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Environmental damage costs from fossil electricity generation in China, 2000~2003*

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Abstract: Electricity consumption increases rapidly with the rapid development of China. The environmental damage costs of electricity generation are very important for both policy analysis and the proper management of the environment. A method was developed in this work to estimate gross environmental damage costs according to emission inventory and environmental cost factors, and to extend the costs from provincial to national level with population density. In this paper, sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter less than 10 μm in diameter (PM_{10}), and carbon dioxide (CO_2) from fossil fired power plants over 6000 kW were selected as index pollutants to quantify the environmental costs of damages on human health and global warming. With the new developed method, environmental damage costs, caused by 3 types of fired power plants in 30 provinces and 6 economic sectors during the years 2000 to 2003, were evaluated and analyzed. It can be seen that the calculated total national environmental damage costs of electricity have rapidly increased from 94930.87×10^6 USD in 2000 to about 141041.39×10^6 USD in 2003, with an average annual growth rate of 14.11%. Environmental damage costs of SO_2, NO_x, PM_{10}, and CO_2 are 69475.69×10^6, 30079.29×10^6, 28931.84×10^6, and 12554.57×10^6 USD and account for 49.26%, 21.33%, 20.51%, and 8.90% of total environmental costs in fossil electricity generation, respectively. With regard to regional distribution, external costs caused by fossil electricity generation are mainly concentrated in the more populated and industrialized areas of China, i.e., the Eastern Central and Southeastern areas.

Key words: Environmental damage costs, Fossil electricity generation, Emission inventory, Uncertainty analysis
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INTRODUCTION

Chinese fossil production electricity has proven to be a large source of air pollution nationwide. According to the Chinese National Statistical Bureau, the total fossil electricity output of China increased from 1107.94 billion kW·h in 2000 to 1578.97 billion kW·h in 2003, with an average annual growth rate of 12.53%. Rapid economic growth and increasing electricity demands resulted in large amounts of sulfur dioxide (SO_2), nitrogen oxide (NO_x), particulate matter less than 10 μm in diameter (PM_{10}), and carbon dioxide (CO_2) pollutants emitted into the ambient atmosphere (Zhu *et al*., 2005). Those caused serious ambient air pollution, regional acid deposition, and the climate change in China (Tian *et al*., 2001; Wei *et al*., 2003).

Environmental damage costs of electricity generation represent the uncompensated monetary values of environmental and health damages it causes (Krewitt and Nitsch, 2003; Roth and Ambs, 2004; Vrhovcak *et al*., 2005). These costs, sometimes called external costs, are imposed on society and the environment, and are not accounted for by the producers or the consumers of electricity (Steen and Borg, 2002). External costs should reflect the value of the damage caused by electricity generation and associated processes (Vrhovcak *et al*., 2005). Most research had only been done in North America and Europe with EXMOD (Ottinger *et al*., 1991; Rowe *et al*., 1996) and ExternE model (Lechón *et al*., 2003; Soderholm

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and Sundqvist, 2003), but few studies have been conducted in developing countries such as China. Traditional economic assessment of energy technologies in China had tended to ignore these effects (Li *et al*., 2004). There have been several estimations of fossil electricity generation external costs in China (Lu and Zhou, 2004; Sun, 2004), but these researches are limited because of outdated data and over-simplified method, which cannot be in agreement with the rapid increasing energy consumption in China after 2000.

The significant contributors from fossil production electricity to the environmental damages are SO_2, NO_x, PM_{10} and CO_2 (El-Kordy *et al*., 2002; López *et al*., 2005; Kuprianov and Tanetsakunvatana, 2006; Smekens and Zwaan, 2006). The most important health impacts of these airborne emissions (PM_{10}, SO_2, and NO_x) are illness and death associated with respiratory disorders (Spalding-Fecher and Matibe, 2003), while CO_2 plays a dominant role in global warming. Therefore, studies on environmental damage costs of fired power stations can provide information useful for specific environmental policy decision. However, policy makers generally prefer information at a higher level of aggregation. Aggregated results are more useful for assessing the significance of acid deposition, climate warming, and air pollution. To this end, the National Development and Reform Commission of China (NDRC) approved a project proposed by our research groups to evaluate the environmental costs of fossil fired power stations in China and put forward corresponding control strategies. Studies providing aggregated estimates of the gross air pollution environmental damage costs from fossil fired electricity generation at the national level in China are scarce because of the lack of necessary data.

This study developed a method, which estimates environmental damage costs with environmental costs factors and emission inventories, to extend the costs to China according to population density. Furthermore, SO_2, NO_x, PM_{10}, and CO_2 were selected as index pollutants to evaluate external costs of fossil fired electricity stations over 6000 kW between 2000 and 2003 of China. In this paper, the regions studied cover 30 provinces, autonomous regions and municipalities in China mainland. Tibet Autonomous Region, Hong Kong Special Administrative Region (HKSAR), Macau Special Administrative Region (MSAR), and Taiwan Province are not included. China is divided into 6 regions in this paper as shown in Fig.1.

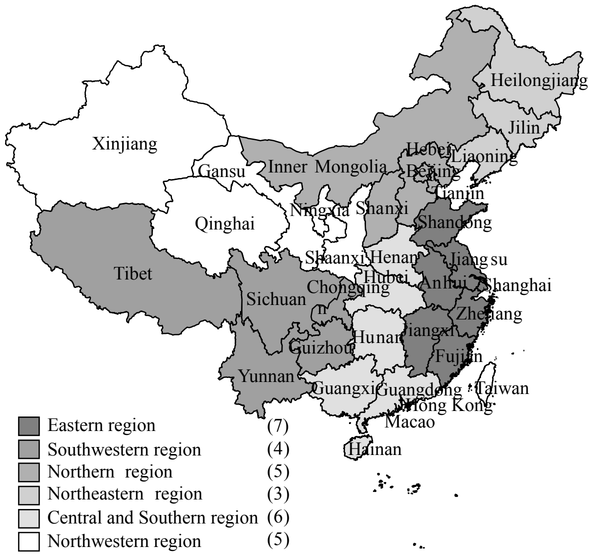

Fig.1 Map of People's Republic of China

METHODOLOGY

Environmental cost

To evaluate the environmental damage costs of fossil electricity generation requires an understanding of the air pollutants emission, dispersion patterns, and human exposure to environmental quality risks, and the dose-response function relating to human health and environmental quality. ExternE approach, aiming at modelling the 'impact pathway' of an environmental burden from the release of pollutants through their interactions with the environment to a physical measure of impact, has estimated damages from airborne pollution in Europe for a wide variety of receptors, including human health, materials, crops, forests, fisheries and natural ecosystems (European Commission, 1995; Kim, 2007). In order to estimate the environmental costs of SO_2, NO_x, PM_{10}, and CO_2 of China, we assumed that (1) different areas of China have the same epidemiology-based exposure-response functions and (2) people of China have the same purchasing power. Therefore, a model for calculating environmental costs of China was developed as follows:

$$C_T(t)=\sum_i\sum_j C_{i,j}(t), \tag{1}$$

$$C_{i,j}(t)=ECF_{i,j}(t)Q_{i,j}(t), \tag{2}$$

where C=environmental costs; ECF=environmental costs factor; Q=pollutant emissions; T=China; t=time; i=province; j=pollutant.

It is reported that the control costs of CO_2 are 19 USD/t (European Commission, 2003). So in this paper, we selected 19 USD/t as CO_2 environmental cost factor of China.

NO_x, SO_2, and PM_{10} environmental cost factors

Kypreos and Krakowski (2005) applied ExternE model and willingness to pay (WTP) method to estimate the environmental costs of Shandong coal electricity generation in 2003. Their results showed that the environmental costs factors of airborne pollutants are SO_2 7057 USD/t, NO_x 4579 USD/t and PM_{10} 5032 USD/t. In this work, the results of Kypreos's work were adopted as environmental costs factors and then extended to all over China according to population density. Therefore, provincial environmental cost factors can be calculated with Eq.(3):

$$ECF_{i,j}(t)=\frac{ECF_{\text{Shandong},j}(2003)D_i(t)}{D_{\text{Shandong}}(2003)}, \tag{3}$$

where D=population density.

According to Chinese statistical data, the population density of different provinces in the period of 2000 to 2003 is illustrated in Fig.2 (NBSC, 2001; 2002; 2003; 2004).

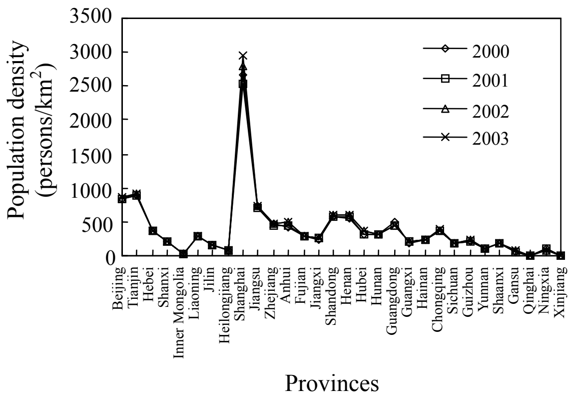

Fig.2 Population density of different provinces in China, 2000~2003

From Fig.2, we can see that the provinces or cities where the population density is always more than 500 persons/km^2 are Shanghai, Tianjin, Beijing, Jiangsu, Shandong, and Henan, in which are all important political, economical, and cultural centres in China. The provinces with relatively low population density are Qinghai, Xinjiang, Inner Mongolia, Gansu, Heilongjiang, and Ningxia. Most of these provinces are in Northern Region.

NO_x, SO_2, PM_{10} emission inventories

The emission inventory of SO_2 from fossil power plants in China can be calculated based on the following formula (Kato and Akimoto, 1992):

$$Q_i^{\text{S}}(t)=\sum_f Q_{i,f}^{\text{F}}(t), \tag{4}$$

$$Q_{i,f}^{\text{F}}(t)=K_{i,f}^{\text{S}}(t)F_{i,f}(t), \tag{5}$$

$$K_{i,f}^{\text{S}}(t)=2(1-P_{i,f}^{\text{S}}(t))(1-r_f^{\text{S}})S_{i,f}^{\text{N}}(t), \tag{6}$$

where Q^{S}=total SO_2 emissions; Q^{F}=SO_2 emissions from different fuels; K^{S}=emission factor of SO_2; F=fuel consumption; S=sulfur content; r^{S}=fraction of sulfur retained in ash; P^{S}=fraction of sulfur removed by pollution control; t=time; i=province; f=fuel type.

The emission inventory of NO_x from fossil power plants in China was calculated based on the following equation (Kato and Akimoto, 1992):

$$Q_i^{\text{N}}(t)=\sum_f Q_{i,f}^{\text{N}}(t), \tag{7}$$

$$Q_{i,f}^{\text{N}}(t)=(1-P_{i,f}^{\text{N}}(t))K_{i,f}^{\text{N}}(t)F_{i,f}(t), \tag{8}$$

where Q^{N}=NO_x emission calculated as NO_2; K^{N}=emission factor of NO_x weighed as NO_2; P^{N}=fraction of NO_x removed by pollution control. All other symbols are the same as those in Eqs.(4)~(6).

There were few emission controls for SO_2 and NO_x in China until 2004, so P^{S} and P^{N} in Eqs.(6) and (8) were set as zero.

Emission inventory of PM_{10} was calculated based on Eq.(9) (Zhang *et al.*, 2006):

$$E_i=\sum_{k,m} A_{i,k,m}ef_{i,k,m}, \tag{9}$$

where i=province; k=fuel type; m=technology;

E_i=PM_{10} emission in different provinces; A=quality of fuel use; ef=emission factor of PM_{10}.

In this paper, emission factors of SO_2 and NO_x of coal, diesel oil and natural gas from fired power plants were adopted by the one based on the data of uncontrolled facilities in developed countries in the mid 1970s (Kato and Akimoto, 1992). These emission factors are consistent with the combustion facilities in China in the 1990s. Considering the average sulfur content of coal and diesel oil in China is 0.85% (Wang, 2002) and 0.1% (Wang *et al.*, 1996) respectively, emission factors of SO_2 and NO_x of coal, diesel oil and natural gas from power plants are summarized in Table 1.

Table 1 Emission factors of SO_2, NO_x and PM_{10} of power plants

Fuel (unit)	Emission factors		
	SO_2	NO_x	PM_{10}
Coal (kg/t)	16.58	9.95	4.16
Diesel oil (kg/t)	4.00	27.40	2.08
Natural gas ($\times10^{-4}$ kg/m^3)	0.01	40.96	1.22

Emission factors of PM_{10} of coal from power plants are calculated based on Eq.(10) (Zhang *et al.*, 2006):

$$ef = EF_{\text{TSP}}\sum_n C_n(1-\eta_n), \tag{10}$$

$$EF_{\text{TSP}} = AC(1-ar), \tag{11}$$

where EF_{TSP}=coefficient of TSP emission; C=proportion of pollution control; n=type of pollution control; η_n=fraction of PM removed by pollution control; AC=ash in the coal; ar=proportion of ash coming from the bottom ash.

Most combustion facilities of fossil electricity generation in China are pulverized coal boilers, 88% of which can achieve 97% efficiency in removing the PM (Hu, 2005). Parameters of AC and ar in Eq.(11) were set to 25% and 20% (Zhang *et al.*, 2006).

Emission factors of PM_{10} of diesel oil and natural gas from power plants are referred from (Kuang *et al.*, 2001). Emission factors of PM_{10} of coal, diesel oil and natural gas from fossil electricity generation are listed in Table 1.

CO_2 emission inventory

CO_2 emission inventory of power plants was calculated based on the method adopted by the Intergovernmental Panel on Climate Change (IPCC, 1995):

$$F=F_{\text{b}}\times Q_{\text{L}}, \tag{12}$$

$$C_{\text{t}} = F\times EF_{\text{C}}, \tag{13}$$

$$S = C_{\text{t}}\times S_{\text{r}}, \tag{14}$$

$$E_{\text{n}} = C_{\text{t}} - S, \tag{15}$$

$$E_{\text{C}} = E_{\text{n}}\times O_{\text{C}}, \tag{16}$$

$$E_{\text{CO}_2} = E_{\text{C}}\times(44/12), \tag{17}$$

where F=fuel consumption; F_b=basic fuel consumption; Q_L=low calorific value; C_t=carbon content; EF_C=carbon emission factor; S=carbon stored; S_r=carbon stored ratio; E_n=net carbon emissions; E_C=actual carbon emissions; O_C=fraction of carbon oxidized; E_{CO_2} =actual CO_2 emissions.

Low calorific values of coal, diesel oil, and natural gas were adopted according to the China Energy Statistical Yearbook (DITSNBS, 1995). Carbon stored ratio refers to the proportion of the fuel by indirect-combustion in total fuel consumption. In this paper, fuel consumption is assumed to be direct combustion, so the carbon storage ratio is zero. Carbon emission factor and fraction of carbon oxidized of three fuels were set value based on the IPCC guidelines for national greenhouse gas inventories (IPCC, 1995). All parameters for estimating CO_2 emission factors are summarized in Table 2.

Table 2 Parameters in estimation of CO_2 emission inventory

Fuel	Q_L (kJ/kg)	EF_C (kg C/GJ)	O_C (%)
Coal	20934	25.8	91.8
Diesel oil	42705	20.2	98.0
Natural gas	38979 (kJ/m^3)	15.3	99.0

RESULTS AND DISCUSSION

Energy consumption of fired power plants in China

According to the official statistics (CEPC, 2001; 2002; 2003; 2004), China's energy consumption of fired power plants over 6000 kW has been growing rapidly during the past four years (Fig.3). Total coal consumption of fired power plants grew from 528.1×10^6 t in 2000 to 779.8×10^6 t in 2003 at annual average growth rate of 13.87%. Total diesel oil usage of power plants growing from 10.41×10^6 t in 2000 to 11.80×10^6 t in 2003 did not increase greatly. Meanwhile total natural gas of fired power stations increased from 15381.63×10^6 m^3 in 2000 to 31657.13×10^6 m^3 in 2003, at annual average growth rate of 27.2%. Provincial fossil fuel consumptions of electricity generation are shown in Fig.4.

It can be shown that there were notable differences among fuel consumption of provinces during the last 4 years. As can be seen from Fig.4a, fairly large coal consumption between 2000 and 2003 occurred in Shandong, Jiangsu, Hebei, Henan, Shanxi, Guangdong and Liaoning provinces, which are important economically developed provinces and prosperous coal mine areas. The sum of their coal consumption reached as high as 382.53×10^6 t in China in 2003, accounting for about 49.06% of the national total coal consumption. Fig.4b shows that the provinces and city where diesel oil consumption exceeds 1.0 million tons are Guangdong, Zhejiang, and Shanghai, which are economically developed areas. Their total diesel oil usage is 10 million tons, accounting for 83.73% of the national gross diesel oil usage. As compared with 2001 and 2002, diesel oil consumption of many provinces decreased in 2003. The decrease can be explained by the worldwide increase of diesel oil price. Fig.4c shows that the provinces and cities where the consumption of natural gas exceeded 1000×10^6 m^3 in 2003 are Shanghai, Beijing, Yunnan, Hebei, Inner Mongolia, Liaoning, and Xinjiang, accounting for 85.34% of national total natural gas consumption.

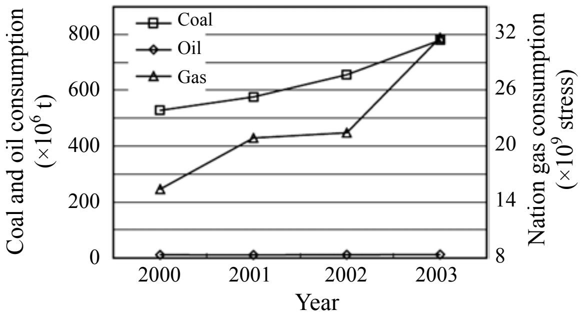

Fig.3 Coal, oil and gas consumption of fossil electricity generation in China, 2000~2003

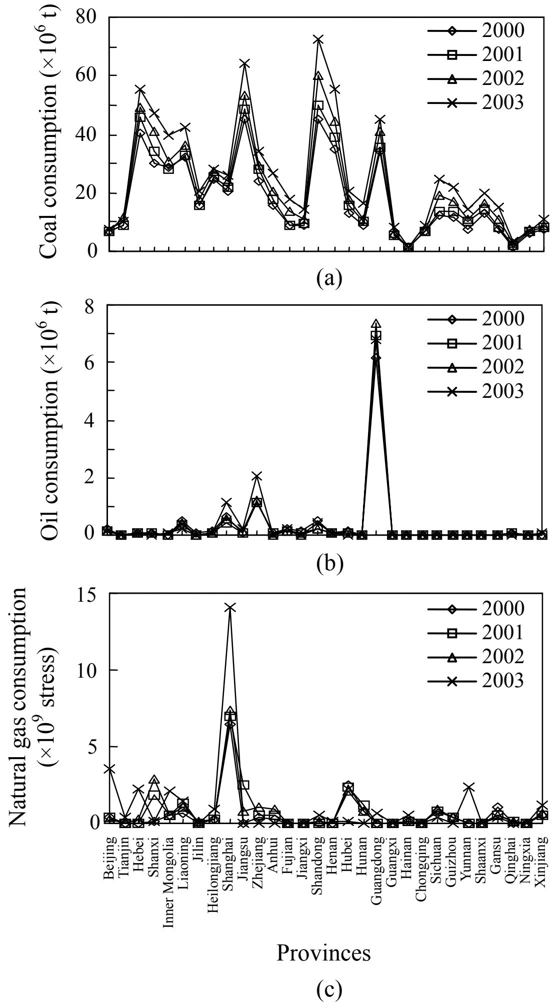

Fig.4 Provincial (a) coal, (b) oil and (c) natural gas consumption of fired power plants in China, 2000~2003

National gross airborne environmental costs from fired power stations

Based on provincial energy consumption (CEPC, 2001; 2002; 2003; 2004), provincial population density, and SO_2, NO_x, PM_{10} and CO_2 emission factors of fossil power plants, the national gross SO_2, NO_x, PM_{10} and CO_2 environmental costs of fossil electricity generation during the period from 2000 to 2003 were estimated as shown in Fig.5.

As shown in Fig.5, with the rapid growth of three types of fuel consumption, total airborne environmental costs from fossil electricity generation increased greatly, the gross environmental damage costs for the years 2000~2003 in China were 94390.87×10^6, 101292.54×10^6, 118435.88×10^6, and 141041.39×10^6 USD respectively, at annual growth rate of 14.11%. In

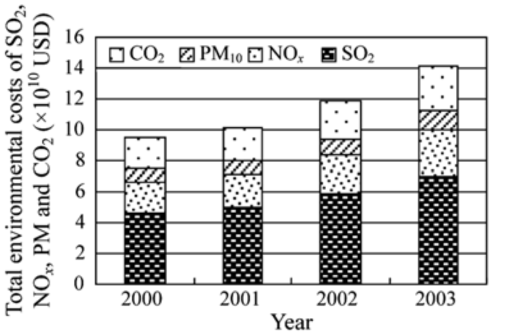

Fig.5 National gross airborne environmental costs from fossil power plants, 2000~2003

2003, the largest environmental cost was SO_2, which was 69475.69×10^6 USD, about 49.26% of total environmental costs. The second one is NO_x, 30079.29×10^6 USD, about 21.33% of total environmental costs. The third one is CO_2, 28931.84×10^6 USD, about 20.51% of total environmental costs. The last one is PM_{10}, 12554.57×10^6 USD, about 8.90%.

Provincial environmental costs of fossil electricity generation

Fossil fuel consumption of electricity generation in 30 provinces was combined with specific airborne emission and environmental costs factors to yield airborne environmental costs estimations at the provincial level. The provincial environmental costs of fired power plants airborne emissions from 2000 to 2003 are shown in Table 3.

Generally, the environmental costs grew steadily in most provinces from 2000 to 2003. The trend is very similar to that of the national level. In contrast, fossil electricity generation environmental costs in Beijing, Inner Mongolia, and Guangxi declined from 2000 to 2001 because of the decreasing of coal consumption. In the meantime, that of Guangdong and Ningxia declined because of the population density drop.

However, remarkable unevenness can be seen among provincial environmental costs of fossil electricity generation. In China's eastern and central provinces, environmental costs are much higher than those in the west, except for Sichuan, Guizhou, and Shaanxi, in which environmental costs are quite high. Between 2000 and 2003, environmental costs of Shanghai City and Jiangsu, Shandong, Henan, Guangdong, Hebei, Zhejiang exceeded 5000×10^6 USD in this period, most of which are located in the east and are traditional industry based or economically intensive and high population density areas. Meanwhile environmental costs in Qinghai, Hainan, Xinjiang, and Ningxia are much lower, at values less than 500×10^6 USD.

Interestingly, environmental costs from fossil fuel electricity generation in Shanghai are over eight times those in three other municipalities, i.e., Beijing, Tianjin, and Chongqing. It is mainly because of the much higher population density, although the fossil energy usage is not the highest as shown in Table 1 and Fig.6.

Table 3 Provincial environmental costs of annual airborne fossil electricity generation in China ($\times10^6$ USD)

Provinces or regions	Provincial environmental costs			
	2000	2001	2002	2003
Northern region	14681.25	15816.79	18144.87	20058.72
Beijing	2043.50	1919.49	2092.60	2418.17
Tianjin	2739.48	2794.74	3630.70	3318.04
Hebei	5736.23	6495.26	7004.71	8003.76
Shanxi	2966.40	3439.71	4119.00	4603.96
Inner Mongolia	1195.64	1167.59	1297.86	1714.79
Northeastern region	6766.47	6914.72	7479.14	8510.45
Liaoning	4054.90	4119.56	4431.10	5166.83
Jilin	1248.68	1252.38	1410.66	1616.40
Heilongjiang	1462.89	1542.78	1637.38	1727.22
Eastern region	48876.45	52019.05	61677.49	74814.44
Shanghai	18717.03	18906.37	22524.89	27090.96
Jiangsu	11446.49	12273.74	13881.08	16609.94
Zhejiang	4348.43	5026.80	5389.03	6424.86
Anhui	2643.81	3129.67	3796.08	4892.27
Fujian	1110.01	1113.96	1643.13	2169.45
Jiangxi	1025.33	1100.93	1283.36	1645.07
Shandong	9585.65	10467.58	13159.92	15981.89
Central and Southern	18008.44	19586.02	22748.71	27082.40
Henan	7017.62	8126.77	9657.60	12047.47
Hubei	1876.91	2226.42	2793.60	3075.69
Hunan	1155.90	1411.28	1460.78	2148.36
Guangdong	7323.89	7182.97	8079.98	8788.99
Guangxi	509.35	496.54	580.90	817.48
Hainan	124.77	142.04	175.85	204.41
Southwestern region	3694.07	4325.76	5315.30	6869.88
Chongqing	975.05	981.98	1021.40	1308.91
Sichuan	1110.54	1270.62	1752.52	2192.37
Guizhou	1100.01	1394.02	1765.10	2276.07
Yunnan	508.47	679.14	776.28	1092.53
Northwestern region	2363.86	2630.18	3070.37	3705.51
Shaanxi	1132.29	1290.74	1546.20	1863.77
Gansu	438.34	447.03	620.68	828.28
Qinghai	64.61	92.87	100.31	121.55
Ningxia	405.83	452.39	448.58	430.26
Xinjiang	322.79	347.15	354.60	461.65
China	94390.84	101292.52	118435.88	141041.40

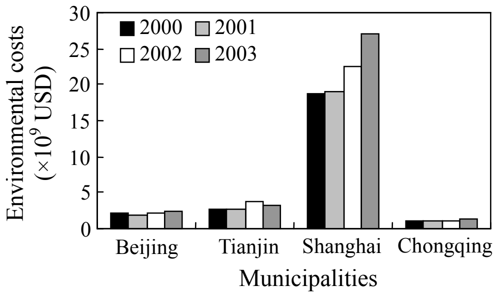

Fig.6 Environmental costs from fired plant station in four municipalities, 2000~2003

Fig.7 shows that fairly large SO_2, NO_x, and PM_{10} environmental costs between 2000 and 2003 occurred in Shanghai, Jiangsu, Shandong, Henan, Guangdong, Hebei, and Zhejiang, while Shanghai is the important municipality in large population density and others are all important provinces in fossil energy use. The sum of SO_2, NO_x, and PM_{10} environmental costs of above provinces in 2003 reached as high as 50017.45×10^6, 22296.32×10^6, and 9064.77×10^6 USD, accounting for about 71.99%, 74.13%, and 75.81% of the national total SO_2, NO_x, and PM_{10} environmental costs. It also shows that the fairly large CO_2 environmental costs between 2000 and 2003 can be attributed to Shandong, Jiangsu, Hebei, Guangdong, Henan, Shanxi, and Shanghai, which are all high in fossil fuel usage especially in natural gas. The total environmental costs of CO_2 of the above provinces in 2003 reached 13904.17×10^6 USD, accounting for 48.06% of the national total CO_2 environmental costs.

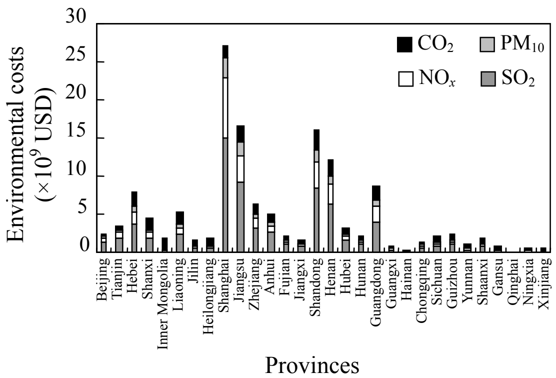

Fig.7 Composition of environmental costs in 2003

The environmental cost of CO_2 is the highest among the airborne emissions compared with SO_2, NO_x, and PM_{10} in ten provinces, namely Inner Mongolia, Heilongjiang, Sichuan, Jilin, Yunnan, Gansu, Xinjiang, Ningxia, Qinghai, and Hainan, most of which are all in low population density and high natural gas, low coal and low diesel oil consumption. On the other hand, among four pollutants, other provinces have the highest environmental costs of SO_2 because of the large use of coal and lack of abatement of SO_2 until the year 2003.

Analysis of uncertainties

Results of this work depend on basic framing assumptions that are based on the model and data value choices. We discuss indications of the uncertainty and the sensitivity of results to some key assumptions. Uncertainty for environmental damage costs of Chinese fossil fired power stations is dominated by three parameters that are not generally taken into account: emission inventories, environmental damage costs factors, and income levels.

Because there are no integrated emission factors for coal, diesel oil and natural gas of fired power plants in China, emission factors of SO_2, NO_x, and PM_{10} used in this paper were from the work of Kato and Akimoto (1992) and Kuang *et al.*(2001) that are for Western developed countries. Furthermore, based on some field-test results in Beijing, the NO_x emission factors of coal may be overestimated somewhat (Hao *et al.*, 2002). So, there may be an uncertainty of emission factors selection. Emission inventory of SO_2 is also linked to sulfur content of fossil fuels. In China, sulfur content of diesel oil and natural gas is relatively consistent, while coal from different provinces has different sulfur content ranging from 0.4%~3.5%. On the other hand, SO_2 emission comes mostly from coal-fired power plants and accounts for 99.6% of that from total fossil fired power plants. Average sulfur content (0.85%) of coal issued by China's official statistics was adopted in this work. Therefore, there may exist bias of sulfur content. Emission inventories are also related to degree of pollutants controls. In this paper, we assumed that there are no fossil fired power stations equipped with any SO_2 and NO_x abatement facility by the end of 2003 (Xu, 2005); however, it is possible slight percentage of fired power plants have simple abatement measures. For SO_2, by the end of 2003, power plants installed capacity of 9000 MW in China were equipped with SO_2 control facilities and half of them being new or under construction, but they shared only 3.2% of total installed capacity. Although efforts to decrease NO_x

emissions may not be as effective as reducing SO_2 emissions, recently, low NO_x burning technologies have been employed in an increasing number by fired power plants in China in order to reduce NO_x emissions. As efficiency of PM abatement adopted may be lower than average value, emission inventories of SO_2, NO_x and PM_{10} may be overestimated.

CO_2 emission inventory is associated with carbon storage ratio set to zero in this paper, so it may cause overestimation of CO_2 emission inventory. Generally, carbon content of fossil fuel is variable and is not a constant, a big difference of carbon content can also exist in the same fuel. For this reason, the unified carbon content used in this paper may result in the imprecise evaluation of CO_2 emissions (Yang and Liu, 2001). On the other hand, fraction of carbon oxidized used in this study was based on the IPCC and could not be traced back to a specific study. However, the country-specific values are known to differ to some extent, especially for coal (Olivier and Peters, 2005). Combustion equipment of fired power plans in China is behind that of western developed countries, incomplete combustion enables the fraction of carbon oxidized not to achieve the level of IPCC (Zhang *et al.*, 2001). Aspects mentioned above may cause uncertainties in emission inventory of CO_2.

Environmental damage costs factors of SO_2, NO_x and PM_{10} are related to dose-response models based on the results from epidemiological studies, whereas dose-response models have uncertainties due to unknown driving force of health effects from various pollutants. The uncertainty resulting is difficult to estimate because of lack of knowledge (Krewitt *et al.*, 1999). The costs of CO_2 emission control vary depending on the emission abatement measures adopted. In China, emission control relying on high carbon fuels and inefficient energy use is cheaper than other countries which have shifted away from carbon intensive fuels (Chae and Hope, 2003). It is reported that environmental damage costs factor of CO_2 is about 18~46 USD/t (European Commission, 2003). We adopted CO_2 control costs factor as external costs factor according to the Chinese situation. As the estimation of CO_2 environmental damage costs amounts to part of the total quantified costs, the value may therefore be underestimated.

We treat the study site (Shandong Province) as willingness to pay (WTP) for estimates and the target site (national level) as not being able to extend the result although it has the same income level because of lack of WTP data at national level. However, there are big differences among provinces. Shanghai has the highest income level, about 2047.53 USD in 2003, while that of Guizhou is lower and is about 255.94 USD. Although income level of Shandong is a little above the middle, about 1132.20 USD (NBSC, 2004), it is not the value of national WTP. Therefore there must be an uncertainty in this field.

CONCLUSION

A method of estimating environmental damage costs of higher level of aggregation was developed. With this method, an estimate of environmental damage costs of fossil fired power plants was carried out in China during the years of 2000 to 2003. Three types of fossil fuels (coal, diesel oil and natural gas) and four pollutants (SO_2, NO_x, PM_{10}, and CO_2) were selected. The gross environmental damage costs from fossil fired power plants for the years of 2000~2003 in China are 94390.87×10^6, 101292.54×10^6, 118435.88×10^6, and 141041.39×10^6 USD respectively, with annual increasing of 14.11%. The environmental costs of SO_2, NO_x, PM_{10}, and CO_2 in 2003 are 69475.69×10^6, 30079.29×10^6, 12554.57×10^6, and 28931.84×10^6 USD, accounting for total national environmental costs 49.26%, 21.33%, 8.90%, and 20.51% respectively.

The analysis of provincial damage costs shows a large variance of environmental costs between different provinces. Eastern and central provinces environmental costs are much higher than those in the west. Between 2000 and 2003, environmental costs of Shanghai City and top six provinces (Jiangsu, Shandong, Henan, Guangdong, Hebei and Zhejiang), exceeded 5000×10^6 USD in this period, most of which are located in the east and are traditional industry based or economically intensive, and high population density areas in China. A comparison of environmental costs among four municipalities shows that Shanghai has eight times environmental damage costs higher than the other three municipalities.

The environmental cost of CO_2 is the highest among the airborne emissions compared with SO_2, NO_x, and PM_{10} in ten provinces, namely Inner Mongolia, Heilongjiang, Sichuan, Jilin, Yunnan, Gansu, Xinjiang, Ningxia, Qinghai, and Hainan. On the other hand, among four pollutants, other provinces have the highest environmental costs of SO_2.

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