Environmental Engineering and Management Journal

May 2021, Vol. 20, No. 5, 841-851
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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HISTORICAL EMISSIONS AND FUTURE MITIGATION OF PRIMARY AIR POLLUTANTS FROM INDUSTRIAL BOILER IN CHINA

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Abstract

Industrial boilers are recognized as a significant anthropogenic emission source of primary air pollutants in China. By using specific and detailed statistical data and comprehensive time-varying dynamic emission factors (EFs), we calculated the temporal-spatial emission characteristics of total suspended particulate (TSP), SO_2 and NOx from industrial boilers during 1980 to 2016 for the first time. Further emission trends from 2016 to 2030 were also forecasted based on the current atmospheric action policy. Our results showed a generally decreasing trend of the annual EFs for TSP, SO_2 and NOx due to implementation of stricter local emission standards, application of advanced emission control technologies, and elimination of small and inefficient boilers. In 2016, national TSP, SO_2 and NOx emissions from industrial boilers were estimated at 5.43, 6.99 and 2.47 million tons (Mt), respectively. The higher emissions of primary air pollutants from coal-fired industrial boilers (CFIBs) were concentrated in northeast and eastern China, while NOx emissions from gas-fired industrial boilers (GFIBs) were mainly concentrated in the Beijing-Tianjin-Hebei region and its surrounding areas. Under a series of current action plans, it would be successful in abating emissions of TSP, SO_2 and NOx by 95%, 94% and 71% in the year of 2030. More attention should be paid to the whole process control of industrial boilers in the future polices making, such as introducing clean fuels for persistent emission reduction at source, strengthening the operation, maintenance and management of pollution control technologies to ensure the best control effect.

Keywords: dynamic emission factors, future mitigation, historical emission, industrial boiler, primary air pollutants

Received: April, 2020; Revised final: September, 2020; Accepted: October, 2020; Published in final edited form: May, 2021

1. Introduction

Industrial boiler is an important thermal power equipment, which is widely used in industrial production, civil heating and other activities. Coal is one of the most essential fuel for industrial boiler in China. The coal combustion process can produce and release many kinds of air pollutants, such as particulate matter (PM), SO_2, NOx, CO, VOCs and heavy metals (Gao et al., 2018; Tao et al., 2017; Tian et al., 2012). Additionally, these pollutants will undergo a series of physical and chemical reactions and produce secondary PM, which contributes to deteriorate regional air quality and pose considerable risks to human health (Feng et al., 2016; Ma et al., 2017; Singh et al., 2018; Wu et al., 2010). Even though most of the provincial cities have transferred the coal-fired industrial boilers (CFIBs) to gas-fired industrial boilers (GFIBs) or moved them to suburban and rural regions driven by the current policies and regulations, there are still many CFIBs located in coal-fired heating stations in China. By the end of 2015, there were approximately 579,200 industrial boilers in China, of which 460,000 were coal-fired industrial CFIBs and the total capacity was about 1.78 million tons/hour (t/h). The coal consumption of CFIBs was 711 million tons (Mt), accounting for 18.7% of the annual coal consumption for the whole industrial activities (NBS, 1981-2017). Moreover, compared with CFIBs, NOx is the most significant gaseous

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pollutant emitted from natural gas combustion (Xue et al., 2016; Yue et al., 2018). With the gradual increase in the number and capacity of GFIBs, the emission of NOx should also be paid more attention to.

In the recently revised version of "Emission standard of air pollutants for boiler" (GB 13271-2014), the strictest emission limits of total suspended particulate (TSP), SO_2 and NOx for CFIBs in the key areas are not higher than 30, 200 and 200 mg/Nm^3, respectively (9% O_2 and Standard Temperature and Pressure). Since 2018, some local governments, such as Shandong province, Xi'an, Hangzhou, and so on, have implemented stricter emission standards. The ultra-low emission retrofit of CFIBs was firstly proposed in Shandong province. After the retrofit of coal-fired boilers with ultra-low emission, the emission standard limits of TSP, SO_2 and NOx are 10, 50 and 200 mg/Nm^3, respectively (9% O_2 and Standard Temperature and Pressure). Particularly, the emission standard of NOx is no more than 100 mg/Nm^3 in the key areas.

Several studies have discussed the emission characteristics, spatial distribution, as well as the emission control policy of PM, SO_2, NOx, CO, heavy metals and VOCs from industrial boilers (Tian et al., 2015; Xue et al., 2016; Yan et al., 2017; Zhao et al., 2012; Zhou et al., 2014; Zhu et al., 2018). Xue et al. (2016) estimated the temporal and spatial emissions characteristics of primary air pollutants from CFIBs in Beijing in the period of 2007-2013. Yan et al. (2017) evaluated the emission characteristics of NOx, SO_2, and CO from gas-fired boilers in Beijing in the year of 2014 by establishing category-specific emission factors from field measurements. Moreover, the emission characteristics of air pollutants emission with different control technologies and combustion fuels have also been discussed (Ruan et al., 2019; Xue et al., 2017; Yang et al., 2009, 2018). Ruan et al. (2019) studied the emission characteristics of PM_{10}/$PM_{2.5}$/$PM_{1.0}$ from two ultralow-emission coal-fired industrial boilers in Xi'an city of China, and gave the PM removal efficiency of fabric filter (FF) for a chain-grate boiler and a circulating fluidized bed (CFB) boiler. However, detailed and comprehensive research on the temporal-spatial characteristics of primary air pollutants emissions from industrial boiler sources (including both CFIBs and GFIBs) in China is still quite limited. Moreover, we have little knowledge on what the past and accelerated emission levels of TSP, SO_2 and NOx are from industrial boilers during the historical period since 1980.

In this study, we did a quantitative assessment of the historical and spatial variation characteristics of TSP, SO_2 and NOx emissions from industrial boiler sources during the period of 1980-2016 using the technology diffusion theory. Furthermore, the mitigation potential of each pollutant till 2030 would be projected based on current emission control and energy-related policies. Particularly, we attempted to develop the technology-based and time-varying emission factors (EFs) of primary air pollutants for a long period through comprehensively considering the technology upgrade of the industrial process and the progress of application ratio for a variety of air pollution control devices (APCDs).

2. Material and methods

In this study, we estimated the air pollutants (TSP, SO_2 and NOx) emissions from industrial boilers by collecting and evaluating the data of industrial boiler types, capacity and APCDs. The provincial EFs of air pollutants were estimated in China from 1980 to 2016 using the Eqs. (1-5). The basic calculation could be described by the following formulas (Xue et al., 2016; Zhao et al., 2012):

$$E_{i,j,p} = A_{i,j} \times EF_{i,j,p} \tag{1}$$

$$EF_{i,j,p} = \sum EF_{k,p} \times W_{i,j,k} \tag{2}$$

$$EF_{k,NO_x} = \left(C_{NO_x} \times Q_k \times 10^{-3}\right) / S \tag{3}$$

$$EF_{TSP,SO_2} = G_{TSP,SO_2}\left(1-\eta_{TSP,SO_2}\right) \tag{4}$$

where E is the atmospheric emissions of TSP, SO_2 and NOx; A is the amount of annual fuel consumption, such as coal and gas consumption; EF is the assumed average emission factors; p, i, j and k represent the type of pollutants, provinces, calendar year and air pollutant control technologies, respectively; W is the capacity proportion of each control technology; C is the emission concentration of pollutants in the flue gas; Q is the flue gas volume; S is the fuel consumption for the tested boiler; G is the pollutant producing coefficient; is the pollutant removal efficiency.

Tian et al. (2015) pointed out that considering the elimination of backward productivity, the improvement of production technique and the upgrade of APCDs, the emission factors of atmospheric pollutants from anthropogenic sources are gradually decreasing. At present study, due to lack of variation data about the types and proportion for pollution control technologies of CFIBs over a long time-continuous period, one of the major challenges was to develop a reasonable representation of the technology-based and time-varying dynamic emission factors of each primary pollutant from industrial boilers. Previous researchers have evaluated the historical and future emissions of heavy metals and carbon aerosol from anthropogenic sources using an S-shaped curve, showing a better fit to the historical and future emissions than linear fits. Thus, based on the theory of technology diffusion, S-shaped curve (Eq. 5) was used to estimate the proportion of boiler types and control measures in different periods, which provided a basis for further determination of the overall pollutants emissions from industrial boilers in different periods (Bond et al., 2007; Streets et al., 2004, 2011; Tian et al., 2015).

$$W_{i,j,k} = \left(W_{a_k} - W_{b_k}\right) e^{\left(-\frac{(j-j_0)^2}{2s_k^2}\right)} + W_{b_k} \tag{5}$$

where: W_a represents the capacity proportion for control technology k pre-1980; W_b represents the capacity proportion for the best control technology k at present; s_k is the shape parameter of the curve for control technology k; j_0 is the beginning time of technology transition.

2.1. Development data of coal-fired industrial boilers

In the annual *Energy Statistics Yearbook*, there is no independent statistics on industrial coal consumption. In this study, the industrial coal consumption was estimated based on the terminal energy consumption of industrial subsectors, and the coal consumption in iron and steel industry and cement industry in the energy balance table of the *Energy Statistics Yearbook* (NBS, 1981-2017). The coal consumption of CFIBs in China during the period of 1980-2016 were calculated. Coal consumption of industrial boilers had been increasing annually during the period of 1980-2012, and the annual average growth rate was about 4.2%. In 2012, the coal consumption peaked at about 810 Mt. After 2012, the coal consumption of industrial boilers showed a downward trend, and by 2016, it was 590 Mt, with a decrease of 27% from 2012. The variation trend of coal consumption of industrial boilers reflected the effect of the implementation of the gradually constructed policy system of total coal control since the 12th Five-Year Plan of China (Wang, 2014).

As for the types of CFIBs, grate boiler (including hand-fired boilers, chain grate boilers, spreader stoker boilers, and other grate-fired boilers) was the main type in all stages of China. Based on the data of the proportion of boiler types in different periods, the capacity proportion of different types of CFIBs in China from 1980 to 2016 was obtained by using S-shaped curve function (Eq. 5). It could be seen that the hand-fired industrial boilers in China were gradually eliminated and the proportion was constantly decreasing driven by adopted policies and measures, such as “the smoke elimination and dust removal” and “the low-efficiency boiler transformation”. The spreader stoker boilers had not been greatly developed due to the massive initial TSP emissions. The chain-grate furnace had become the main type of CFIBs, and the capacity ratios of CFB and PC boilers also increased gradually.

The installation proportion and types of dust removal devices of CFIBs in different regions of China were obtained by using S-shaped curve function (Eq. 5), as shown in Fig. 1.

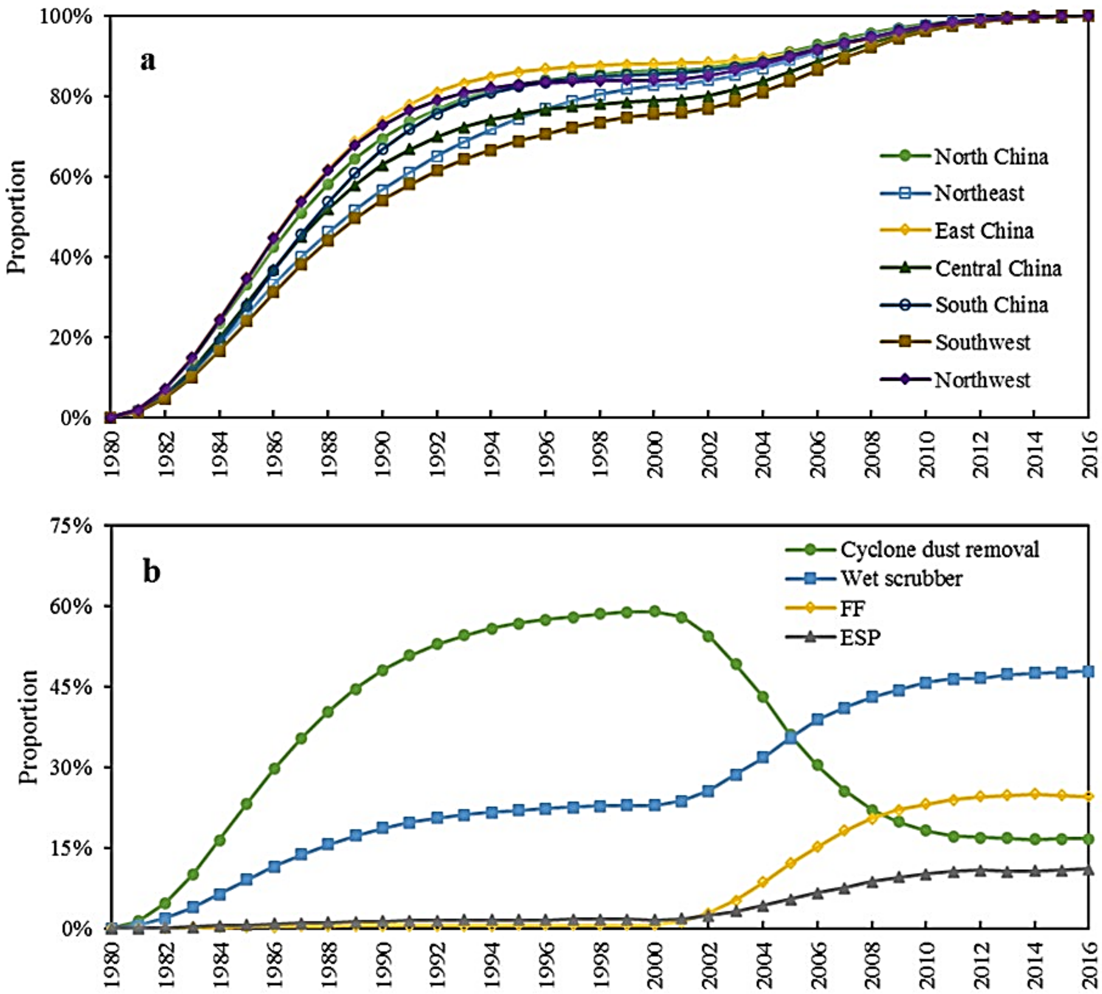

Fig. 1. Installation (a) and types (b) proportion of dust removal devices in different regions of China, 1980-2016

Generally, the installation rate of dust removal facilities had been increasing year by year since 1980. With the continuous improvement of emission standards and regulatory requirements for industrial boilers, CFIBs in all regions were basically equipped with dust removal facilities, the installed rate was nearly 100%. Since 1980-2015, the development of dust removal technology of CFIBs in China had been presented in two main stages. In the first stage (1980-2005), the cyclone dust removal technology shared the largest proportion, and in the second stage (after 2006), the wet scrubber had the highest proportion, while the proportion of FF and electrostatic precipitators (ESP) technology increased gradually. The installation proportion and types of different dust removal devices for CFIBs with different capacities in 2015 were obtained. Wet scrubber was the main dust removal device of CFIBs, followed by FF, with a proportion of 51.9% and 21.2% of the total capacity, respectively.

The installation proportion and types of desulfurization devices of CFIBs in different regions of China was obtained and shown in Fig. 2. The emission limits of SO_2 from CFIBs was added to the emission standard of air pollutants for boiler (GB 13271-1991) in 1991 for the first time. The installation rate of desulfurization facilities had been increasing year by year since 1990. In 2015, the installation ratio of desulfurization facilities in different regions reached to 15%~43%, in which the North China was the highest. For desulfurization devices of CFIBs with different capacity, 72.5% of CFIBs were not install desulphurization devices in 2015. Wet desulphurization was the main desulfurization technology, accounting for 19.4% of the total capacity.

For denitrification devices, the emission limits of NOx from CFIBs was firstly added to the emission standard of air pollutants for boiler (GB 13271-2014) in 2014. So, the installation proportion of denitrification devices for CFIBs was low and there were 94.5% of CFIBs not install denitrification devices in 2015. Therein, 99% of CFIBs with the capacity below 35 t/h did not install denitrification devices. Only 18 % of CFIBs with the capacity above 35 t/h installed denitrification devices, of which SNCR and SNCR+SCR were the dominant technologies.

2.2. Development data of gas-fired industrial boilers

A long-term activity level database for GFIBs were established based on official statistical data from the energy balance table in China Energy Statistic Yearbook (1996-2017). The gas consumption of GFIBs in China during the period of 1995-2016 was calculated. The annual gas consumption of GFIBs was 3.3×10^{10} m^3 in the year of 2016, reflecting an annual average growth rate of 37.5% compared with that in 1995.

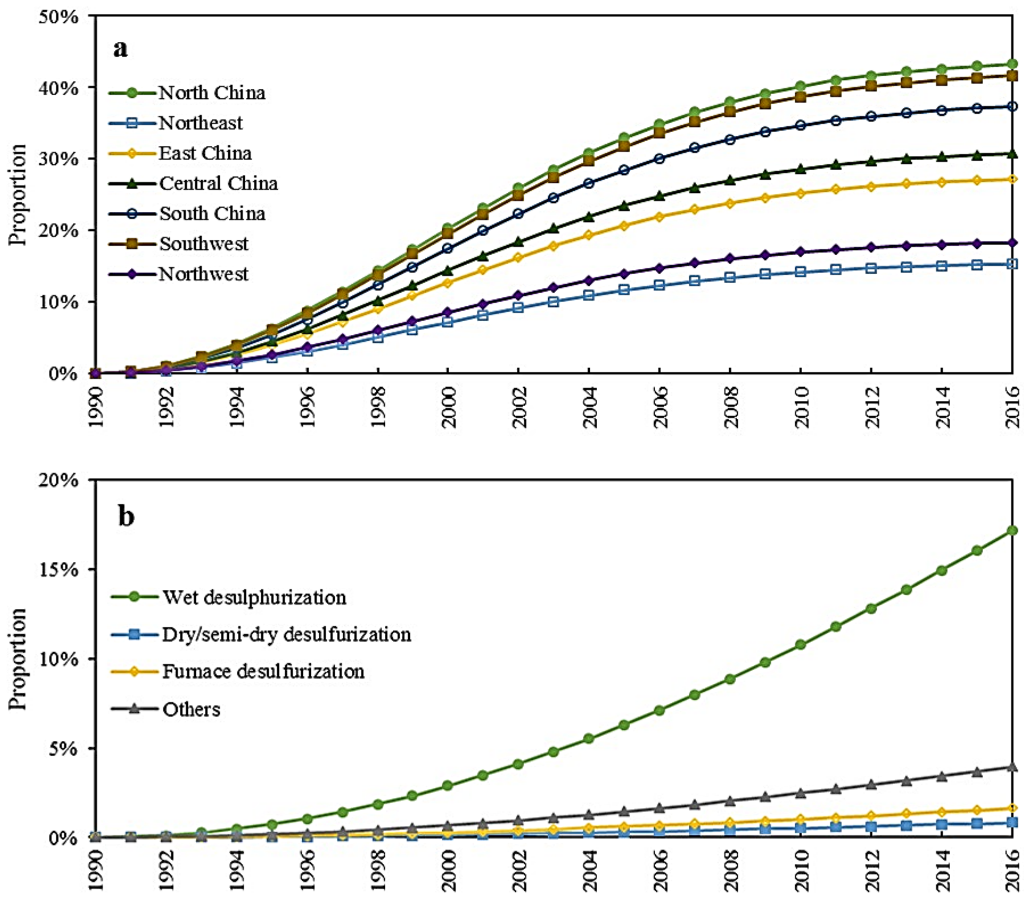

Fig. 2. Installation (a) and types (b) proportion of desulfurization devices in different regions of China, 1990-2016

The main type of GFIBs was chamber combustion boilers (CCBs). The average capacity per unit of GFIBs was 6.5 t/h in the year of 2015 (NEMC, 2016). The total capacity of GFIBs in Beijing was the highest, reaching to 65,200 t/h, and accounting for 33% of the total capacity of GFIBs in China. CCBs accounted for 86% of the total amount and 98% of the total capacity of GFIBs in Beijing. Because of the high concentration of NOx emission from atmospheric combustion boilers (ACBs) and the difficulty of low nitrogen retrofit, CCBs were still dominant type for GFIBs.

NOx is the primary pollutant emitted from gas-fired boilers. In view of the problem of NOx emission from GFIBs, Beijing took the lead in low nitrogen retrofit of GFIBs. In June 4, 2016, the *Regulation of the Beijing Municipal Reward Replaces Subsidy for the Gas (oil) Boiler Low-NOx Retrofit* was proposed by Beijing municipal government (BMEPB, 2016). At present, low nitrogen combustion technologies of gas-fired boilers mainly include staged combustion, surface premixed combustion and flue gas recirculation (FGR). Therein, FGR technology is a dominant low NOx combustion technology, which can reduce the NOx emission by returning a part of the flue gas into the combustion zone. Due to the relatively low temperature and O_2 content of the returning flue gas, FGR technology can decrease the chamber temperature and O_2 concentration in the combustion zone, and then inhibit the formation of thermal-NOx.

2.3. Analysis of potential uncertainty

The potential uncertainty of total emissions of air pollutants from industrial boilers were analyzed by Monte Carlo simulations. Akimoto et al. (2006) pointed out that China's energy consumption statistics may be seriously underestimated between 1996 and 2003, and the uncertainties of early statistics were relatively higher than that of recent statistics. Therefore, in order to quantify the uncertainty of long-term activity level data, the period of 1980-2016 was roughly divided into two stages: the transition stage of economic development and pollution control (1980-2005); the total emission control stage of atmospheric pollutants (2006-2016) (Zhu, 2016).

In this study, a normal distribution with a coefficient of variation (CV, the standard deviation divided by the mean) of 10% was estimated for probability distribution and variation coefficient for industrial boilers. The variation coefficient of the official statistical data of activity level in China from 1980 to 2005 was assumed to be about 1.5 times than that from 2006 to 2016.

3. Results and discussion

3.1. Emission factors of primary air pollutants of industrial boilers

The dynamic EFs of TSP, SO_2 and NOx from CFIBs in China from 1980 to 2016 were illustrated in Fig. 3. The EFs were closely related to the revision of emission standards for boiler. EFs of TSP, SO_2 and NOx showed a gradually declining trend resulting from the upgraded APCDs and the shutdown of outdated industries. The variation of EFs of TSP and SO_2 from CFIBs could be divided into three stages. In the first stage, from 1980 to 2000, the average annual declined ratio of EF_{TSP} and EF_{SO2} were 2.7% and 0.7%, respectively.

In the second stage, from 2001 to 2014, after the implementation of GB 13271-2001, the application proportion of wet scrubber, FF and ESP technologies increased gradually. The application of desulfurization facilities had also increased significantly in this stage. The average annual decreased ratio of EF_{TSP} and EF_{SO2} were increased, reaching to about 7.4% and 1.8%, respectively. In the third stage, after the implementation of GB 13271-2014, the emission limits of TSP and SO_2 were further tightened.

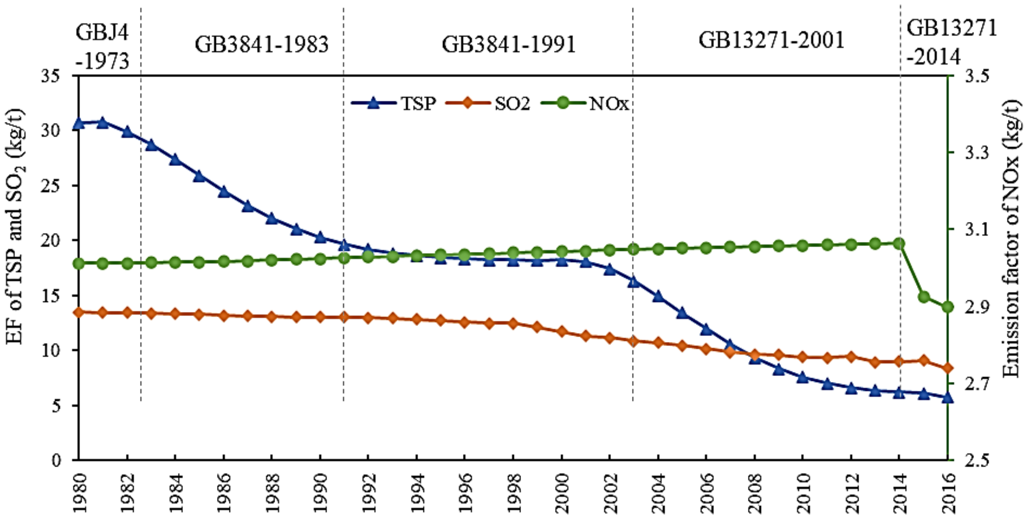

Fig. 3. Average EF_{TSP}, EF_{SO2} and EF_{NOx} of CFIBs during varied emission standards in different period of China, 1980-2016

The application proportion of efficient dust removal devices such as FF and ESP increased and the EFs of TSP and SO_2 further reduced. In the year of 2016, EF_{TSP} and EF_{SO2} from CFIBs decreased to 5.7 kg/t and 8.4 kg/t, respectively.

Furthermore, the emission control for NOx started later than TSP and SO_2. The emission limits of NOx from CFIBs were added to the emission standard of air pollutants for boiler (GB 13271-2014) in 2014 for the first time. Thus, EF_{NOx} of CFIBs began to decrease after 2014. In 2016, EF_{NOx} of CFIBs was 2.90 kg/t, which was 5% lower than that in 2014. With the continuous elimination of CFIBs with small capacity and the improvement of pollution control level by measures like "coal-to-gas", "replacing small boilers by large ones" and "upgrading and reconstruction", the emission of primary air pollutants from CFIBs still have great emission reduction potential. Based on the field measurements of 1107 "low NOx" retrofitted and unabated GFIBs, technology-based EFs of NOx were obtained and reported in our previous study (Yue et al., 2018).

3.2. Temporal trend (1980-2016) of air pollutants emissions from coal-fired industrial boilers in China

The historical trend of air pollutants emissions from CFIBs in different regions of China from 1980 to 2016 were illustrated in Fig. 4. The total emissions of TSP, SO_2 and NOx since 1980 firstly increased and then decreased. In 2016, emissions of TSP, SO_2 and NOx from CFIBs in China were estimated at about 5.43, 6.99, and 2.41 Mt, respectively. For TSP, the sharp emission decline occurred in 2008, and the total emission of TSP decreased by 45% from 9.78 Mt in 2008 to 5.43 Mt in 2016.

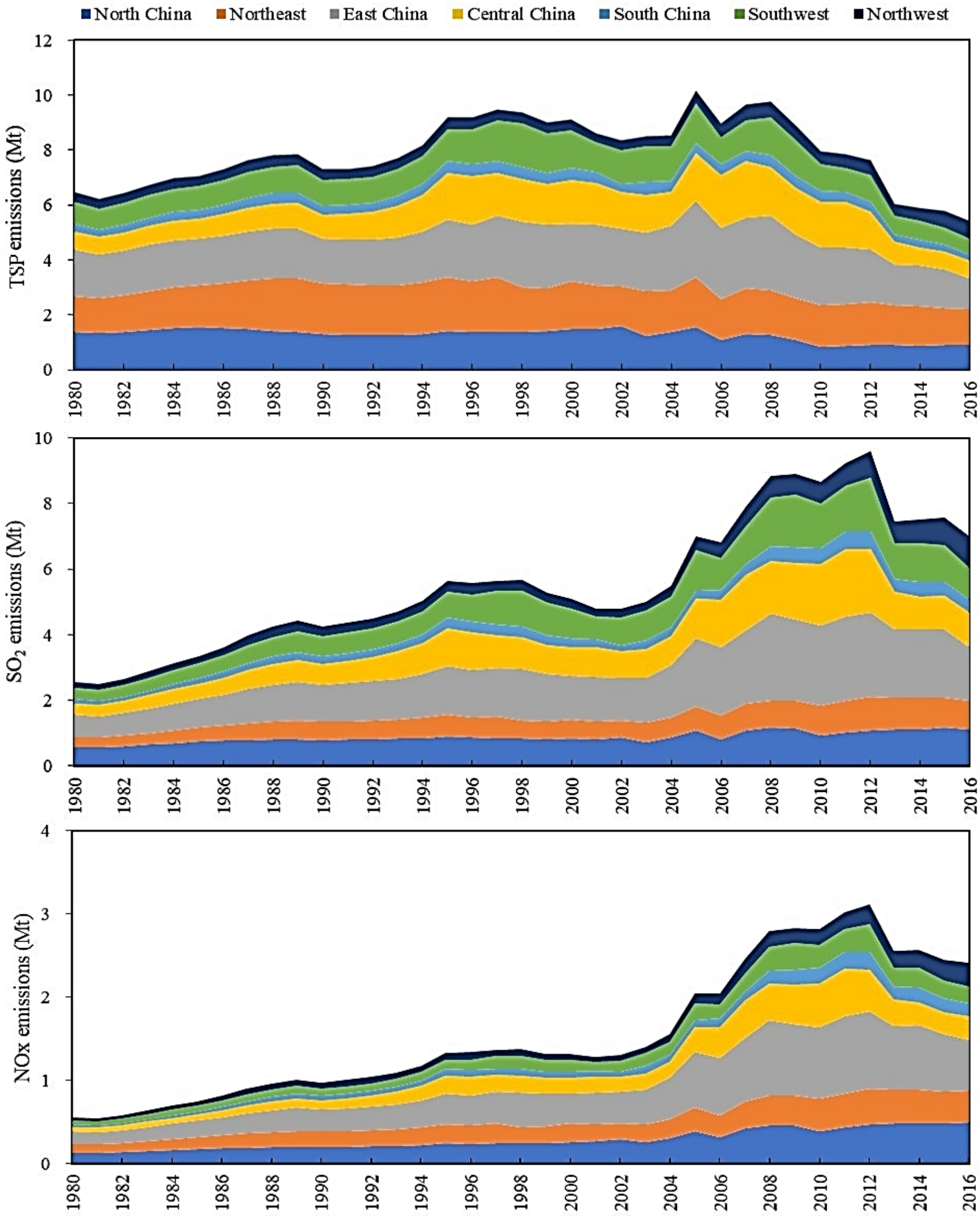

Fig. 4. Emissions of TSP, SO_2 and NOx from CFIBs in different regions of China, 1980-2016

It could be mainly on account of the increased application proportion of efficient dust removal devices (FF, ESP and ESP, see Fig. 1) and the decreased growth rate of coal consumption of CFIBs since 2008.

For SO_2 and NOx, the installation ratio of desulfurization and denitrification devices of CFIBs was relatively low till 2015, so the emissions of SO_2 and NOx were mainly affected by the coal consumption of CFIBs. The coal consumption of CFIBs peaked in the year of 2012, and decreased thereafter. Therefore, the sharp decline of SO_2 and NOx emissions occurred after 2012, and the total emissions of SO_2 and NOx decreased by 29% and 25% from 9.61 and 3.12 Mt in 2012 to 6.99 and 2.41 Mt in 2016, respectively. Due to the continuous improvement of the removal efficiency of APCDs and the slowdown of coal consumption, TSP, SO_2 and NOx emissions declined gradually.

Fig. 5 illustrated the spatial distribution of TSP, SO_2, and NOx in 2016. The large variations in spatial emission originated from differences in the level of economic development, industrial structure, and population density of each province.

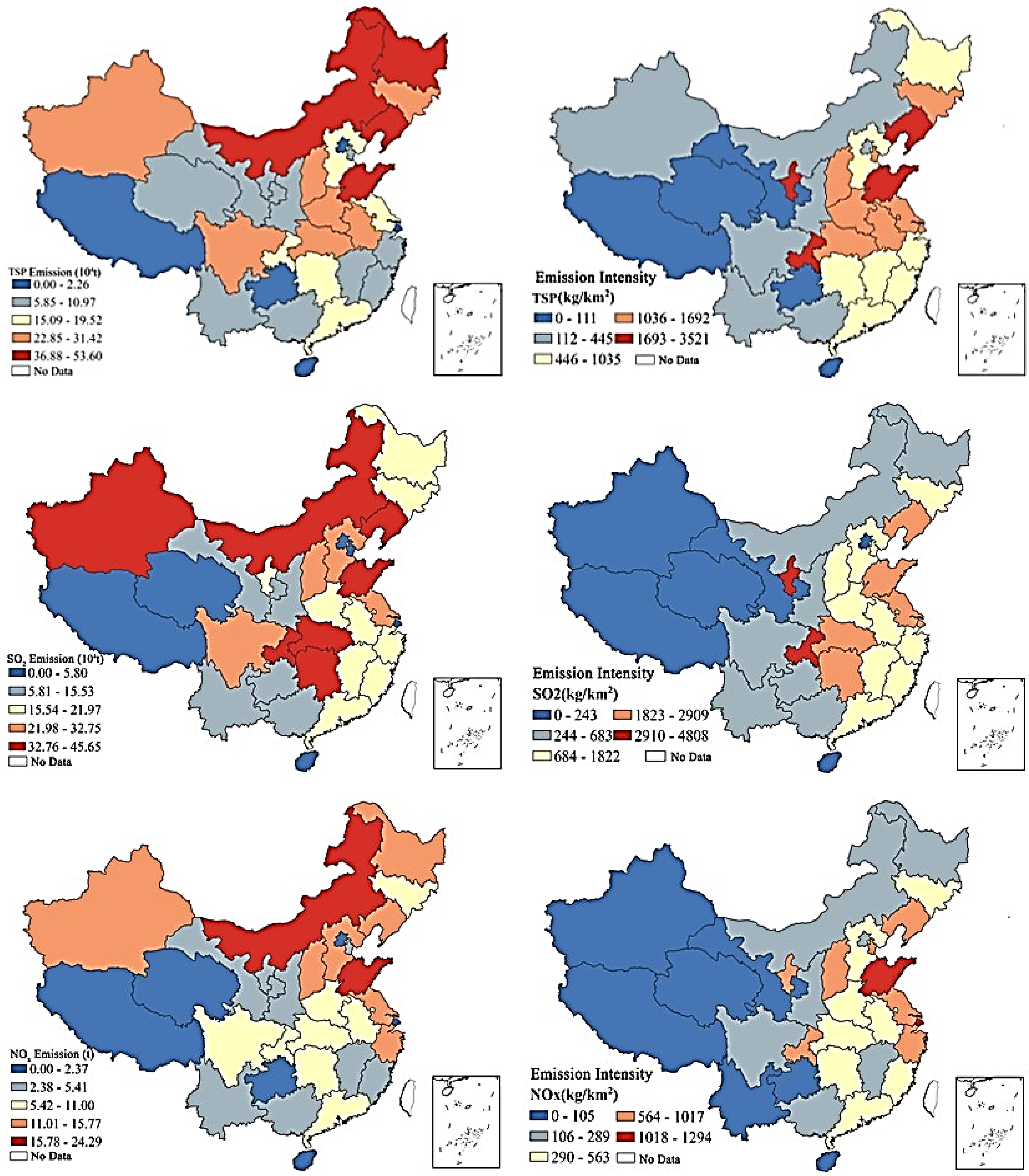

Fig. 5. Spatial emissions and emission intensity of TSP, SO_2 and NOx from CFIBs in different regions of China in 2016

The high emissions of TSP were mainly concentrated in the northern, northeast and eastern China. The five provinces with the highest TSP emissions were Liaoning, Heilongjiang, Shandong, Inner Mongolia and Xinjiang, which accounted for 38.5% of the total TSP emissions from CFIBs in China. The highest emission intensity of TSP was occurred in Liaoning, which was 3521 kg/km^2. For SO_2, the high emissions were mainly concentrated in the eastern, central and southwest China. Shandong, Inner Mongolia, Liaoning, Hunan and Chongqing were the five provinces with highest SO_2 emissions, accounting for 31.5% of the total SO_2 emissions from national CFIBs. Therein, the highest emission intensity of SO_2 was occurred in Chongqing (4808 kg/km^2), which was attributed to the smallest land area of Chongqing, about 1.8~14.4 times lower than the other four provinces. For NOx, the high emissions were mainly concentrated in northern, eastern and northeast China. The five provinces with the highest NOx emissions were Shandong, Inner Mongolia, Shanxi, Liaoning, and Heilongjiang, which accounted for 34.1% of the total NOx emissions from CFIBs in China. Shandong had the highest emission intensity of 1294 kg/km^2.

Emissions of TSP, SO_2 and NOx from CFIBs with uncertainties from 1980 to 2016 were summarized. The average uncertainty level (95% confidence interval) were calculated to be (-49.55~62.92%), (-48.49~63.14%) and (-43.83~47.46%) in the estimates of TSP, SO_2 and NOx emissions from CFIBs in 1980-2016, respectively. The uncertainties were mainly attributed to the relatively imprecise statistical data, poor resolution of combustion technologies and APCDs for CFIBs. Notably, the uncertainties of TSP, SO_2 and NOx emission during 2006-2016 was lower than that in the period of 1980-2005. With the acquisition and application of more reliable activity data with a relatively small coefficient of variation from statistical yearbooks and reports, the uncertainties had been decreasing from the beginning to the end of the historical period gradually. In 2016, the uncertainties of TSP, SO_2 and NOx emissions from CFIBs were estimated to be (-44.70%~60.57%), (-35.46%~47.71%) and (38.03%~36.48%), respectively.

3.3. Temporal trend (1995-2016) of air pollutants emissions from gas-fired industrial boilers in China

The historical trend of NOx emissions and its uncertainties bound of GFIBs in China from 1995 to 2016 were illustrated in Fig. 6. NOx emissions from GFIBs in China has been increasing rapidly. From 1995 to 2016, the annual average growth rate of NOx emission from GFIBs was 42%, and the emission of NOx from GFIBs was reached about 56,000 t in 2016. The uncertainty levels (95% confidence interval) in the estimation of NOx emissions from GFIBs were calculated to be (-49.41%~53.98%) in 1995-2005 and (-33.74%~37.87%) in 2006-2016, respectively.

Spatial distribution and emission intensity of NOx from GFIBs in different regions of China in 2016 were shown in Fig. 7. NOx emission from GFIBs in China mainly concentrated in the Beijing-Tianjin-Hebei (BTH) region and its surrounding areas. The emission of NOx from GFIBs in BTH region was 19,943 t, accounting for 35% of the national total emission. Additionally, natural gas production in Sichuan, Shaanxi and Xinjiang accounted for 22%, 30% and 21% of the national total natural gas production, respectively. The emissions of NOx from these three regions were also high. As for emission intensity, Beijing, Tianjin and Shanghai were the three dominant regions with high emission intensities of 492 kg/km^2, 371 kg/km^2 and 319 kg/km^2, respectively. Thus, with the development of the “coal to gas” policy in China, the number and capacity of GFIBs were increasing. At the same time, the total amount of NOx emission from GFIBs presented an increasing trend year by year, and the key areas such as BTH region and the surrounding areas has become the main areas of NOx emission of GFIBs.

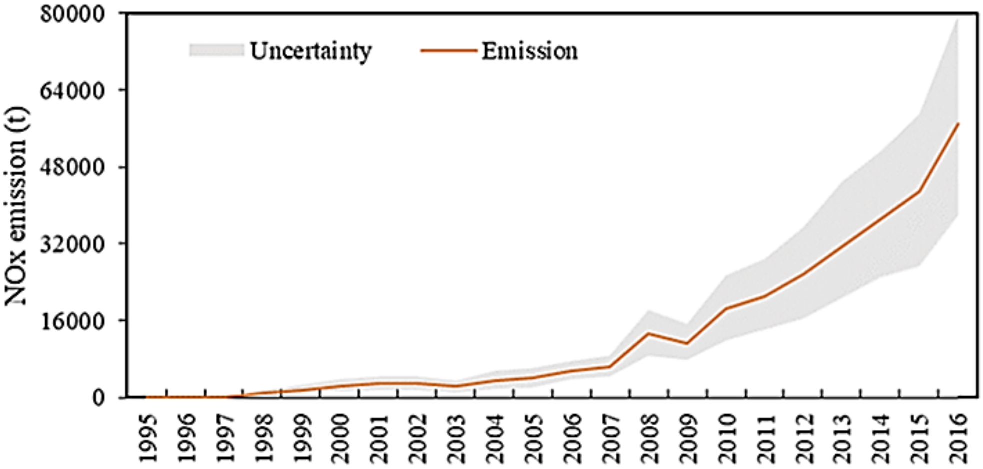

Fig. 6. The emission and uncertainty bound of NOx from GFIBs in China, 1995-2016

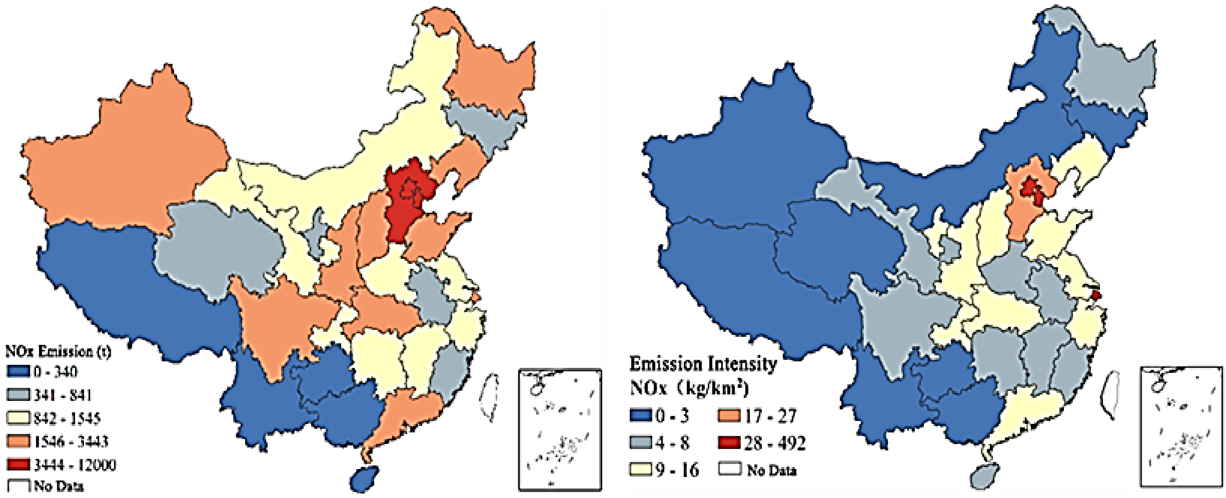

Fig. 7. Spatial emissions and emission intensity of NOx from GFIBs in different regions of China

3.4. Mitigation potential of industrial boilers in 2020 and 2030

In June 2018, the State Council promulgated the "*Three-year Action Plan for Winning the Battle for Safeguarding the Blue Sky*" (Three-year Action Plan). As one of the major sources of air pollutants, great attentions were paid to industrial boilers with actions of either elimination small and inefficient boilers or applied efficient emission control technology to large boilers. In 2020, all provinces and municipalities will achieve the goals setting in the "Three-year Action Plan". In general regions, the CFIBs below 10t/h should be basically eliminated and new CFIBs with the capacity below 35t/h will not allow to build. In key regions, CFIBs below 35t/h should be basically eliminated, and CFIBs above 65t/h should reach the ultra-low emission requirements. GFIBs in key regions should be applied with low nitrogen reforming technologies and the NOx emission will not be higher than 80 mg/m^3.

Additionally, in 2030, the general region will achieve the goal of key regions in 2020, and the CFIBs with the capacity of 35~65 t/h in key regions will reach ultra-low emissions requirements with the emission limits of 10, 35, and 50 mg/m^3 for TSP, SO_2 and NOx, respectively. For GFIBs, NOx emission in general regions will achieve the goal of key regions in 2020, and NOx emission of GFIBs will not be higher than 30 mg/m^3 in key areas. Based on this "Three-year Action Plan", the setting parameters of two pollution control scenarios (2020 scenario and 2030 scenario) given. In these two scenarios, we assumed that the energy consumption of CFIBs and GFIBs remains constant from 2016 to 2030 and only the emission reduction caused by the change of two pollution control scenarios is considered.

Emissions of primary air pollutants from CFIBs in different regions of China in the two scenarios were illustrated in Fig. 8. The emissions of TSP, SO_2 and NOx from CFIBs in 2020 scenario will be about 2.10, 0.89 and 1.10 Mt with the average emission reductions of 61%, 87% and 56%, respectively, compared to the reference year of 2016. In 2030 scenario, emissions of TSP, SO_2 and NOx from CFIBs will be about 0.27, 0.40 and 0.73 Mt with the average emission reduction of 95%, 94% and 71%, respectively, compared to the reference year of 2016. For regional emissions, the emission reduction rate will be the highest in eastern China and lowest in southern China. Central and Southwest China will gradually become the regions with highest TSP and SO_2 emissions from CFIBs, while eastern China will still be the region with highest NOx emission.

NOx emissions from GFIBs in different regions of China in the target years were calculated in Table 1. Total NOx emissions from GFIBs in 2020 and 2030 will be about 37,652 and 16,054 tons, respectively, with average emission reductions of 34% and 72% compared to the reference year of 2016. For regional emissions, the emission reduction rate will be higher in northern China and eastern China. Northern, southwest and northwest China will gradually become the regions with the highest NOx emission from GFIBs.

In summary, for TSP, the total emission from industrial boiler sources in the target years of 2020 and 2030 will be about 2.10 and 0.27 Mt, respectively, with the average emission reductions of 61% and 95% compared to the reference year of 2016. For SO_2, the total emission from industrial boiler sources in the target years of 2020 and 2030 will be about 0.89 and 0.40 Mt, respectively, with the average emission reductions of 87% and 94% compared to the reference year of 2016. For NOx, the total emission from industrial boiler sources in the target years of 2020 and 2030 will be about 1.15 and 0.74 Mt, respectively, with average emission reductions of 56% and 71% compared to the reference year of 2016. For regional distribution, due to the variation of coal quality and APCDs of industrial boilers in different regions, the potential reduction in each region is also distinct. The largest emission reductions of primary air pollutants occurred in Eastern China.

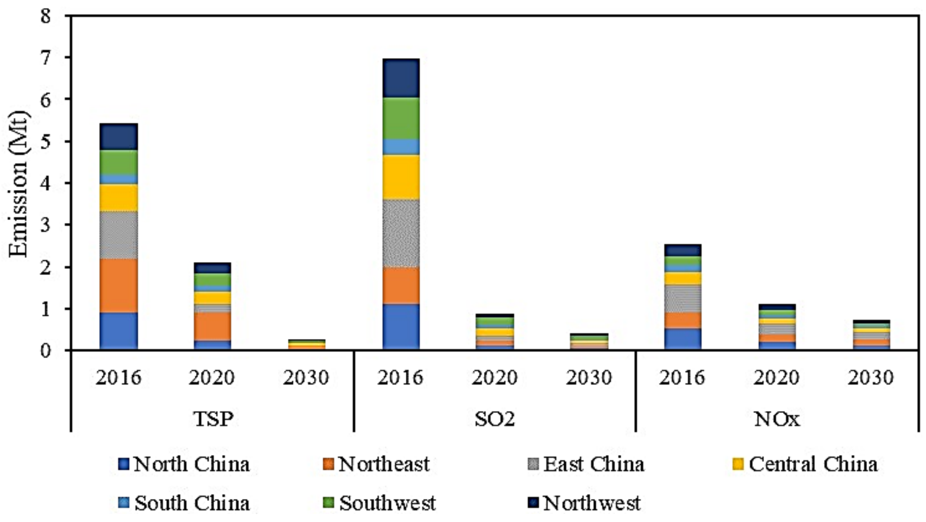

Fig. 8. Primary air pollutants emissions from CFIBs in different regions of China in the target years

Table 1. NOx emissions from GFIBs in different regions of China in the target years

Region	***Emission (t)***			***Reduction rate (%)***	
	2016	**2020**	**2030**	**2020**	**2030**
North China	23377	10487	4700	55	80
Northeast	4476	4476	1840	0	59
East China	9051	4695	2061	48	77
Central China	4276	3610	1504	16	65
South China	2436	2436	1001	0	59
Southwest	4780	4780	1965	0	59
Northwest	8398	7168	2983	15	64
Total	56791	37652	16054	29	70

4. Conclusions

In this study, based on the specific and detailed statistical data at a provincial level and comprehensive time-varying dynamic emission factors, the historical and spatial variation characteristics of TSP, SO_2 and NOx emissions from industrial boiler sources during the period of 1980-2016 have been calculated quantificationally. Under current action plan and environmental policy, future emissions of primary air pollutants from industrial boilers were estimated in the year of 2020 and 2030.

Our research indicated that the revision of emission standards promoted the progress of control technologies, leading to the decrease of EFs annually. In 2016, the total emissions of TSP, SO_2 and NOx from industrial boiler sources in China were estimated at about 5.43, 6.99 and 2.61 Mt, respectively. The higher emissions of these three pollutants from CFIBs were mainly concentrated in northeast and eastern China. While NOx emission from GFIBs was mainly concentrated in BTH region and its surrounding areas. Based on the current action plan, the measures were successful in abating emissions of TSP, SO_2 and NOx from industrial boiler sources by 95%, 94% and 71% in the year of 2030, respectively. However, for the control measures, it mainly focused on end-of-pipe emission control for large operating boilers. High efficiency of NOx, TSP and SO_2 control devices were extensively equipped after enforcement of the new emission standard. We suggest that more attention should be paid to the whole process control of industrial boilers in the future polices making. Now, coal is still a dominant energy in China. In the one hand, clean fuels will be introduced gradually, from which can be achieved persistent emission reduction. In the other hand, strengthen the operation, maintenance and management of pollution control technologies so as to ensure the best control effect of control measures. Ultimately, the relevant policies for pollution prevention and control of industrial boilers will to be formulated and promoted according to the actual situation and local conditions.

Acknowledgement

This study was supported by the National Natural Science Foundation of China (No.21607008), the Beijing Natural Science Foundation (No.8192014), the National Key Research and Development Program of China (No.2016YFC0208103), the Building of Innovation Team Plan (No. IG201804N). We also thank the editors and the anonymous reviewers for their valuable comments and suggestions on our paper.

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