total installed capacity of units with CEMS data accounted for 73% of all the units for provinces where

CEMS data were available, and the fractions of small (<300 MW), medium (300–600 MW) and large (≥600 MW) units with CEMS data were estimated at 47%, 78% and 76% in installed capacity, respectively. The numbers indicate that the plants with CEMS tend to be large units and those without CEMS are often small ones. For units lack of CEMS data, the average pollutant concentrations from CEMS in the same category of installed capacity were applied to calculate the emissions. Due to lack of on-line monitoring and thereby poorer operation of emission control devices, however, the emissions from units without CEMS could be relatively large, and underestimation in emissions for those units were possibly made in this work. For provinces lacking activity levels or CEMS data at the unit level, provincial level emission factors were applied based on previously published CEMS data (Cui et al., 2018), and the coal consumption of each unit was assumed to be proportional to its installed capacity and calculated based on the total provincial consumption.

The parameters used in BEI, UEI (A) and UEI (B) methods are summarized in Table S2 in the Supplementary material. In general, the sulfur and ash contents of coal in more developed eastern provinces were less than those of other provinces, and the removal efficiencies calculated with CEMS data were higher than those obtained from environmental statistics. Fig. S2 in the Supplementary material illustrates the probability distributions of the removal efficiencies of SO_2 and PM in BEI and UEI (B) for power units in Jiangsu Province as an example. Through Monte Carlo simulation, the 95% CIs of SO_2 removal efficiencies were 27.32%–99.59% and 84.90%–100% in BEI and UEI (B), respectively, and the analogous numbers for PM were 92.43%–100% and 99.71%–100% (noting values larger than 100% from the simulation were discarded). The removal efficiencies in UEI (B) exhibited more concentrated distributions than those in BEI.

2.3. Evaluation of implementation of emission standards for power sector

The current Emission Standard of Air Pollutants for Thermal Power Plants GB13223-2011 (MEP, 2011) dictates the concentration limits and monitoring requirements of air pollutants from thermal power sector. To further reduce emissions, an “ultra-low emission policy” for coal-fired power plants was set in 2014 (NDRC et al., 2014). The policy requires that the emissions from coal-fired boilers should be reduced to the level of natural gas boilers, i.e., the flue gas concentrations of SO_2, NO_x and PM should not exceed 35, 50 and 5 mg/m^3, respectively. Compared to the strictest limit of GB13223-2011, the maximum flue gas concentrations of SO_2, NO_x and PM at power plants should be further reduced by 30%, 50% and 75% respectively. In this study, the implementation of emission standards for the power sector was evaluated based on the CEMS data filtered as described above, and two scenarios were developed to assess the potential benefits of the current standards and ultra-low emission policy for 2015. Scenarios 1 and 2 refer to cases in which all coal-fired power plants meet the requirement of GB13223-2011 and the ultra-low emission policy, respectively. Given the temporal variation of flue gas concentrations detected by CEMS, a reasonable “guarantee rate” of 95% was applied, i.e., an individual plant was deemed to meet the standard if less than 5% of its hourly concentrations exceeded the corresponding limit. For power plants that met the emission standard in 2015, their “in compliance” emissions were set the same as the actual emissions in the UEI (B) method. Otherwise, their 95 percentiles of flue gas concentrations were reduced to the corresponding concentration limit, and their “in compliance” emissions were calculated by scaling the actual emissions with the ratio of the standard limit to current 95 percentile of hourly concentrations measured by CEMS.

3. Results and discussions

3.1. Emission factors

Table 1 summarizes the average emission factors of coal-fired power plants in selected provinces using the three methods. The emission factors of most provinces in UEI (A) and UEI (B) were relatively close to each other, implying consistency between the flue gas volume and coal consumption data provided by official environmental statistics. There were relatively large differences between emission factors in UEI (A) and UEI (B) for Hubei, Guizhou and Heilongjiang provinces. Given the potentially larger uncertainty in measuring the volume of emitted flue gas compared to coal consumption, UEI (B) may be more reliable for calculating annual average emission factors. Due mainly to lower flue-gas concentrations of all concerned species measured by CEMS compared to those estimated bottom-up, the national emission factors of SO_2, NO_x and PM calculated in UEI (B) were 1.00, 1.00 and 0.25 kg/t respectively, 78%, 71% and 94% lower than those in BEI. The emission factors used in BEI were likely overestimated, as the removal efficiencies of various species obtained from environmental statistics were not updated in a timely fashion and considering the actual operational condition of APCDs for individual plants. The removal efficiencies of SO_2 and NO_x remained at zero for some small power plants. Therefore, the environmental statistics which depended largely on previous experience of environmental management by local government could not fully track the progress of emission controls for power sector in recent years. As shown in Table 1, there were significant regional differences in emission factors among the provinces attributed to their different mixes of unit type, fuel qualities and emission control technologies. The results of UEI (B) were taken as examples to analyze the reasons. The emission factors of eastern provinces with more developed economies were smaller than those in other areas, and the discrepancies came from the mixed influence of fuel qualities and the rates of penetration and operations of APCDs. For example, the average sulfur content of coal in Heilongjiang in Northeast China (mainly lignite) was 0.31%, smaller than that in Anhui in East China, at 0.53%. However, the calculated SO_2 emission factor for Heilongjiang was 2.6 times of that for Anhui, resulting largely from a much lower FGD penetration rate in Heilongjiang (66%) than that of Anhui (97%). Similarly, Heilongjiang exhibited the highest NO_x emission factors at 1.69 kg/t, with the lowest penetration (32%) and removal rates (69%) of NO_x control devices.

The average emission factors and their 95% CIs were calculated by unit size and boiler type based on online monitoring data (UEI (B)), as summarized in Table 2. There were 772 units with pulverized coal (PC) combustion and 267 with circulating fluidized bed combustion (CFBC). Large units exhibited smaller emission factors, attributed mainly to better coal quality and higher removal efficiencies. As illustrated in Fig. 2, the sulfur and ash contents of coals combusted in small units were generally higher than those for large ones, and their APCDs operated less effectively, with lower removal efficiencies for various species. One exception is that the average sulfur content of small units at 0.6% was lower than that of medium units at 1.0%. The SO_2 emission factor for small units, however, was estimated to be 47% larger than for medium units, driven mainly by the lower removal efficiency for smaller units (89%) than medium ones (96%).

We compared our emission factors with those of other studies for 2015. Based on data for one province (Guangdong), Dai (2016) calculated the average SO_2 emission factors of coal-fired power plants at 0.43–1.88 and 0.76–3.16 kg/t-coal with and without use of CEMS data, respectively. The smaller emission factors from CEMS than those based on a mass balance method are consistent with this

Table 1
Average emission factors of typical pollutants calculated with different methods for coal-fired power plants in selected provinces. Units: kg/t-coal.

Province	EF_{SO2}			EF_{NOx}			EF_{PM}		
	UEI (A)	UEI (B)	BEI	UEI (A)	UEI (B)	BEI	UEI (A)	UEI (B)	BEI
Heilongjiang	2.50	1.42	3.73	2.50	1.69	4.48	0.75	0.49	12.61
Shaanxi	1.86	1.67	8.38	1.06	1.02	3.60	0.46	0.43	1.43
Shanghai	0.44	0.39	2.27	0.63	0.58	2.27	0.07	0.07	0.56
Jiangsu	1.23	0.75	3.87	1.60	0.92	2.85	0.27	0.17	3.06
Zhejiang	0.81	0.62	4.50	1.12	0.77	3.37	0.16	0.11	4.91
Anhui	0.54	0.54	2.32	0.69	0.67	3.22	0.17	0.16	1.43
Fujian	0.79	0.72	3.12	0.82	0.75	5.32	0.17	0.15	1.11
Hubei	2.42	1.31	8.23	1.87	1.24	3.71	0.29	0.19	5.48
Guizhou	3.39	2.09	7.74	2.62	1.26	5.40	0.40	0.22	2.60
Guangxi	1.70	1.54	3.23	0.94	0.81	3.74	0.30	0.30	0.90
National average	1.50	1.00	4.49	1.52	1.00	3.48	0.32	0.25	4.17

Table 2
Emission factors of electric generating units in UEI (B) by capacity and boiler type for China's coal-fired power plants in 2015. 95% CIs are given in parentheses. Units: kg/t-coal.

	Capacity size/MW	Units	SO_2		NO_x		PM	
			95% CI	average	95% CI	average	95% CI	average
Total	<300	410	(1.02–1.37)	1.19	(1.20–1.43)	1.32	(0.24–0.35)	0.29
	300–600	356	(0.72–0.91)	0.81	(0.68–0.77)	0.73	(0.14–0.19)	0.17
	≥600	273	(0.51–0.62)	0.56	(0.51–0.57)	0.54	(0.10–0.16)	0.13
Pulverized Coal	<300	183	(0.90–1.46)	1.18	(1.40–1.84)	1.62	(0.26–0.49)	0.37
	300–600	318	(0.72–0.93)	0.82	(0.66–0.75)	0.70	(0.15–0.20)	0.17
	≥600	271	(0.51–0.62)	0.56	(0.51–0.57)	0.54	(0.11–0.16)	0.13
CFBC	<300	227	(0.99–1.43)	1.21	(0.97–1.18)	1.08	(0.20–0.27)	0.24
	300–600	38	(0.61–0.89)	0.75	(0.71–1.14)	0.93	(0.12–0.20)	0.16
	≥600	2	–	0.21	–	0.51	–	0.12

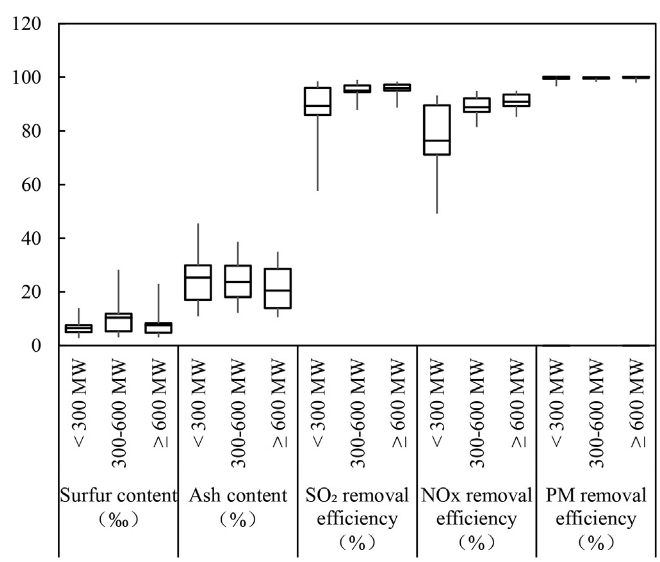

Fig. 2. Key parameters for electric generating units of various sizes in China in 2015. The sulfur and ash content were calculated based on official environmental statistics (BEI), and the removal efficiencies were calculated with CEMS data (UEI (B)). The black horizontal lines in the box represent the mean values, the boxes denote the 25 and 75 percentiles, and the whiskers denote the 5 and 95 percentiles.

study. Due to the larger sample size, however, much wider ranges of emission factors were obtained in this work: 0.02–18.34 and 0.26–46.00 kg/t-coal based on CEMS and mass balance method, respectively. The discrepancy in the emission factor range resulted partly from the CEMS data involved in the calculation and partly from the data processing method. The hourly concentrations in the flue gas of some power plants were very high but stable. In particular, the annual average concentrations of two units in Shaanxi and Xinjiang exceeded 2000 mg/m^3, resulting in CEMS-based emission factors higher than 18 kg/t-coal. Moreover, the removal efficiencies of some small power plants were determined to be zero in the official environmental statistics, leading to a much higher upper bound of mass-balance-based SO_2 emission factors than those of Dai (2016). A similar situation was found for NO_x. The SO_2 and NO_x emission factors in this study were close to but slightly higher than those in Cui et al. (2018), attributed partly to the similar source of online monitoring data analyzed in these two studies. With the data assessment and screening in this work, extremely low pollutant concentrations in the flue gas from online monitoring were excluded while some high concentrations remained, leading to somewhat higher emission factors compared to Cui et al. (2018).

3.2. Annual emissions of the coal-fired power sector

Summarized in Table 3 are the emissions of SO_2, NO_x and PM from the coal-fired power sector calculated with UEI (B) and BEI, by regional grid (see the provincial emissions in Table S3 in the Supplementary material). Incorporating CEMS data, the SO_2, NO_x and PM emissions from the coal-fired power sector in the country were estimated at 1321, 1430 and 334 Gg (UEI (B)), respectively, i.e., 75%, 63%, and 76% smaller than those in BEI using the mass balance method. The differences between the two methods varied in the six grids, with those for North and East China particularly large. For example, the SO_2 emissions in UEI (B) were 84% smaller than those in BEI for North China, and the NO_x and PM emissions in UEI (B) were 76% and 86% smaller than those in BEI for East China, respectively. In contrast, the analogous differences for Northwest China were much smaller, at 64%, 40% and 55% for SO_2, NO_x and PM, respectively. This might be because stricter air pollution control policies were required in more economically developed regions, including northern and eastern provinces (MEP et al., 2014, 2015), leading to bigger changes in emissions of anthropogenic pollutants.

Table 3
Emission estimates for China's coal-fired power sector by regional grid for 2015 using different methods and emission scenarios. Units: Gg.

Grid	BEI			UEI (B)			Scenario 1			Scenario 2		
	SO_2	NO_x	PM	SO_2	NO_x	PM	SO_2	NO_x	PM	SO_2	NO_x	PM
Northeast	448.5	457.1	293.3	159.0	227.1	51.0	144.8	165.3	40.2	52.6	78.1	7.6
Northwest	659.9	386.6	163.9	235.2	231.0	73.7	146.5	161.5	34.2	49.1	79.2	7.6
North	2094.3	949.8	335.8	327.6	380.3	75.8	327.6	372.8	75.8	152.3	218.0	21.8
East	641.4	984.3	353.0	185.6	238.0	49.1	179.6	217.1	42.1	70.8	124.9	11.1
Central	726.3	488.7	138.5	234.6	199.2	51.9	216.4	189.6	41.5	61.0	90.2	8.8
South	641.4	549.6	108.9	178.7	154.5	32.6	156.0	122.4	21.1	31.6	52.7	5.6
Total	**5211.7**	**3816.1**	**1393.4**	**1320.8**	**1430.1**	**334.1**	**1170.8**	**1228.7**	**254.8**	**417.4**	**643.2**	**62.6**

Such changes may not be reflected as quickly in the traditional "bottom-up" method than in the CEMS data, thus causing greater discrepancies between the two methods. In UEI (B), six provinces with the largest coal consumption, including Inner Mongolia, Xinjiang, Shanxi, Shandong, Jiangsu and Henan, emitted 46% of China's total SO_2 from the coal-fired power sector, followed by Guizhou where coal with high sulfur content is widely used. NO_x emissions from coal-fired power plants in Inner Mongolia, Xinjiang, Jiangsu and Shandong exceeded 100 Gg, while those in Beijing and Hainan were less than 10 Gg. The emissions of all the three species in North China were the largest, attributed mainly to large electricity generation and coal consumption in the region.

Fig. 3(a–c) illustrates the spatial distribution of air pollutant emissions from the coal-fired power sector for China in 2015. The emissions were the most spatially intensive in East and North China, which together accounted for almost half of total coal consumption by the sector. This was further illustrated by the ratio of emissions to land area for each province: Shandong, Tianjin, Jiangsu and Shanghai exhibited larger ratios than other provinces. Regarding the regional power grids, the largest ratios were found for all three species in East China, reaching 0.39, 0.50 and 0.10 t/km^2 for SO_2, NO_x and PM respectively, while the lowest at 0.08, 0.08 and 0.02 t/km^2 were in Northwest China. The locations of power plants and spatial distribution of air pollutant emissions imply that power plant construction in China was still largely influenced by population and economic densities, despite specific national energy policies that seek to relocate electricity generation such as one commonly translated as "Transmission of Electricity from Western Areas to East China." The emission intensity defined as the ratio of emissions to Gross Domestic Product (GDP) presents an opposite case, as illustrated in Fig. 3(d–f). Larger emission intensities were found for less developed regions such as Xinjiang, Inner Mongolia and Ningxia. With 19% of the national population and 26% of GDP in 2015, East China was estimated to account for 14%, 17% and 15% of the national power emissions of SO_2, NO_x and PM respectively. In contrast, Northwest China accounted for 7% of the country's population and 5% of the its GDP, but contributed 18%, 16% and 22% of SO_2, NO_x and PM emissions from the coal-fired power sector, respectively. The results indicate that areas with more developed economies and intensive industrial production like East China cannot totally meet the demands of energy and electricity by themselves, and that the policies of electricity transmission from less developed regions will elevate air pollutant emissions in those regions.

The effects of size distribution of units on pollutant emissions are also explored. In UEI (B), large units (≥600 MW) were estimated to account for 38%, 37% and 38% of SO_2, NO_x and PM emissions from the whole coal-fired power sector, respectively, smaller than their

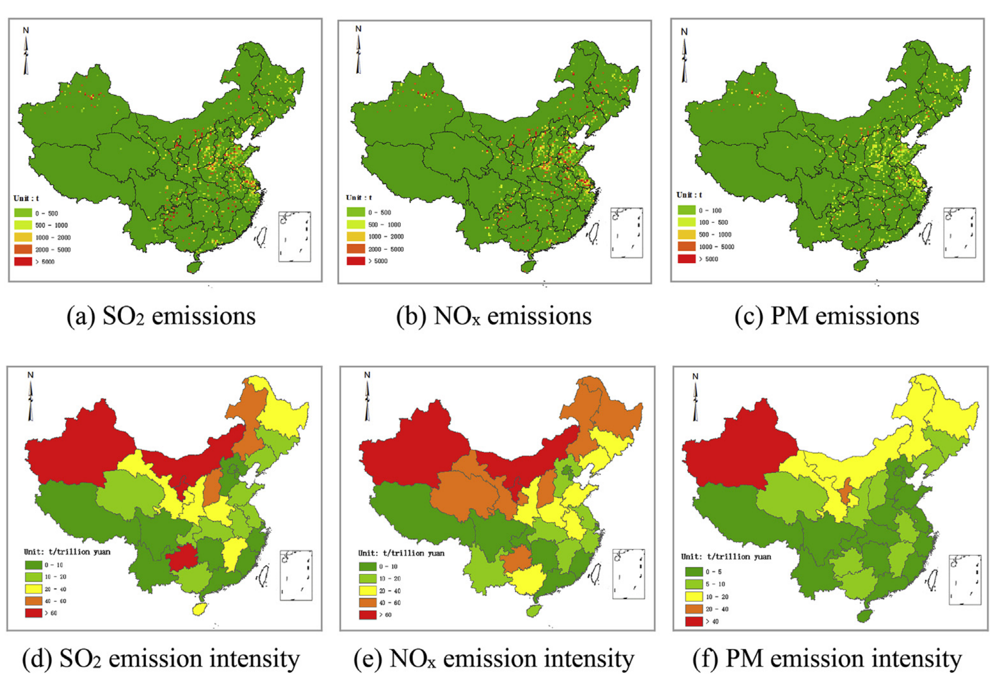

Fig. 3. Spatial distribution of typical pollutant emissions of China's coal-fired power plants in UEI (B) in 2015: (a–c) the gridded emissions at the resolution of 27 km × 27 km, and (d–f) the provincial emission intensities.

share of installed capacity (43%) and coal consumption (46%). The analogous numbers for small units (<300 MW) were calculated at 22%, 25% and 24% for SO_2, NO_x and PM, respectively, larger than their share of installed capacity (20%) and coal consumption share (16%). The result suggests more effective implementation of pollutant emission control measures at larger power generating units than smaller ones.

Fig. S3 in the Supplementary material illustrates the monthly variations of flue gas concentrations for more and less economically developed provinces. Clear declining trends for SO_2 and NO_x are indicated by correlation coefficients (R) derived by linear regression, while much bigger fluctuations were found for PM. Attributed to the measurement limitation particularly at low concentration levels, it is more difficult to obtain reliable and stable PM concentrations with CEMS compared to other species (Yang, 2013). The reduction rates for SO_2 were estimated at 3.2 and 1.8%/month for more and less developed provinces, respectively, implying bigger progress of SO_2 controls for the more developed (and usually more polluted) regions. The reduction, however, was smaller than that reported by Karplus et al. (2018) around July 2014, suggested as a strong response to the deadline for compliance with the national standard (GB13223-2011). For NO_x, the reduction rates were closer for the more and less developed regions. Previous studies without CEMS data commonly assumed that the monthly distributions of emissions were proportional to those of energy consumption or electricity production (Zheng et al., 2009; Kurokawa et al., 2013). Fig. S4 in the Supplementary material compares the monthly variations of SO_2 and NO_x emissions from coal-fired power sectors between inventories with and without CEMS data (respectively, UEI (B) in this work and the Multi-resolution Emission Inventory for China, MEIC: http://www.meicmodel.org). For northern China, the coefficients of variance (CVs) were calculated respectively at 24% and 19% for monthly SO_2 and NO_x emissions in UEI (B), larger than 9% for both species in MEIC. Similarly, the monthly variation of UEI (B) emissions was larger that in MEIC for southern China, and the CVs were bigger than those for north. The results suggest that this widely accepted assumption probably underestimates the temporal variation of annual emissions from the power sector.

3.3. Effects of emission standard implementation

3.3.1. Flue gas concentrations “in compliance”

The annual average concentrations of air pollutants in flue gas were assessed to judge whether each given plant met the emission standard or not (Chen, 2016; Cui et al., 2018; Karplus et al., 2018; Zhao et al., 2014). Given temporal variation in the concentrations, however, an annual average value below the emission standard hardly guaranteed compliance when the criterion is that 95% of hourly concentrations must meet it (called the “95 percentile” criterion below). We take two units as examples to illustrate this point: Unit A in Guangdong, with installed capacity of 270 MW, and Unit B in Jiangsu, with installed capacity of 55 MW. As shown in Fig. S5 (a) in the Supplementary material, the annual average and 95 percentile of SO_2 concentrations in the flue gas of Unit A were calculated at 95 and 151 mg/m^3 based on the CEMS measurement respectively, both lower than the limit of the national standard (200 mg/m^3). Fig. S5 (b) in the Supplementary material shows a different case in which the average SO_2 concentration in the flue gas of Unit B (106 mg/m^3) was smaller than the national standard but the 95 percentile of hourly concentrations (600 mg/m^3) was far larger. Unit A was thus deemed in compliance with the national standard while Unit B was not.

Shown in Fig. 4 are the annual average monitored SO_2 concentrations and 95 percentiles of hourly concentrations of all power units in selected provinces with relatively large numbers of units, in order to assess the success of implementation of both the national standard and the ultra-low emission policy. In each panel, the units with concentrations exceeding the limits (illustrated by the two horizontal lines) failed to meet the corresponding standard, with percentages indicating the fractions of “in compliance” units for the province. As shown in Fig. 4 (c), for example, 94% of electric generating units in Jiangsu met the national standard GB13223-2011 (green line) but only 5% met the ultra-low emission policy (orange line) as indicated by red arrows, based on the 95 percentile of hourly flue-gas concentrations. If the annual average concentration was selected as the criterion instead of the 95 percentile of hourly concentrations, the rates of “in compliance” units would rise to 97% and 22% (indicated by blue arrows) for GB13223-2011 and the ultra-low emission policy respectively. Compared to less-developed northeastern and southwestern provinces, the differences between these two criteria were smaller for the provinces located in East and South China including Jiangsu (Fig. 4 (c)), Hubei (Fig. 4 (d)) and Guangdong (Fig. 4 (e)). The average ratios of 95 percentile to average SO_2 concentrations were estimated to be 1.7, 1.8 and 1.8 for these three provinces, respectively, and those low ratios imply relatively stable operation of power units with less emission fluctuation in the provinces. Moreover, the “in compliance” rates for all those provinces exceeded 90% when the 95 percentile of SO_2 concentration was used as the criterion. The largest difference between the two criteria was found for Yunnan in South China, with the average ratio of 95 percentile to annual average SO_2 concentrations reaching 3.0 (Fig. 4 (f)). In general, the fractions of units that met the ultra-low emission policy were much smaller than those for GB13223-2011 in all the provinces. Nearly no unit met the requirement of ultra-low emission policy in Hubei and Yunnan, implying that the policy had not taken effect in all provinces by 2015.

For NO_x and PM, the eastern and southern provinces similarly exhibited larger rates of “in compliance” units. Relatively lower rates were found for Heilongjiang for all three species, due to the less penetration of APCDs. The rates of units that met the NO_x emission limit in GB13223-2011 were smaller than those for SO_2 and PM for all provinces, implying the strictness of GB13223-2011 for NO_x control. The emission limit for NO_x in the ultra-low emission policy is 50% lower than that of GB13223-2011, much smaller than 83% for both SO_2 and PM. Given the extremely strict emission limit of PM at 5 mg/m^3, the “in compliance” rates for PM were much smaller than the other two species for the ultra-low emission policy.

3.3.2. Predicted “in compliance” emissions

Table 3 also summarizes the emissions of China's coal-fired power sector under full implementation of the national standard GB13223-2011 and ultra-low emission policy (Scenarios 1 and 2). Compared to UEI (B), emissions would have declined by 150, 201, and 79 Gg for SO_2, NO_x and PM respectively in Scenario 1, and by an additional 753, 586 and 192 Gg in Scenario 2. The ongoing emission control measures in the power sector left little opportunity for the current national standard to drive further progress, except in Northeast and Northwest China. Dramatically larger reductions would have been required to achieve Scenario 2 compared to Scenario 1 for all species, implying far greater efforts needed to achieve the ultra-low emission target. Regarding regional differences, the emissions of SO_2, NO_x and PM for Northwest China in Scenario 1 would have needed to decrease by 38%, 30% and 54% respectively compared to UEI (B), as the penetration rate of APCDs in the power sector was still small for this region. The emission abatement required for North China (which serves the Greater Beijing area) to have achieved Scenarios 1 and 2 would have been smaller compared to other regions, as multiple short-term

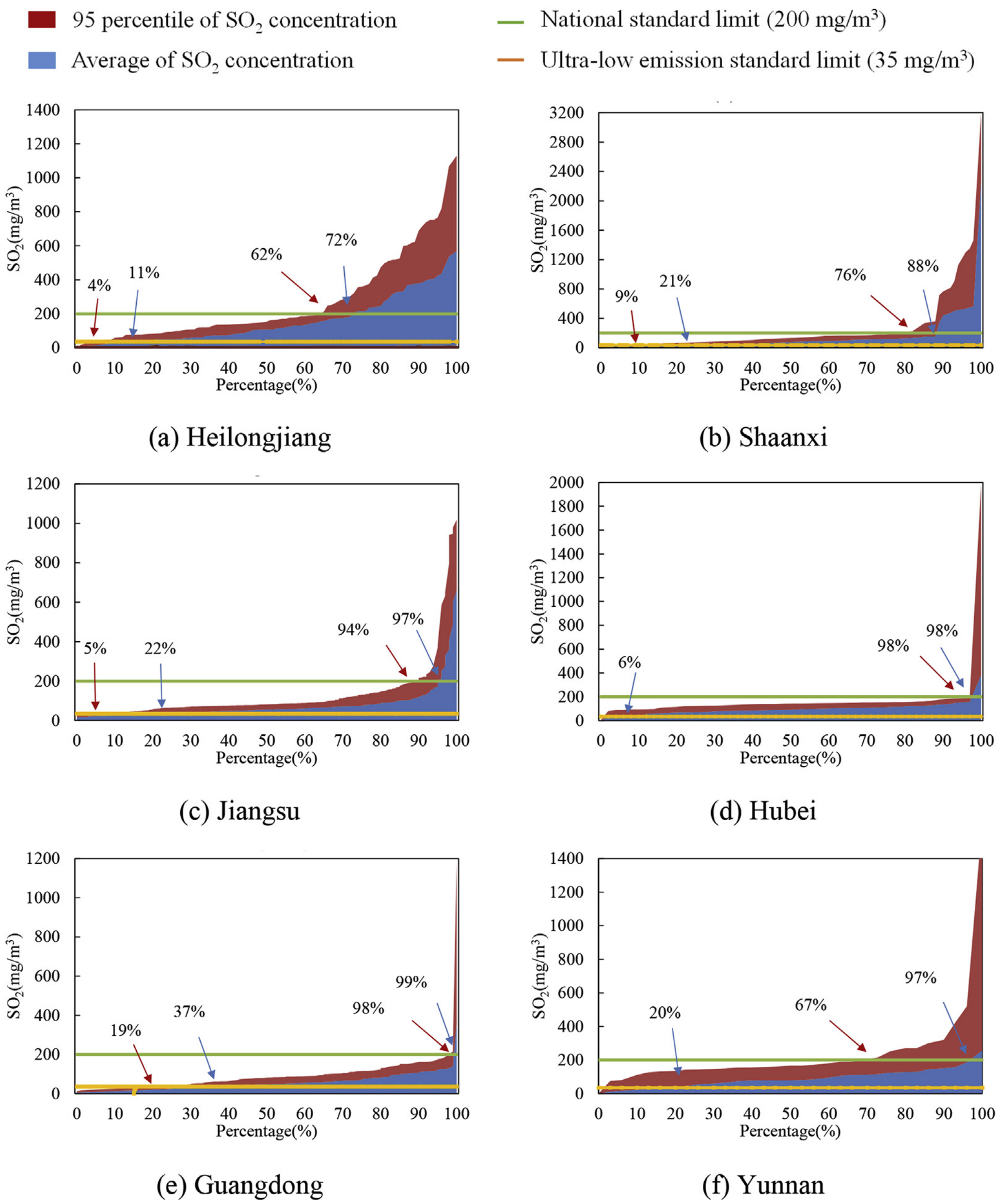

Fig. 4. Distribution of average and 95 percentile of hourly SO_2 concentrations at coal-fired power generation units for six typical provinces. The blue areas present the average SO_2 concentrations and the red areas present the differences between the average and 95 percentile of SO_2 concentrations. The green and orange lines represent the national standard limit (200 mg/m^3) and ultra-low emission standard limit (35 mg/m^3) of SO_2, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

campaigns and long-term emission control policies separate from the two national ones analyzed here had already been implemented to improve air quality in this key region.

Fig. 5 compares the emissions of the coal-fired power sector and their fractions of total national emissions over the last ten years reported in different studies. Using the traditional "bottom-up" method, MEIC, Xia et al. (2016), and Zhao et al. (2018) (providing an inventory that integrates the results from various studies including Wang et al. (2014) and Zhao et al. (2017)) produced very similar estimates for 2006 but deviated in later years, attributed mainly to different interpretations of the effects of emission controls. All the studies found that SO_2 and PM emissions from the power sector declined from 2006 to 2015 with gradually increased application of APCDs. MEIC estimated a 77% reduction in SO_2 emissions, larger than 65% by Xia et al. (2016) and 70% by Zhao et al. (2018). The result implies a more optimistic judgment of the success of national SO_2 control policies by MEIC. NO_x emissions increased from 2006 to 2010 and then decreased despite growth of coal consumption, indicating the effectiveness of improved penetration and operation of SCR in the power sector after 2010. The fractions of power sector emissions to national total emissions of SO_2, NO_x and PM were calculated to have declined from 48 to 53%, 31–36% and 8% in 2006 to 22–28%, 14–21% and 5–6% in 2015, respectively, in these three inventories without CEMS data. Incorporating CEMS data, however, the fractions in 2015 sharply decreased to 8%, 7% and 1% for the three species in UEI (B) of this work, and would have declined further under the two scenarios with full implementation of the emission control policies. The result indicates that the contribution

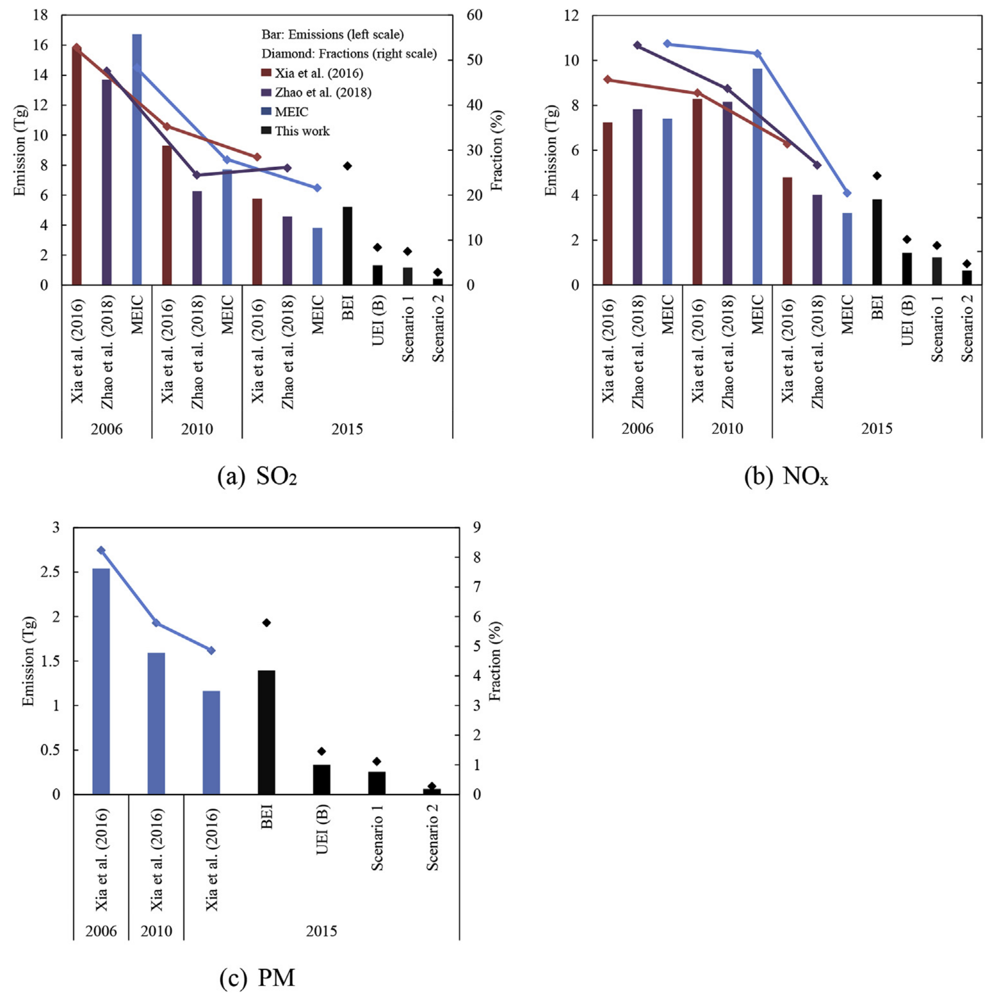

Fig. 5. The annual emissions from coal-fired power sector and their fractions to China's total emissions estimated in different studies. The bars represent the pollutant emissions and the diamonds denote their corresponding fractions.

of the power sector to total national emissions declined significantly in recent years, as the sector has been the foremost target of emission abatement for over ten years. More stringent measures are thus recommended for other sources like industrial boilers and processes to further reduce national emissions efficiently. It should be acknowledged, however, that the emissions in UEI (B) could be underestimated in this work, particularly for the small power units without CEMS. Based on UEI (B), an additional test was conducted in which the emissions from small units without CEMS data were estimated with the traditional “bottom-up” method instead of using the average concentrations from other small units with CEMS for each province. The discrepancies between the national total emissions from coal-fired power sector in this additional case and UEI (B) were calculated at 18%, 9% and 46% relevant to UEI (B) for SO_2, NO_x and PM, respectively. Therefore, incomplete coverage of CEMS in the sector led to moderate uncertainty for SO_2 and NO_x emissions. The uncertainty for PM was larger, implying that the small units without CEMS might still play an important role in emissions and that more careful supervision on those units is further needed.

4. Conclusions

The emissions of SO_2, NO_x and PM from the coal-fired power sector in China were reexamined by collecting, analyzing and incorporating CEMS data. This resulted in significant reduction of emission factors of the sector compared to the previous bottom-up approach, and annual emissions for 2015 were estimated to be 75%, 63% and 76% smaller in the current study. The differences imply that the progress of emission controls in the sector in recent years were not fully detected using conventional mass balance methods, attributed mainly to unclear operational conditions of APCDs. Online measurements with proper data screening better capture the abatement of air pollutant emissions from improved controls. However, the incomplete coverage of CEMS data may result in moderate uncertainty in emission estimates. The benefit of full implementation of current emission standard was found to be limited, because of the success of measures that have already been taken. Full achievement of the ultra-low emission policy, however, would have resulted in an estimated additional 68%, 55% and 81% reduction in SO_2, NO_x, and PM emissions, respectively. As the potential of further emission abatement has declined for the power sector, more stringent policies are encouraged for other industrial sources to reduce the national emissions effectively in the future.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.05.021.

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