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Primary air pollutant emissions of coal-fired power plants in China: Current status and future prediction

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ABSTRACT

To explore the atmospheric emissions of coal-fired power sector in China, a unit-based method was developed based on detailed information of unit type, fuel quality, emission control technology, and geographical location. During 2000–2005, the period when power sector developed fastest in the past 20 years, SO_2, NO_x and PM emissions of coal-fired power plants increased by 1.5, 1.7 and 1.2 times, respectively. The SO_2, emission of coal-fired power sector was estimated to be 16 097 kt in 2005, and would decrease to 11 801 kt in 2010, attributed mainly to the wide application of the flue gas desulfurization (FGD) technology. The NO_x emission, however, would increase from 6965 kt in 2005 to 9680 kt in 2010, since few NO_x control measures would be taken during the five years. The TSP, PM_{10}, and $PM_{2.5}$ emissions in 2005 were estimated to be 2774, 1842 and 994 kt, and the values would be 2540, 1824 and 1090 kt in 2010 respectively. The wet FGD would play an important role on dust emission removal. Through faithful implementation of closing small units and emission control policies in the acid rain and sulfur dioxide control zones, approximately 33%, 6% and 25% of SO_2, NO_x, and TSP emissions respectively could be further reduced in 2010. Emissions in 2015 and 2020 of coal-fired power plants were predicted applying scenario analysis. For SO_2 and TSP, optimistic situation can be achieved through reasonable control policies; in contrast, NO_x would probably be a more serious issue in future.

1. Introduction

Coal-fired power plant has been considered as a very important source of regional air pollution and ecosystem acidification, due to its huge emissions of acidic pollutants. A series of studies have used top-down method to estimate the emissions of SO_2 (Wang, 2001; Streets et al., 2003; Ohara et al., 2007), NO_x (Hao et al., 2002; Tian, 2003; Streets et al., 2003; Ohara et al., 2007; Zhang et al., 2007a) and PM (Zhang et al., 2007b; Yi, 2006a) from Chinese power sector around year 2000 or before. On one hand, most of those studies treated power plant as one single sector in an anthropogenic emission inventory framework. They generally ignored the discrepancy of technology and fuel characters among power units of different types, which can be of great effect on emission levels. On the other hand, those studies did not reflect the rapid increase of coal consumption and electricity generation since 2000, and the results were no longer applicable for policy making in the future. With increasing environmental pressure, Chinese government has made the decision that coal-fired power sector would be the most important source of regional atmospheric emission abatement in the near future, and power plants are thus anticipated to face more stringent environmental regulations related to siting and operation. To supply a clear emission picture of power sectors for policy making, this study explored the current and historical emissions of power plants as well as the emission

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control effects of possible policies through an innovative unit-based method. The future power sector emissions till 2020 were tentatively predicted through scenario analysis, considering different levels of energy consumption and control measures.

2. Methods

2.1. Unit-based methodology

The studied regions covered 31 provinces over mainland China. Hong Kong, Macao and Taiwan were not included since detailed information of those areas was not available. SO_2, NO_x, and PM were the target species. Different from previous studies, emissions were estimated through a bottom-up unit-based methodology. A Chinese power sector database was established, in which all the information related with emissions was compiled at unit level, including geographical location, capacity, boiler type, starting year, annual running hour, fuel type, sulfur content, coal consumption per unit electricity-supply, and emission control technology of SO_2, NO_x and PM. The total capacity of coal-fired power plants was 230 and 356 GW in 2000 and 2005, respectively. The data between 2001 and 2004 were deduced according to the information of newly built or retired units in corresponding years. In 2010, the national capacity of coal-fired power plants would be expected to increase by 90% and reach 681 GW compared with that in 2005.

Annual emission of each unit was seriatim calculated based on unit-specific fuel consumption and emission factor, and then aggregated to regional level. Emissions of SO_2, NO_x and PM from power plants at province level were calculated using Eqs. (1)–(3) respectively.

$$E_{SO_2,i} = \sum_j A_{j,i} \times \mathrm{Scont}_{j,i} \times (1-\mathrm{Sr}) \times (1-\eta_j) \quad (1)$$

$$E_{NO_x,i} = \sum_k \sum_m \sum_n A_{i,k,m,n} \times \mathrm{EF}_{NO_x,k,m,n} \quad (2)$$

$$E_{PM,y,i} = \sum_k \sum_n A_{i,k} \times \mathrm{AC}_i \times (1-\mathrm{ar}_k) \times f_{k,y} \times C_{k,n} \times (1-\eta_{n,y}) \quad (3)$$

where subscripts i, j, k, m, n, and y stand for province, power unit, boiler type, fuel type, emission control technology and particulate size; EF is the emission factor; A is the coal consumption; C is the application rate of emission control technology; η is the removal efficiency of emission control technology; Scont is the sulfur content of fuel; Sr is the sulfur retention in ash; AC is the ash content of fuel; ar is the ratio of bottom ash; and f is the particulate mass fraction by size.

2.2. Activity level

As shown in Eq. (4), the coal consumption of each unit was estimated according to its annual operation hours and coal consumption per unit electricity-supply. For the unit lack of these two parameters, national average values were applied. As shown in Fig. 1, the average annual operation hours of Chinese coal-fired power plants increased from 4900 to 5800 h during 2000–2005. However it dropped quickly to 5300 h in 2007, since the operation of new power plants has alleviated the pressure on electricity-supply and thus lowered the average operation hours. In this study, the annual average operation time was assumed to be 5100–5200 h in 2010. Regarding the consumption rate, the national average values for units smaller than 100 MW, 100–200 MW, 200–300 MW, 300–600 MW, and larger than 600 MW were respectively 440, 379, 365, 335 and 326 gce kWh^{-1}.[1] With rapid increase of large units, the national value declined from 392 to 357 gce kWh^{-1} during 2000–2007 (NBS, 2006). In this study, the national average value was calculated to be 353 gce kWh^{-1} in 2010 according to the unit fractions by size and corresponding coal consumption rates.

$$A_j = 1.4 \times U_j \times T_j \times E_j \times 10^{-6} \quad (4)$$

where A is the coal consumption (kt); U is the unit size (MW); T is the annual operation hours; E is specific coal consumption per unit electricity-supply (gce kWh^{-1}).

National coal consumptions of power sector during 2000 and 2010 are shown in Fig. 2. In 2005, the national coal consumption of power sector was 1069.7 Mt, and it would reach 1735.2 Mt in 2010, with an annual average increase rate of 10.2%. Moreover, significant variation on distribution by unit size was found. Due to the construction of large units, the coal consumption of units larger than 600 MW in 2005 only accounted for 11.2% and the value would increase to 37.0% in 2010, while the share of units smaller than 100 MW would decrease from 23.8% to 11.2%.

2.3. Emission factors

As shown in Eq. (1), the sulfur content (Scont) of fuel is the key factor influencing SO_2 emissions. In this study, the data of sulfur content were obtained from each specific unit. Fig. 3(a) shows the sulfur content distribution by each province in 2005. Relatively high-sulfur content was found in southwestern China, while northeastern was the region with lowest sulfur content. The national average sulfur content of coal used by power sector was 1.01% in 2005. Confirmed by the field measurements by Tsinghua University (unpublished yet), the sulfur retention ratio (Sr) during the combustion process of power plants was determined as 0.05–0.10. Another factor influencing SO_2 emissions is the application rate of flue gas desulfurization (FGD) system. Fig. 3(b) shows the application rate of FGD by province. In 2005, the capacity of units with FGD was 45 GW, only 13% of the total capacity of coal-fired plants. During 2005–2010, coal-fired power plant is the major source for SO_2 control. All the units built after 2004, as well as substantial existing ones, were required to be installed with FGD. The units with FGD would reach 477 GW in 2010, approximately 70% of the total capacity. Southwestern China would be the area with largest application rate of FGD, followed by northern China.

[1] Data source: National power industry statistic 2007 (internal information)

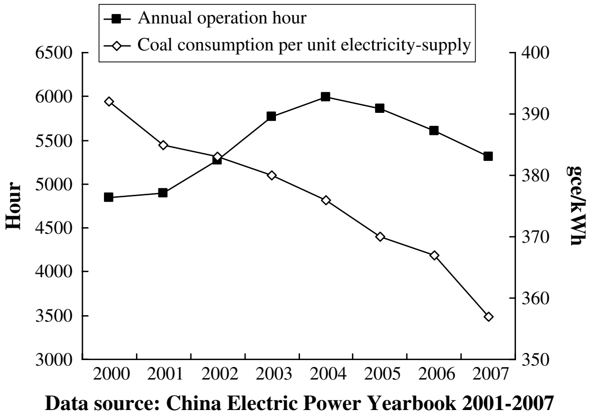

Fig. 1. Average annual operation hour and coal consumption per unit electricity-supply of coal-fired power plants in China during 2000–2007.

NO_x emission rates are influenced by different factors, however, previous studies usually applied an average emission rate (8.85 kg NO_x emitted per ton coal combusted) due to lack of detailed source information (Hao et al., 2002). In this study, we explored a technology-based method. A database was first established, which contained over 140 emission rates derived from unpublished testing results by Tsinghua University and other domestic measurements (Tian, 2003; Zhu et al., 2004; Bi and Chen, 2004; CRAES, 2006; Yi, 2006a). These emission rates were classified into different sets by fuel quality, boiler type, and emission control level. Emission factors by type were then obtained by averaging the values in corresponding datasets. Table 1 gives the NO_x emission factors used in this study, ranging from 4.0 to 11.5 kg t^{-1}.

Emission factors of particulate matters (PM) were estimated mainly based on the model developed by Zhang (2005), in which the unabated emission factors were calculated as a product of the fuel ash content and the ratio of fly ash. The ash content of coal consumed by each region was calculated from the ash content of mining coal and the coal transportation flow matrix by CCTA (2003) and Jiang (2004). The national average of ash content in coal was 21.7% in 2005. The ratio of bottom ash (ar) during the combustion process was determined as 0.20 for pulverized boilers and 0.85 for grate boilers (SEPA, 1996). The percentages of PM_{10} and $PM_{2.5}$ in unabated total particulates (TSP), and the removal efficiencies of PM emission control technology, were obtained from a series of domestic measurements (unpublished studies by Tsinghua University; Yi et al., 2006b) as summarized in Tables 2 and 3. Since wet FGD is becoming more and more prevalent, its benefits on PM control should be considered in the emission estimates. Table 3 summarizes recent results and provides the values used in this study.

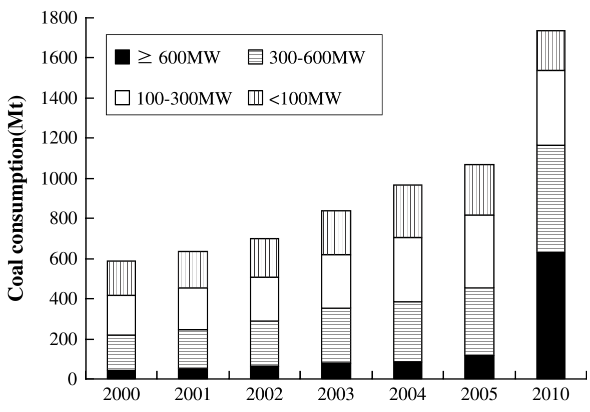

Fig. 2. Coal consumption of power plants by unit size during 2000–2010 (Mt).

3. Results

3.1. Emissions from 2000 to 2005

Emissions of SO_2, NO_x and PM from coal-fired power plants from 2000 to 2005 were calculated using the unit-based activity data and emission factors, as shown in Fig. 4.

During 2000–2005, the period when power sector in China developed fastest within the past 20 years, SO_2 emissions increased by 1.5 times, and, notably by 1.8 times in northwestern and 1.6 times in central & southern China. SO_2 emission from coal-fired power plants in 2005 was estimated to be 16 097 kt, approximately 53% of the national emissions. As listed in Table 4, five provinces with largest coal consumption, including Shandong, Henan, Hebei, Shanxi, and Jiangsu, emitted over 1000 kt SO_2 each, followed by Guizhou and Sichuan where high-sulfur coal was commonly used. SO_2 emissions of power plants in Beijing, Hainan, and Qinghai, were less than 100 kt. Emissions from units less than 300 MW, which accounted for half of the total capacity, reached 10 124 kt, accounting for 63% of the total emissions.

Even faster than SO_2, NO_x emission increased by 1.6 times during 2000–2005. Southwestern and central & southern were the areas with fastest emission increase by 1.9 and 1.7 times respectively. The NO_x emission from coal-fired power plants in 2005 was estimated to be 6965 kt, approximately 36% of the total national emissions. Each of Jiangsu, Shandong, and Henan emitted over 500 kt NO_x, while Hainan and Qinghai less than 20 kt. The LNB-installed units which accounted for 62% of the total capacity and consumed 53% of coal in the power sector, emitted 3255 kt NO_x, 47% of the total emissions. This implied that the emission control effect of LNB was quite poor (less than 30% according to our estimate). Regarding the fuel quality, anthracite would cause higher NO_x emission due to relatively low content of volatile matter compared with bituminous. In 2005, the share of anthracite and lean coals was about 20%, and the units using those coals emitted 2230 kt NO_x, 32% of the total emissions.

The primary PM emission increased to 2848 kt by 1.2 times during 2000–2004, and southwestern and northwestern were the areas with fastest increase by 1.4 times. In 2005, the emission by power sector dropped slightly to 2774 kt, less than 10% of the total national emissions. Each of Henan, Jiangsu and Shandong emitted over 200 kt. Emissions of PM_{10} and $PM_{2.5}$ were 1842 and 994 kt, respectively. Large discrepancy of size characteristics was

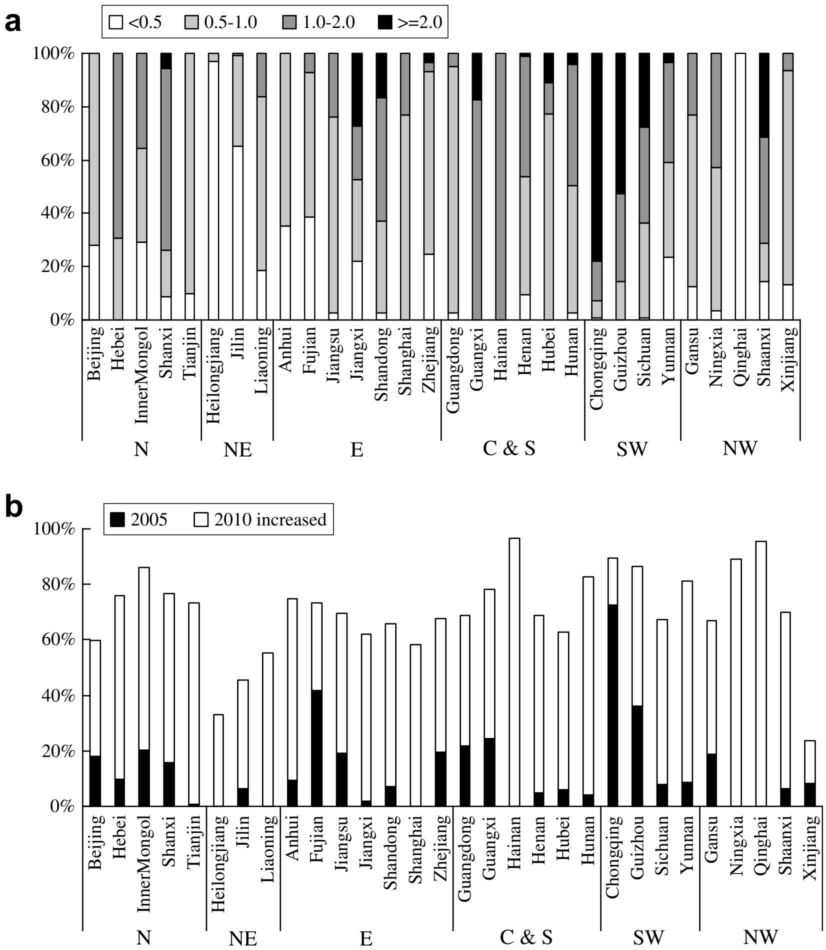

Fig. 3. Percentage of coal consumption with different sulfur contents by region (a) and percentage of unit installed with FGD by region (b) (N: North China, NE: Northeast China, E: East China, C&S: Center and South China, SW: Southwest China, and NW: Northwest China).

found between pulverized boilers and grate boilers. The ratios of $PM_{2.5}$ and PM_{10} to TSP emission from grate boilers were 65% and 89% respectively, much higher than those from pulverized boilers (31% and 63% respectively). The main reason is that wet scrubber and cyclone commonly applied in grate boilers have much lower removal efficiency to fine particles than electrostatic precipitator (ESP) applied in pulverized boilers.

We mainly compared our estimation with other studies for year 2000, as well as other years if applicable. As shown in Fig. 5(a), the SO_2 emission from coal-fired power sectors in 2000 has been estimated to be in the range 7500–13330 kt. Our result, 10 950 kt, was higher than most other studies except for EDGAR. In 2005, our estimate was even 15% higher than that estimated by State Environmental Protection Administration (SEPA). The reason is that 1) the activity level obtained with unit-specific method was somewhat higher than the national statistics, which was confirmed by Akimoto et al. (2006) and 2) the sulfur retention used in the official estimation was commonly 0.15, higher than that used in this study. Similar situation was also found for NO_x. As shown in Fig. 5(b), the NO_x emission range of power sector was estimated to be 2430–5120 kt in 2000, and our result was 4340 kt, lower than

Table 1
NO_x emission factors used in this study ($kg\,t^{-1}$)

Unit Size	Boiler type	With LNB		Non-LNB	
		Bituminous/lignite	Anthracite/lean coal	Bituminous/lignite	Anthracite/lean coal
≥100 MW	Tangentially-fired	4.05	7.80	6.60	10.07
	Swirl Burner	5.46	9.56	7.40	11.46
	W-flame	5.62	11.17	N/A	N/A
<100 MW	Tangentially-fired	N/A	N/A	6.17	9.36
	Swirl burner	N/A	N/A	6.93	10.65

Table 2
Size fraction of unabated particulate matter from coal-fired power plants in China

Unit size (MW)	Boiler type	Fraction			Literature
		$>PM_{10}$	$PM_{2.5-10}$	$PM_{2.5}$	
29	Grate	0.72	0.18	0.1	Unpublished
50	Pulverized	0.64	0.3	0.06	Yi et al., 2006b
50	Pulverized	0.77	0.16	0.07	Unpublished
50	Pulverized	0.80	0.14	0.06	Unpublished
100	Pulverized	0.61	0.37	0.02	Liu et al., 2003
100	Pulverized	0.80	0.13	0.07	Unpublished
125	Pulverized	0.88	0.10	0.02	Unpublished
140	Pulverized	0.91	0.08	0.01	Yi et al., 2006b
165	Pulverized	0.80	0.15	0.05	Unpublished
200	Pulverized	0.84	0.12	0.04	Yi et al., 2006b
200	Pulverized	0.83	0.12	0.05	Unpublished
200	Pulverized	0.85	0.11	0.04	Unpublished
220	Pulverized	0.83	0.15	0.02	Yi et al., 2006b
600	Pulverized	0.82	0.16	0.03	Yi et al., 2006b
600	Pulverized	0.86	0.11	0.03	Yi et al., 2006b
–	Pulverized	0.56	0.28	0.16	Huang et al., 2003
Data used in this study	Pulverized	0.78	0.17	0.05	–
Data used in this study	Grate	0.63	0.23	0.14	Klimont et al., 2002

EDGAR and Zhu et al. (2004), but higher than other studies. Regarding PM, Zhang et al. (2007b) estimated the emission from Chinese power sector as 2390 kt in 2001, consistent with the result of this study, 2413 kt.

3.2. Emissions in 2010

Although coal consumption during 2005–2010 would sharply increase by 62%, SO_2 emissions from coal-fired power plants would decrease to 11 801 kt, attributed mainly to the installation of FGD. Emissions from units less than 300 MW would keep being a major contributor, accounting for 63% of total emissions. Although each of Shandong, Hebei, and Henan would decrease the emission by over 400 kt during 2005–2010, these provinces would still be the largest emission areas in 2010. Meanwhile, there would be small emission increase in some western provinces, like Qinghai, Chongqing and Xinjiang.

Different from SO_2, no further stringent control measures for NO_x have been planned except the emission standard amendment in 2003. Advanced technologies such as selective catalyst reduction (SCR) would not be widely used except in Beijing till 2010. Thus NO_x emission would keep increasing in the near future and would reach 9680 kt in 2010. The LNB-installed units, increasing to 77% of the total capacity, would emit 6380 kt NO_x, 66% of the total emissions by power sector. The emissions of Shandong, Henan, Jiangsu and Inner Mongolia would exceed 700 kt. During 2005–2010, Inner Mongolia and Shanxi would have the largest emission increase, i.e. 391 and 221 kt respectively. Shanghai and Beijing, however, would have their NO_x emission reduced attributed to the application of SCR.

Although no stricter control policies are planned for PM, the emission in 2010 would decrease to 2540 kt. The main reason for that is the widely installation of wet FGD system, which has similar PM removal efficiency as wet scrubber. However, $PM_{2.5}$ emission would increase slightly, owing to the poor control effect of FGD to fine particles. The PM emissions of Henan and Zhejiang would exceed 200 kt, while Hebei, Jiangsu and Shandong would reduce their PM emissions by 44, 30 and 21 kt respectively.

Table 3
The removal efficiency of particulate matter from coal-fired power plants in China

Unit size	Boiler type	Control	Removal efficiency (%)			Literature
			$>PM_{10}$	$PM_{2.5-10}$	$PM_{2.5}$	
15	CFBC	ESP	98.01	94.63	87.31	Yi et al., 2006b
50	Pulverized	ESP	99.45	98.70	95.56	Yi et al., 2006b
50	Pulverized	ESP	99.53	94.39	90.88	Unpublished
50	Pulverized	ESP	99.61	99.16	97.86	Unpublished
100	Pulverized	ESP	99.92	99.02	90.60	Liu et al., 2003
125	Pulverized	ESP	99.37	98.7	94.62	Unpublished
140	Pulverized	ESP	99.52	96.48	92.59	Yi et al., 2006b
165	Pulverized	ESP	99.54	98.22	94.41	Unpublished
200	Pulverized	ESP	99.56	97.26	94.87	Yi et al., 2006b
200	Pulverized	ESP	99.11	95.71	92.65	Unpublished
200	Pulverized	ESP	99.74	98.39	96.84	Unpublished
600	Pulverized	ESP	99.95	99.71	99.16	Yi et al., 2006b
600	Pulverized	ESP	99.95	99.16	96.75	Yi et al., 2006b
–	Pulverized	ESP	98.38	95.70	89.86	Huang et al., 2003
29	CFBC	Wet	98.65	87.98	71.73	Unpublished
140	Pulverized	FGD	92.87	82.49	61.68	Yi et al., 2006b
165	Pulverized	FGD	91.77	76.78	52.18	Unpublished
200	Pulverized	FGD	94.66	83.31	54.16	Yi et al., 2006b
200	Pulverized	FGD	90.46	78.22	46.34	Unpublished
300	Pulverized	FGD	92.35	89.11	53.89	Wang et al., 2008
Data used in this study		ESP	99.25	97.61	93.62	
Data used in this study		FGD	92	82	53	
Data used in this study		Wet	99.00	90.00	50.00	Zhang, 2005
Data used in this study		Cyclone	90.00	70.00	10.00	Zhang, 2005

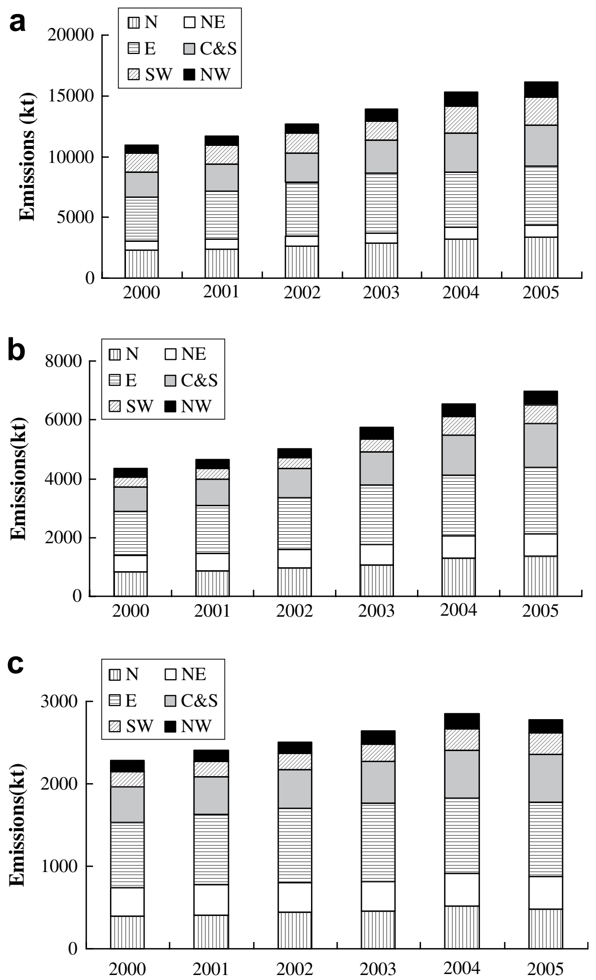

Fig. 4. Emissions of coal-fired power plants from 2000 to 2005 (kt): (a) SO_2, (b) NO_x and (c) PM.

3.3. Spatial allocation

To better understand the regional distribution of the power emissions, the spatial allocation of emissions based on unit information was made using a 36×36 km grid system covering most part of mainland China. The emission of each power plant was assigned to corresponding grid cell where the plant was located.

Gridded coal-fired power emissions of SO_2, NO_x, and PM in 2005 are shown in Fig. 6. It can be seen from the figure that eastern region with nearly one-third of total coal-fired power emissions had the highest emission intensity for all the species, followed by central & southern, northeastern and northern regions. Those areas, which covered only 43% of country territory but contained 78% of national population and 87% of GDP in 2005, accounted for 78%, 84%, and 85% of the national power emissions for SO_2, NO_x and TSP respectively. The spatial distribution of power emissions implied that power constructions in China were still largely influenced by the population density and economy strength.

4. Policy analysis of emission control

4.1. Closing small units

The emission of small units is a serious problem in China. Due to low combustion efficiency and poor emission control technology, the energy consumption and pollutant emissions of small units were extremely high in recent years. In 2000, the units smaller than 100 MW added up to 56 GW and had a coal consumption of 181 Mt, accounting for 25% of the total unit size and 29% of coal consumed by power sectors. The emission fraction of those small units for SO_2, NO_x, TSP and $PM_{2.5}$ reached to 31%, 32%, 55% and 69% respectively. During 2000–2010, along with rapid development of large units and retirement of some small units, the share of NO_x, TSP and $PM_{2.5}$ emissions from units smaller than 100 MW would decrease gradually to 16%, 41% and 49% respectively. Since FGD system would be applied with most large power units, the SO_2 emission share of small units would increase to 33%. Compared with unit size and energy share (9.0% and 11.2% respectively in 2010), the emission of small units would still be very high.

Facing this huge challenge, more stringent regulations for small units are, or will be, taking effect. According to latest policy, the units smaller than 50 MW, and the units smaller than 100 MW with a working period more than 20 years, should be pushed to close gradually in near future. Moreover, all the new-built condensing steam units should be larger than 300 MW. If all the units below 25 MW (most are grate boilers) were shut down by 2010, approximately 2173, 622, and 540 kt emission abatement of SO_2, NO_x, and TSP would be achieved, and the emission share of units smaller than 100 MW would be further reduced to 17%, 8%, and 22% respectively, implying the significant benefits of closing small units.

4.2. Emission control in acid rain and SO_2 control zones

Since 1998, approximately 11.4% of national territory have been designated as the acid rain control zones and SO_2 pollution control zones (Two-Control Zones for short) to protect those areas which were, or might be, affected by acid deposition or ambient SO_2 pollution (Hao et al., 2000). The total capacity in the Two-Control Zones in 2000 was 138 GW, and it would increase to 313 GW by 2010. In this study, SO_2 emissions from coal-fired power plants in the Two-Control Zones in 2000, 2005 and 2010 were estimated to be 6981, 9472 and 6659 kt, approximately 64%, 61% and 56% of the national emissions respectively, without satisfying abatement.

According to the Two-Control Zones regulation, all the power units in the zones should be installed with FGD systems till 2010 if sulfur content of coal consumed is higher than 1.0%. In fact, however, this policy has not been implemented strictly. In 2010, the capacity of units with sulfur content higher than 1.0% would still be 33 GW in the Two-Control Zones. If these units could be also installed with wet FGD by 2010, approximately 1671 kt SO_2 and 100 kt TSP emissions would be further reduced, and the SO_2 emission share from power units in the Two-Control Zones would sharply decrease to 49%, implying that there

Table 4
Emission estimate by region in 2005 and 2010 (kt)

Region	2005					2010				
	SO_2	NO_x	TSP	PM_{10}	$PM_{2.5}$	SO_2	NO_x	TSP	PM_{10}	$PM_{2.5}$
Northern	**3347**	**1377**	**481**	**312**	**165**	**2157**	**2114**	**414**	**305**	**188**
Beijing	89	54	15	9	5	47	21	9	6	4
Hebei	1218	429	177	117	63	708	539	133	100	62
Inner Mongol	664	376	131	84	44	497	768	135	100	61
Shanxi	1177	423	118	78	42	796	645	106	77	47
Tianjin	199	96	40	25	12	109	141	31	22	13
Northeastern	**990**	**752**	**395**	**269**	**146**	**854**	**869**	**387**	**270**	**153**
Heilongjiang	176	261	115	80	44	183	290	119	83	46
Jilin	185	171	116	80	43	183	202	122	84	47
Liaoning	629	321	163	109	59	488	378	146	103	60
Eastern	**4880**	**2269**	**902**	**597**	**321**	**3791**	**3075**	**837**	**598**	**355**
Anhui	311	239	84	52	26	257	380	80	54	32
Fujian	200	141	54	36	19	186	208	58	40	23
Jiangsu	1107	626	224	148	80	803	781	194	140	85
Jiangxi	357	107	51	29	13	280	153	49	30	16
Shandong	1823	605	211	146	83	1328	800	190	143	88
Shanghai	477	198	84	51	24	342	214	60	41	22
Zhejiang	605	352	194	136	76	596	538	207	151	89
Central & southern	**3374**	**1464**	**575**	**383**	**209**	**2578**	**2080**	**534**	**385**	**231**
Guangdong	674	392	111	69	35	622	586	116	78	43
Guangxi	323	78	42	26	13	281	126	42	29	17
Hainan	36	12	4	2	1	10	20	2	1	1
Henan	1272	567	229	156	87	873	786	210	154	93
Hubei	646	258	107	74	42	503	319	95	70	42
Hunan	423	156	81	55	31	290	243	69	53	34
Southwestern	**2272**	**639**	**259**	**176**	**99**	**1575**	**894**	**225**	**168**	**106**
Chongqing	202	70	19	15	10	242	109	23	19	12
Guizhou	902	184	60	39	20	670	287	56	41	25
Sichuan	898	259	122	86	49	517	295	101	77	48
Yunnan	270	126	57	36	19	146	202	45	32	20
Northwestern	**1235**	**463**	**163**	**104**	**54**	**846**	**648**	**143**	**98**	**57**
Gansu	192	118	24	15	7	165	150	22	15	8
Ningxia	278	86	40	25	13	149	149	27	20	13
Qinghai	4	5	2	1	1	5	20	2	2	1
Shaanxi	647	173	67	42	21	396	234	57	38	22
Xinjiang	114	82	30	21	12	130	95	35	23	12
Total	**16 097**	**6965**	**2774**	**1842**	**994**	**11 801**	**9680**	**2540**	**1824**	**1090**

are still considerable potentials for SO_2 emission reduction for power plants in Two-Control Zones.

Taking both closing small units and control policies in Two-Control Zones into account, the SO_2, NO_x and TSP emissions of national coal-fired power sector in 2010 would be further reduced by 33%, 6% and 25% respectively compared to the results described in Section 3.2.

5. Future projection

Several studies predicted Chinese emissions based on their future energy consumption estimation (Streets and Waldhoff, 2000; Klimont et al., 2001; Ohara et al., 2007). Choosing 1995 or 2000 as the base year, however, those studies generally did not expect the tremendous increase in fuel consumption during 2000–2005, and the forecasted energy level (including coal consumption by power sector) was commonly underestimated. In this study, both coal consumption and emission control strategies of power sectors during 2010–2020 were evaluated through scenario analysis for future emission projection.

5.1. *Energy consumption*

The future electricity demand and coal consumption were estimated through the elasticity of electricity, the ratio of electricity growth rate to GDP growth rate. During 2000–2005, the national elasticity of electricity increased dramatically along with the fast economy growth and development of high-energy-consumed industries. Though dropped slightly after 2005, it still kept higher than 1.20. It was believed that the electricity growth rate would become less than GDP growth after 2010, and the elasticity of electricity would thus decrease below 1.0, owing to adjustment of industry structure and implementation of energy saving (NDRC, 2004; SPERI, 2007).

In this study, high (H), medium (M) and low (L) energy scenarios were assumed. As listed in Table 5, elasticity of electricity and macro economy data taken from NDRC (2004) and Wu (2007) were adjusted according to latest national energy plan (SPERI, 2007) and applied in the projection. The H scenario describes a picture of relatively rapid economy and electricity growth, and a coal-dominated

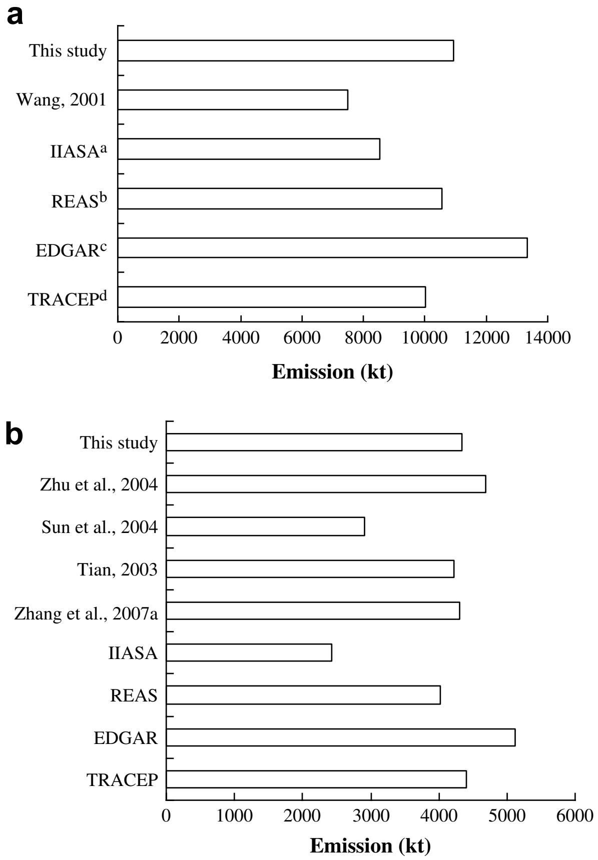

Fig. 5. Emission comparisons with other studies in 2000 (kt): (a) SO_2, (b) NO_x. [a]http://www.iiasa.ac.at/rains/global_emiss/global_emiss1.html. [b]Ohara et al., 2007, [c]http://www.mnp.nl/edgar/model/v32ft2000edgar/. [d]Streets et al., 2003.

energy structure in which the coal-fired electricity would still account for more than 70% in power sector. The M scenario describes a picture with the same economy and electricity growth as H, but with changes in energy structure, in which considerable switch to clean fuels, such as natural gas and hydro power, would be achieved in power sector. The L scenario describes a scenario with the same energy structure as M, but a slower economic and electricity growth, emphasizing more on sustainable development. Under the scenarios, the development of coal-fired power sector during 2010–2020 would slow down compared with that during 2000–2010. The coal consumption in 2020 was estimated to reach 2769, 2510, and 2176 Mt in H, M and L respectively.

The obtained results were compared with those by IEA (2007). IEA provided two energy scenarios, the Reference (REF) scenario as the usual scenario and the Policy Alternative (POLICY) scenario in which policies of energy saving and energy structure adjustment would be implemented. The unit capacity estimated in this study was higher than IEA, but the coal consumptions were very close between the M scenario in this study and REF scenario by IEA, in which a more conservative coal consumption rate (355–360 gce kWh^{-1} in 2015) was used.

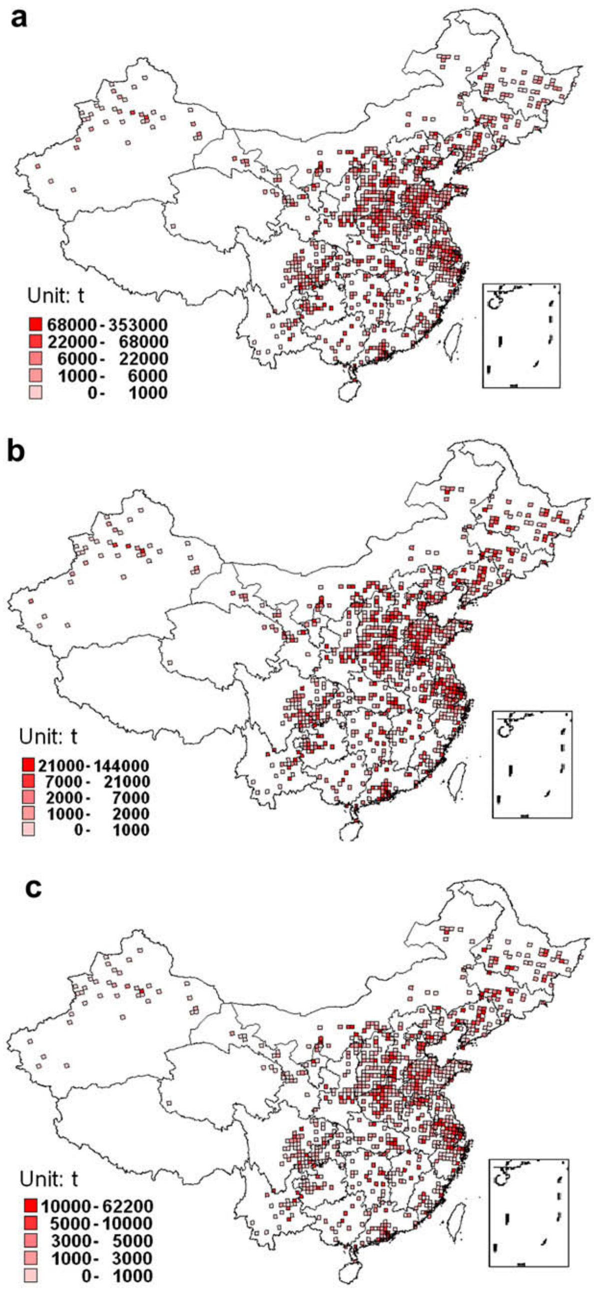

Fig. 6. Gridded coal-fired power emissions of SO_2 (a), NO_x (b), and PM (c) at 36×36 km level in China in 2005 (unit in the legends: t).

5.2. Emission control policy

After 2010, coal-fired power sector would still be an important emission control source. FGD would be doubtless widely applied as it is since 2005. Moreover, the application rate of SCR and filter fabric (FF) would also rise though with an uncertain rate. In this study, base (1), normal (2) and strict scenarios (3) were designed to describe different emission control policies. Base scenario is a pessimistic one in which the emission control for all

Table 5
Scenarios of coal consumption of power sectors during 2010–2020

	2015			2020		
	High	Medium	Low	High	Medium	Low
GDP growth rate (%)	8.0	8.0	7.5	7.5	7.5	6.5
Elasticity of electricity	0.90	0.90	0.80	0.85	0.85	0.70
Electric growth rate (%)	7.2	7.2	6.0	6.4	6.4	4.6
Percentage of coal-fired electricity (%)	77	72	72	70	64	64
Total electricity (10^3 GWh)	6149	6149	5813	8376	8376	7261
Coal-fired electricity (10^3 GWh)	4723	4440	4197	5905	5352	4640
Coal-fired units (GW)	926	871	823	1230	1115	967
Coal consumption (Mt)	2281	2126	2009	2769	2510	2176

The values of GDP growth rate, elasticity of electricity, and electric growth rate refer to the average annual rate of five year's period, i.e. 2011–2015 for columns 2015, and 2016–2020 for columns 2020.

the species would remain at the current stage, without any further measures to cut emissions of existing units. FGD, LNB and ESP would be required for all the new-built units compulsorily. The normal scenario emphasizes the implementation of closing and substitution of small old units. Grate boilers with wet scrubber and cyclone dust collectors would be replaced with large units with high combustion efficiency and advanced emission control technologies. During 2015–2020, SCR technology and FF would be gradually installed on new-built units. Based on the normal one, the strict scenario is an optimistic one, which stressed most on emission abatement. FGD would be installed on all the existing units using high-sulfur coals in the Two-Control Zones. SCR and FF would be largely applied since 2010. According to national policy on energy saving and emission control, we mean the normal scenario would be the most applicable for the coal-fired power sector in the future. The projected application rate of different emission control technologies is summarized in Fig. 7.

5.3. Emission forecast

Owing to relatively slow increase of energy consumption and implementation of emission control policy, the emissions of coal-fired sectors would be futher restrained after 2010. Fig. 8 shows the emission projection of coal-fired power plants under all the possible scenarios. The estimation under M2 would be the "best guess" of future emissions, while other scenarios could be consulted for the uncertainty caused by different levels on coal consumption or emission control.

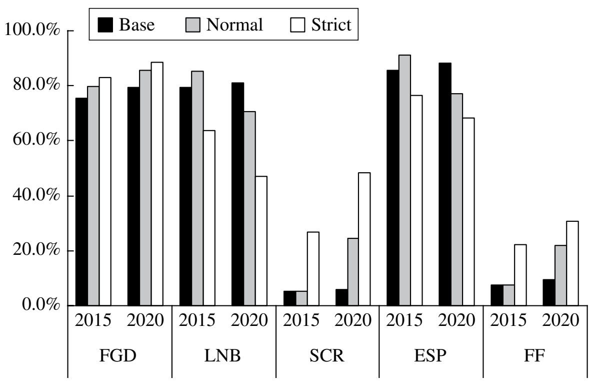

Fig. 7. The application rate of emission control technologies in 2015 and 2020.

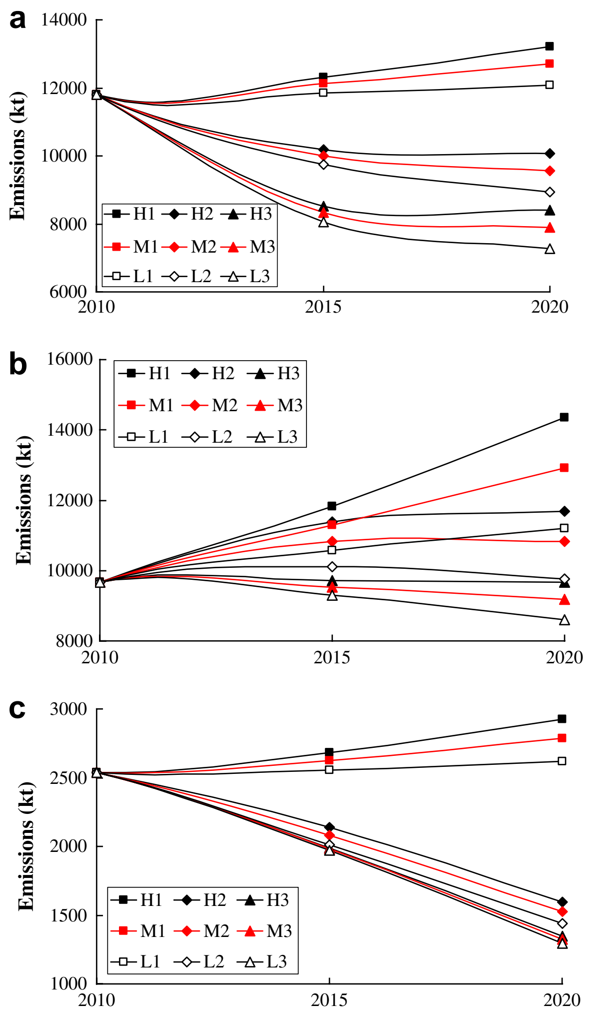

Fig. 8. The coal-fired power emissions of SO_2 (a), NO_x (b) and TSP (c) during 2010–2020 under different scenarios (kt). Letters H, M, and L represent the high, medium and low increase scenarios of coal consumption respectively. Numbers 1, 2 and 3 represent the base, normal and strict scenarios of emission control.

During 2010–2020, the SO_2 emission would increase only under base control scenario (L1, M1 and H1) by 2–12%, and it would decrease by 15–24% and 29–38% respectively under normal (L2, M2 and H2) and strict control scenarios (L3, M3 and H3). Under M2, the emission in 2020 is estimated to be 9560 kt, and it would vary between the range 7889–12 702 kt under medium coal consumption scenarios with different control stages (M1, M2 and M3), and the much smaller range 8941–10 077 kt under normal control scenarios with different coal consumption levels (L2, M2 and H2). This result implied that the implementation of control policies would have a more significant influence on SO_2 emission than the activity levels.

Similarly, and even more obvious trends can also be found for PM emissions. The PM emissions from coal-fired power sector would increase by 3–15% under base control scenarios during 2010–2020. However, it would decrease by 37–43% under normal control scenarios, indicating the great benefits of closing small units and grate boilers. Under M2, the emission in 2015 and 2020 was estimated to be 2083 and 1528 kt respectively, approximately 79% and 54% of the emissions under M1 in corresponding years. Under strict scenarios, the emission in 2015 and 2020 would reach 1969–1989 and 1296–1347 kt respectively, without significant abatement compared with normal control scenarios.

The situation for NO_x is a bit different. The emission during 2010–2015 would increase under all the scenarios except the ones with strict control policies at medium and low activity levels (M3 and L3). During 2015–2020, the emissions under all the strict control scenarios (L3, M3 and H3), and the normal control scenario with low activity levels (L2) would decrease along with the application of SCR. However, the emission under all the scenarios except M3 and L3 would still be higher than that in 2010. Under M2, the NO_x emission in 2015 and 2020 would keep constant at around 10 835 kt, higher than the SO_2 emission of 10 000 and 9560 kt respectively. This result indicated that the NO_x emission from power plants would become a more serious problem. Moreover, the effect of control policies and activity levels on NO_x emission is more complicated than SO_2 and TSP, implying that NO_x emission control needs an even more comprehensive consideration in the future.

In conclusion, the SO_2 and PM emissions of power sector could be effectively controlled with the measures of closing small units and the wide application of FGD and high-efficiency dust collectors. Thus those control policies should be followed through in the future. However, NO_x emission of power sector would probably increase along with the energy consumption growth, and become a new challenge for Chinese air pollution control. Therefore new policy should be planned for NO_x emission abatement as soon as possible.

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