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Reducing mercury emissions from coal combustion in the energy sector

Prepared for:

The Ministry of Environment Protection of China

and

UNEP Chemicals

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Disclaimer

Based on the agreement between United Nations Environment Programme (UNEP) and Ministry of Environment Protection of China (MEP), UNEP agreed to co-operate with MEP with respect to the project entitled: "Reducing mercury emissions from coal combustion in the energy sector" in China. Tsinghua University and China Electricity Council have been subcontracted by MEP to execute the project and the report is made on this basis. Due to the limited time and budget, the results from this study are subject to high uncertainties. The contents, terms used and statements made in this report do not reflect the official views and policies of UNEP or Chinese government. Due to the lack of data, Hong Kong, Macao and Taiwan are not included in the report.

This report has been developed as a part of the above mentioned project for UNEP Chemicals Branch, Division of Technology, Industry and Economics.

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1. Introduction

1.1. Background

Mercury is a hazardous chemical damaging to human health and the environment. Mercury is highly toxic in most of its chemical forms. It is also persistent, which means that it does not degrade or transform, and it is biomagnifying, meaning that it accumulates to higher concentrations in the food chain. Mercury is a global pollutant and can be found in the environment all over the globe, even in regions very far from any emission source.

The United National Environment Programme (UNEP) has regarded mercury as a global pollutant. At its twenty-fifth session in February 2009, the General Council (GC) decided to commence an Intergovernmental Negotiating Committee (INC) and prepare a global, legally-binding instrument on mercury. Because of these decisions, UNEP initiated the mercury emission background study which includes the current and future trends in mercury emissions, and the alternative mercury control technologies and measures. As part of the background study, the project entitled “Reducing mercury emissions from coal combustion in the energy sector” focused on China, India, Russia and South Africa, and aimed to develop guidance materials, the Process Optimization Guidance (POG) Document, to reduce mercury emissions from coal combustion, and improve mercury emission inventories and related information.

In November 2009, UNEP and Ministry of Environment Protection of China (MEP) signed the agreement to co-operate with respect to the project entitled “Reducing mercury emissions from coal combustion in the energy sector” in China. Tsinghua University and China Electricity Council have been subcontracted by MEP to execute the project.

In this project, information on coal used and status of air pollution control in Chinese power plants were collected. Coal samples from selected coal mines and power plants were analyzed with regard to mercury content. To the extent possible, information on measurements of mercury in stack flue gases were collected from literature. The information collected was used to develop an inventory of mercury emissions from coal-fired power plants in China. Future mercury emissions were estimated based on the status quo and emission control implementation scenario.

1.2. Major tasks

The major tasks of this project are as follows,

(1) Coal information

Collect available information on: the amount of coal consumed for electricity production by coal classification; available information on coal analysis, including Hg, Cl, and Br content.

Collect available information or estimate the coal consumption (projected coal use) for electricity generation for the target year 2020.

Analyze coal samples. Develop a coal sampling plan and analyze the coal samples. Analyses include ultimate and proximate analysis; including water, ash, volatile matter, Hg, Cl and Br content. Provide a summary report setting out the analytical results for each coal type analyzed, together with information on the laboratory and analytical procedures used and quality assurance assessment of the results.

(2) Power plant information:

Collect available national and provincial information on installed power plant capacity and electricity generation by coal combustion in 2008;

Collect available information on the installed configuration of any air-pollution control equipment and its typical operational efficiency by pollutant (PM, SO_2, NO_X, and Hg);

Collect information on any available results of measurements of Hg emissions from power plants.

(3) Develop improved mercury emissions factors

Develop example emission factors based on data sets from selected power plants which have as complete datasets as possible (including coal characteristics, air pollution control device configuration and actual stack measurements as available) identified in literature. Analyze the fate of mercury during coal combustion and the removal efficiency of air pollution control devices.

(4) Develop the mercury emission inventory and analyze its uncertainty

Develop the mercury emission inventory based on results from the above tasks (coal use, power plant information, and emissions factors). Develop an uncertainty analysis model for mercury emissions from coal-fired power plants and analyze the uncertainty of mercury emission inventories

(5) Distribute the report on the improved emission inventories to the national experts and stakeholders for comments.

(6) Develop future mercury emission estimates based on the status quo and mercury control implementation scenario.

1.3. Methods

In this project, literature review, sample survey, and modeling analysis were used to calculate mercury emissions from coal-fired power plants in China.

Most of the information, including the installed capacity, electricity generation, amount of coal consumption of coal-fired power plants, the installed configuration of air pollution control equipment and its typical operational efficiency, mercury emission factors and mercury removal efficiency of air pollution control devices (APCDs) in power plants, were collected through literature review and mainly cited from statistical yearbooks, annual reports of power sector, and published journal articles.

The coal quality information, including mercury and halogen contents, were determined through both literature review and sample analysis. In this study, 177 coal samples from coal mines in 15 provinces were analyzed to give their water, ash, volatile matter, Hg, Cl and Br content. However, considering there are over 10000 coal mines in China, the coal sampled in this project is very limited.

Considering that the mercury concentrations in coal and mercury removal efficiency have large variations, a probabilistic emission factor model was developed and Monte-Carlo method was employed to assess the mercury emission from coal-fired power plants in China.

The coal sampled in this project is limited by time and budget, and therefore cannot give a full picture of the mercury content and quality of coal in China. Besides, the data on mercury emissions from Chinese power plants given by literature are still rare and this project was not able to measure the mercury emission factors in typical power plants. Therefore, the results from this project are still subject to high uncertainties.

2. Coal Consumption and Quality in China

2.1. Coal consumption for electricity production

The coal consumption for power sector in China has been growing rapidly since 2000 (see **Figure 1**). From 2000 to 2008, the total amount has grown by 150% with an annual increasing rate of 12%. Nevertheless, the standard coal consumption rate had a significant decrease of 47 g/kWh.

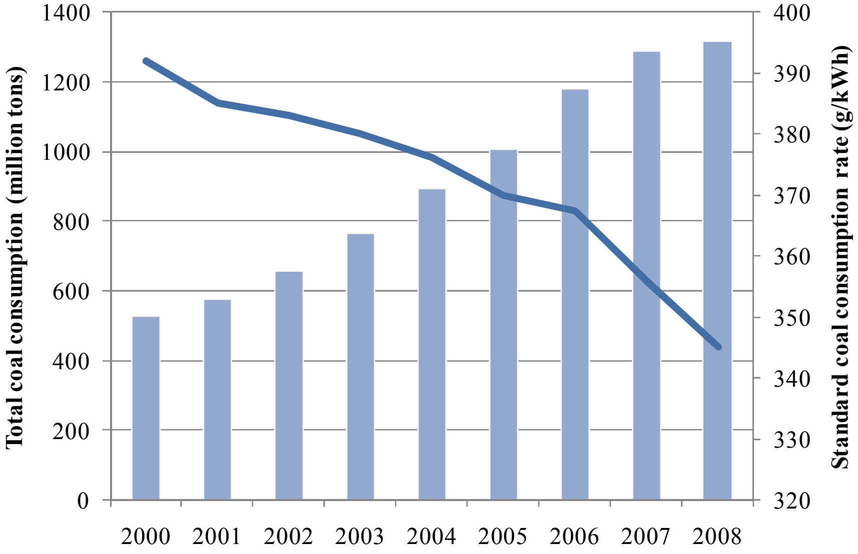

Figure 1 Trends of total coal consumption and standard coal consumption rate for the power sector in China from 2000 to 2008

(Data source: China Electricity Council, Annual Development Report for Chinese Electricity Power Sector, 2006-2009)

The total coal consumption for Chinese electricity production in 2005 was 1009 million tons. The figure for 2008 was 1319 million tons which accounted for 52.4% of the total coal consumption (2793 million tons) in China. **Figure 2** shows the coal consumption for Chinese power sector by province in 2005 and 2008. Inner Mongolia, Shandong and Jiangsu were the top three consumers whose coal consumption were over 100 million tons.

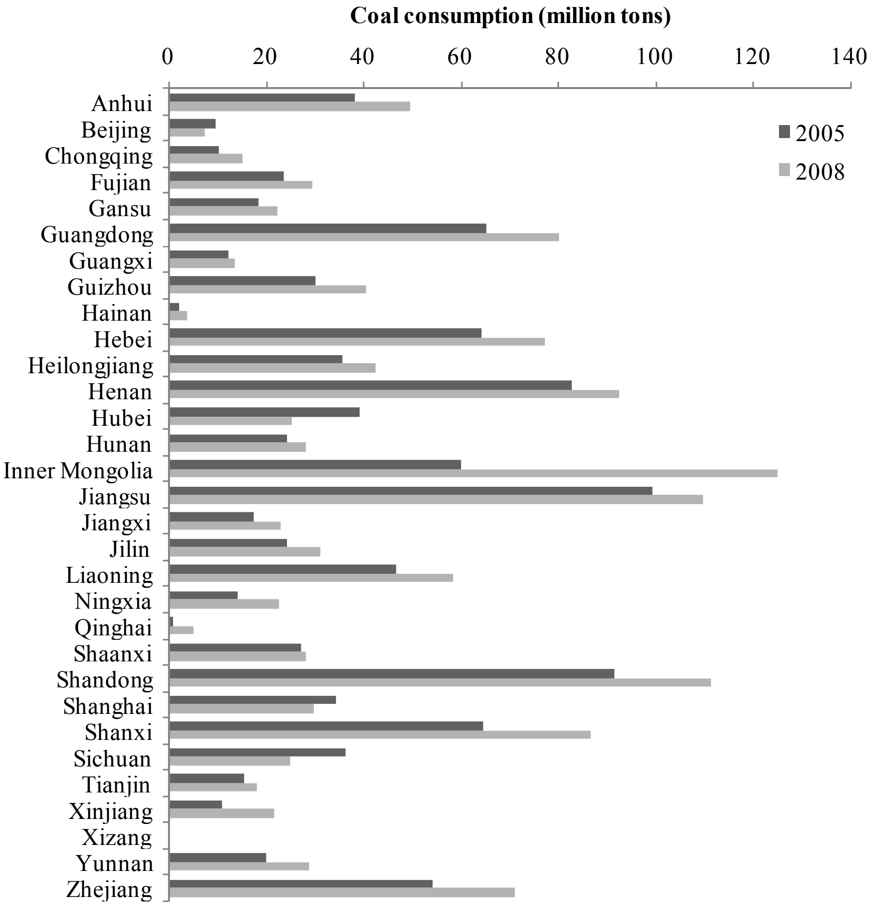

Figure 2 Coal consumption for electricity production in China

(Data source: China Electricity Council, Annual Development Report for Chinese Electricity Power Sector, 2006-2009)

2.2. Existing information on analysis of Chinese coal

The key parameter for the mercury emission factor is the mercury content of coal. Literature review was conducted on the mercury content of coal in China and summarized as **Table 1**. Ren et al. (2006) summarized information of 619 samples and calculated the national average mercury content of coal in China, which was 0.33 mg/kg. USGS (2004) analyzed 305 coal samples in China and gave an average mercury content of 0.16 mg/kg. Based on data from USGS and other studies, Streets et al. (2005) estimated the mercury content of Chinese coal by province, and gave a value of 0.19 mg/kg for the average mercury content of raw coal in China.

Table 1 Mercury content of raw coal in China given by literature (mg/kg)

	Zheng et al. (2007)	Zheng et al. (2007)	Ren et al. (2006)	Streets et al. (2005)	USGS (2004)	ITPE (2003)	Huang & Yang (2002)	Wang et al. (2000)	Zhang et al. (1999)	Ni et al. (1998)
Anhui	0.21	0.26(29)	0.46(50)	0.26	0.19(11)	0.37	0.26	0.22		
Beijing	0.34		0.10(1)	0.44	0.55(1)			0.34		
Chongqing			0.64(12)		0.15(7)					
Fujian				0.08	0.07(3)	0.08				
Gansu			1.35(1)	0.05	0.05(5)					
Guangdong			0.10(1)	0.15	0.06(2)	0.25				
Guangxi				0.30	0.35(5)	0.28				
Guizhou	1.14		0.70(133)	0.52	0.20(16)	0.14	0.52		0.55	0.5
Hainan				0.15						
Hebei	0.46		0.16(33)	0.14	0.14(15)		0.8	0.13		
Heilongjiang	0.13		0.12(14)	0.09	0.06(10)		0.14	0.12		
Henan	0.17	0.57(1)	0.14(115)	0.25	0.21(27)	0.32	0.17	0.3		
Hubei			0.23(1)	0.16	0.16(3)					
Hunan	0.07		0.08(14)	0.10	0.14(10)		0.07			
Inner Mongolia	0.16	0.19(4)	0.17(14)	0.22	0.16(16)	0.63	0.02	0.28		
Jiangsu	0.09		0.18(10)	0.16	0.35(6)	0.04	0.09			
Jiangxi	0.16		0.13(4)	0.22	0.27(7)			0.16		
Jilin	0.34		0.34(2)	0.20	0.07(5)			0.33		
Liaoning	0.17	0.23(1)	0.14(16)	0.17	0.19(9)		0.13	0.2		
Ningxia			0.28(19)	0.20	0.21(4)					
Qinghai			0.31(4)	0.04	0.04(1)					
Shaanxi	0.64		0.30(3)	0.11	0.14(11)	0.07	0.08	0.16		
Shandong	0.28	0.37(22)	0.18(11)	0.18	0.13(19)	0.22	0.21	0.17		
Shanghai										
Shanxi	0.08	0.17(4)	0.17(79)	0.16	0.15(88)	0.07	0.2	0.22	0.16	
Sichuan	0.18		0.35(14)	0.14	0.09(11)					
Tianjin								0.18		
Xinjiang	0.03		0.09(6)	0.02	0.03(6)					
Xizang								0.03		
Yunnan	0.30	0.3(1)	0.32(56)	0.29	0.14(7)		0.34		0.38	
Zhejiang			0.75(2)	0.35		0.35				
National Average	**0.19**		**0.33(619)**	**0.19**	**0.16(305)**		**0.15**	**0.22**	**0.16**	

As shown in Table 1, the mercury content of the coal from Guizhou, Gansu, Zhejiang, Chongqing, Yunnan and Hebei is over 0.3 mg/kg. There are more coal samples from Guizhou, Hebei, Inner Mongolia, and less coal samples from Gansu, Chongqing, Zhejiang and Shaanxi province. For most of these provinces, the mercury contents of coal given by different researchers vary at a large range.

In addition, there are about 1.5% of the coal burned in China are imported from other countries. **Table 2** gives the mercury content of coal produced by some countries, among which Vietnam, Indonesia, Mongolia, and Australia are major coal suppliers to China.

Table 2 Mercury content of raw coal from other countries (mg/kg)

Country	Coal type	Mercury in coal	Range	Reference
Australia	Bituminous	0.215	0.03-0.4	Pirrone et al., 2001
Argentina	Bituminous	0.1	0.03-0.18 (2)	Finkelman, 2004
Botswana	Bituminous	0.09	0.04-0.15 (11)	Finkelman, 2004
Brazil	Bituminous	0.19	0.04-0.67 (4)	Finkelman, 2004
Colombia	Subbituminous	0.04	>0.02-0.17 (16)	Finkelman, 2004
Czech Rep.	Bituminous	0.25	<0.02-0.73 (24)	Finkelman, 2003
Egypt	Bituminous	0.12	0.04-0.36 (14)	Finkelman, 2003
Germany	Bituminous		0.7-1.4	Pirrone et al., 2001
Indonesia	Lignite	0.11	0.02-0.19 (8)	Finkelman, 2003
	Subbituminous	0.03	0.01-0.05 (78)	US EPA, 2002
Japan	Bituminous		0.03-0.1	Pirrone et al., 2001
New Zealand	Bituminous	0.31	0.02-0.6	Pirrone et al., 2001
Peru	Anth.+Bit.	0.27	0.04-0.63 (15)	Finkelman, 2004
Philippines	Subbituminous	0.04	<0.04-0.1	Finkelman, 2004
Poland	Bituminous		0.01-1.0	Pirrone et al., 2001
Romania	Lig.+Subbit.	0.21	0.07-0.46 (11)	Finkelman, 2004
Russia	Bituminous	0.11	<0.02-0.84 (23)	Finkelman, 2003
Slovak Rep.	Bituminous	0.08	0.03-0.13 (7)	Finkelman, 2004
South Africa	Bituminous		0.01-1.0	Pirrone et al., 2001
South America	Bituminous	0.08	0.01-0.95 (269)	US EPA, 2002
Tanzania	Bituminous	0.12	0.04-0.22 (15)	Finkelman, 2004
Thailand	Lignite	0.12	0.02-0.57 (11)	Finkelman, 2003
Turkey	Lignite	0.11	0.03-0.66 (143)	Finkelman, 2004
Ukraine	Bituminous	0.07	0.02-0.19 (12)	Finkelman, 2003
United Kingdom	Bituminous		0.2-0.7	Pirrone et al., 2001
USA	Subbituminous	0.1	0.01-8.0 (640)	US EPA, 1997
	Lignite	0.15	0.03-1.0 (183)	US EPA, 1997
	Bituminous	0.21	<0.01-3.3 (3527)	US EPA, 1997
	Anthracite	0.23	0.16-0.30 (52)	US EPA, 1997
Vietnam	Anthracite	0.28	<0.02-0-14 (3)	Finkelman, 2004
Zambia	Bituminous	0.6	<0.03-3.6 (12)	Finkelman, 2004
Zimbabwe	Bituminous	0.08	<0.03-0.5 (3)	Finkelman, 2004
Yugoslavia	Lignite	0.11	0.07-0.14 (3)	Finkelman, 2004

Considering that the halogen content of coal is an important factor affecting mercury speciation, transformation and emission in the flue gas, the information on chlorine content in Chinese coal were also collected, as shown in **Table 3**. According to the data give by USGS (2004), the average chlorine content of the coal in China is 436 mg/kg, lower than that in American coal, which is 628 mg/kg. Coal from Liaoning, Chongqing, Jiangxi and Shaanxi has a chlorine content of over 500 mg/kg.

Studies on the bromine content of coal were quite rare. Zhao et al. (2002) summarized the results of 271 coal samples in China and gave a national average as 9 ppm. The mean values for North and South China were 12 ppm and 8 ppm, respectively. Vassileva et al. (2000) reported that the bromine content in a coal sample from Shanxi province was 13 ppm. The chlorine and bromine content of coals from other countries was also reported in their study (see **Table 4**)

Table 3 Chlorine content of raw coal in China given by literature (mg/kg)

	USGS (2004)	Tang & Chen(2002)		USGS (2004)	Tang & Chen(2002)
Anhui	585(11)	238(19)	Jiangxi	608(7)	
Beijing	160(1)	325(2)	Jilin	324(5)	
Chongqing	700(7)		Liaoning	271(9)	772(4)
Fujian	211(3)		Ningxia	546(4)	85(28)
Gansu	248(5)		Qinghai	170(1)	
Guangdong	162(2)		Shaanxi	1132(11)	633(27)
Guangxi	166(5)	219(5)	Shandong	392(19)	293(51)
Guizhou	251(16)	195(3)	Shanghai		
Hainan			Shanxi	361(88)	426(90)
Hebei	749(15)	167(3)	Sichuan	478(11)	
Heilongjiang	402(10)		Tianjin		
Henan	500(27)	92(6)	Xinjiang	392(6)	
Hubei	160(3)		Xizang		
Hunan	558(10)	285(9)	Yunnan	196(7)	49(4)
Inner Mongolia	435(16)	516(11)	Zhejiang		
Jiangsu	235(6)	280(7)	**Average**	**436(305)**	**350(269)**

Table 4 Chlorine and bromine content of coals from other countries (mg/kg)

	Cl concentration	Br concentration	No. of samples
Bulgaria	154	529	7
Australia	445	18	8
USA	229	9	7
Japan	325	8	6
Canada	233	11	3
South Africa	260	6	1
Ukraine	500	1620	1

2.3. Coal sampling and analysis

2.3.1. Distribution of coal samples

In this study, 177 samples were collected from coal mines in 15 provinces, including Inner Mongolia, Shaanxi, Shandong, Henan, Hebei, Heilongjiang, Liaoning, Guizhou, Yunnan, Sichuan, Chongqing, Xinjiang, Gansu, Anhui and Jiangsu. **Figure 3** shows the locations of sampled coal mines in this study (red dots) and in the USGS database (grey dots).

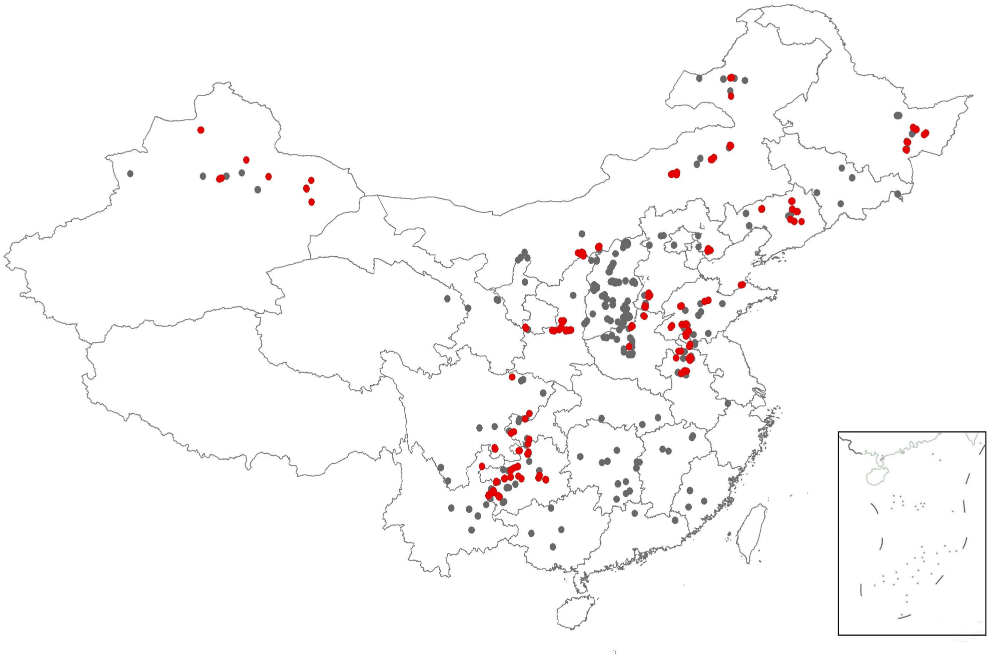

Figure 3 Locations of all the sampled coal mines in this study

Besides, 65 coal samples from 23 power plants in China were also collected and analyzed.

2.3.2. Coal sampling and preparation method

ISO 18283-2006 (Hard Coal and Coke – Manual Sampling) and ASTM D4596-09 (Standard Practice for Collection of Channel Samples of Coal in a Mine) were used for coal sampling. Stockpile Random Sampling (SRS) and Loader Random Sampling (LRS) were adopted in this study. In SRS method, the surface of the stockpiles is divided into a certain amount of zones based on the shape and scale of the stockpile, and coal is randomly sampled from each of these zones. In LRS method, samples are randomly collected from the coal loader such as train or truck fleet. The weathered layer, from the coal surface to 0.4–0.5 cm depth, is removed before sampling. The sampling spots are at least 10 meters away from each other. At each sampling spot, 0.5 kg of subsample is collected. Twenty sampling spots are required for subsample collecting. These subsamples were blended to make one valid sample.

Sample preparation referred to ASTM D2013-03 (Standard Practice for Preparing Coal Samples for Analysis). The samples were first air dried to constant weight, and then pulverized into 80 meshes (200 μm in diameter).

2.3.3. Coal analysis methods

Table 5 gives the methods used for coal analysis in this project.

Table 5 Coal analysis method

Item	Method	Reference
Proximate analysis		GB/T 212-2001
Moisture	Air Drying	
Ash	Slow Ashing	
Volatile	Thermostatic Firing	
Fixed Carbon	Calculation	
Calorific value	Oxygen Bomb Calorimeter	GB/T 213-1996
Ultimate analysis		ASTM D5373-2008
Carbon	Carbon Dioxide Absorption	
Hydrogen	Water Absorption	
Nitrogen	Pyrolysis and Titration	
Oxygen	Calculation	
Sulfur	Pyrolysis and Coulometry	GB/T 214-2007
Mercury	Direct Combustion and CVAAS	ASTM D6722-2001
Chlorine	Hydrolysis and Potentiometry	GB/T 3558-1996
Bromine	Photoelectric Colorimetry	

2.4. Results of coal analyses

2.4.1. Proximate and ultimate analysis of raw coal samples

Table 6 shows the results from proximate and ultimate analysis of the sampled coals. Most coal burned in China is bituminous coal or sub-bituminous coal.

Table 6 Results from proximate and ultimate analysis of the sampled coals

Item	Coal type	Number of samples	Mean	Min	Max
M_{ad} (%)	Bituminous	25	4.37	0.39	15.71
	Subbituminous	87	4.88	0.38	19.71
	Anthracite	34	1.43	0.51	4.49
	Lignite	31	4.59	0.34	17.80
A_d (%)	Bituminous	25	10.38	5.68	21.88
	Subbituminous	87	25.14	8.16	38.97
	Anthracite	34	24.90	7.85	58.04
	Lignite	31	43.89	30.80	61.81
V_{daf} (%)	Bituminous	25	32.81	17.42	42.12
	Subbituminous	87	35.95	17.88	51.12
	Anthracite	34	11.90	6.65	16.81
	Lignite	31	39.77	18.48	51.45
FC_d (%)	Bituminous	25	60.03	51.09	68.94
	Subbituminous	87	47.76	34.83	62.44
	Anthracite	34	66.44	35.59	83.67
	Lignite	31	33.66	20.55	43.25
$Q_{net,d}$ (MJ/kg)	Bituminous	25	29.11	26.94	31.87
	Subbituminous	87	23.17	19.47	26.78
	Anthracite	34	25.51	12.95	32.75
	Lignite	31	16.14	8.24	19.19
C_d (%)	Bituminous	25	74.60	67.17	80.39
	Subbituminous	87	60.17	48.84	69.79
	Anthracite	34	67.58	36.85	83.79
	Lignite	31	43.80	30.88	51.02
H_d (%)	Bituminous	25	4.36	3.20	5.05
	Subbituminous	87	3.65	2.17	4.61
	Anthracite	34	2.70	0.90	3.79
	Lignite	31	2.85	1.66	3.61
N_d (%)	Bituminous	25	1.08	0.68	1.51
	Subbituminous	87	0.94	0.47	1.53
	Anthracite	34	0.94	0.50	1.42
	Lignite	31	0.70	0.39	0.97
O_d (%)	Bituminous	25	8.90	2.21	14.37
	Subbituminous	87	9.06	0.91	20.00
	Anthracite	34	2.51	0.43	5.01
	Lignite	31	7.12	0.25	13.72
$S_{t,d}$ (%)	Bituminous	25	0.69	0.25	1.95
	Subbituminous	87	1.05	0.04	9.33
	Anthracite	34	1.37	0.15	5.34
	Lignite	31	1.64	0.11	7.19

2.4.2. Mercury contents in raw coal samples

The results from the 177 samples show that the mercury contents of bituminous, subbituminous and anthracite coal are 0.147 mg/kg, 0.145 mg/kg and 0.150 mg/kg, respectively. However, the mercury content of lignite coal is 0.280 mg/kg, which is higher than that of other coal types.

The mercury contents of coal from Guizhou, Inner Mongolia and Shaanxi vary at a broad range. Guizhou, as the famous mercury mining area in China, has attracted great attention on the mercury content of coal. The average mercury content of caol sampled from Guizhou in this study is 0.213 mg/kg, which is at the same level as that given by USGS (0.20 mg/kg), but much lower than that given by Zheng et al. (2007a) and Ren et al. (2006).

Table 7 Mercury in Chinese raw coals (mg/kg)

Coal type	Number of coal samples	Min	Max	Mean
Bituminous	25	0.009	1.134	0.147
Subbituminous	87	0.008	2.248	0.145
Anthracite	34	0.009	0.541	0.150
Lignite	31	0.030	1.527	0.280

2.4.3. Halogen contents in raw coal samples

Among the 177 samples, only one sample has high chlorine concentration (3000 mg/kg), there are 10 samples with low chlorine concentration (500~1500 mg/kg), and the rest are with even lower chlorine concentration (< 500 mg/kg). The average chlorine content of the 177 coal samples in this study is 269 mg/kg, at the same level as given by from Ren et al. (2006). The chlorine contents of bituminous, sub-bituminous and anthracite coal are 292 mg/kg, 273 mg/kg and 269 mg/kg, respectively. Lignite has a lower chlorine content, 186 mg/kg.

Compared to chlorine contents, there is less variation among the bromine contents of coal sampled in this study. The average bromine content of the 177 coal samples is 54 mg/kg, within the range of those values given for Chinese coal in literature (0.5~70ppm).

The method used in this study was photoelectric colorimetry. To further confirm the accuracy of this method, we are developing a new analytical system based on ASTM D7359-08 for bromine analysis. It will take some time to get the samples analyzed and make the comparison of different methods.

Table 8 Halogen in Chinese raw coals (mg/kg)

Coal type	No.	Cl			Br		
		Min	Max	Mean	Min	Max	Mean
Bituminous	25	60	720	292	32	85	55
Subbituminous	87	30	3280	273	21	105	55
Anthracite	34	70	780	269	22	98	51
Lignite	31	40	370	186	29	92	55

2.5. Analytical results of coal samples from power plants

2.5.1. Proximate and ultimate analysis of coal samples from power plants

Table 9 shows the results of proximate and ultimate analysis for coal sampled from power plants. The dominant coal type of these samples is also bituminous or subbituminous. The anthracite coal has a sulfur content of over 2%.

Table 9 Proximate and ultimate analysis of coal sampled from power plants

Item	Coal type	Number of samples	Mean	Min	Max
M_{ad} (%)	Bituminous	10	6.80	1.32	10.00
	Subbituminous	33	5.52	0.95	18.07
	Anthracite	14	1.33	0.75	2.03
	Lignite	8	2.42	1.07	8.70
A_d (%)	Bituminous	10	13.57	7.79	36.82
	Subbituminous	33	23.31	12.70	38.22
	Anthracite	14	28.90	10.38	35.55
	Lignite	8	43.20	39.62	47.33
V_{daf} (%)	Bituminous	10	35.74	23.19	47.97
	Subbituminous	33	33.47	17.24	49.73
	Anthracite	14	14.83	11.00	16.71
	Lignite	8	30.09	19.62	54.88
FC_d (%)	Bituminous	10	55.20	46.66	60.43
	Subbituminous	33	50.57	38.16	58.79
	Anthracite	14	60.61	54.28	77.22
	Lignite	8	39.72	24.53	47.22
$Q_{net,d}$ (MJ/kg)	Bituminous	10	27.59	26.80	28.95
	Subbituminous	33	23.71	19.94	26.63

	Anthracite	14	23.68	20.91	31.16
	Lignite	8	17.21	14.11	19.24
C_d (%)	Bituminous	10	69.54	55.99	74.99
	Subbituminous	33	62.35	51.55	70.46
	Anthracite	14	62.27	53.88	80.86
	Lignite	8	46.54	38.04	50.84
H_d (%)	Bituminous	10	4.15	3.12	5.16
	Subbituminous	33	3.66	2.78	4.99
	Anthracite	14	2.90	2.53	3.76
	Lignite	8	2.83	2.34	3.58
N_d (%)	Bituminous	10	0.97	0.69	1.57
	Subbituminous	33	0.86	0.72	1.10
	Anthracite	14	0.99	0.86	1.30
	Lignite	8	0.75	0.56	1.01
O_d (%)	Bituminous	10	11.24	2.36	18.10
	Subbituminous	33	8.50	1.49	12.90
	Anthracite	14	2.23	1.34	3.26
	Lignite	8	5.38	1.66	11.98
$S_{t,d}$ (%)	Bituminous	10	0.53	0.35	0.80
	Subbituminous	33	1.32	0.23	11.20
	Anthracite	14	2.71	0.30	5.56
	Lignite	8	1.30	0.15	2.91

2.5.2. Mercury and halogen contents in coal sampled from power plants

Table 10 shows the mercury and halogen content of coals from power plants. In general, the average mercury content of power coal is slightly lower than that of the raw coal. The mercury content of bituminous coal samples is less than 0.050 mg/kg.

The average chlorine content of power coal is similar to that of raw coal, while the average bromine content of power coal is higher than that of raw coal. The anthracite coal has relatively higher chlorine content.

The difference between mercury contents of coal used in power plants and that of raw coal is mainly because of the sources of power coal collected. These power coal samples mainly origin from Shendong coal basin, Indonesia, Shanxi and Zhungeer, which produce low mercury coal. For example, ten out of the 177 samples from coal mines were from Shendong Coal Basin. The mean value of these ten samples is 0.023 ppm. In US EPA's report (2002), the mercury content of coal from Indonesia ranged from 0.01~0.05 ppm. This should be the reason why the mean mercury content for bituminous coals sampled from power plants (0.045 ppm) is three times lower than the mean mercury content for bituminous coals sampled from mines (0.147 ppm).

We have to admit that the number of samples in this study is quite small compared to the total numbers of coal mines and power plants in China. Further study is necessary to reduce the uncertainties.

Table 10 Mercury content of coal sampled from power plants (mg/kg)

Coal type	Number of coal samples	Min	Max	Mean
Bituminous	10	0.009	0.213	0.045
Subbituminous	33	0.019	0.532	0.132
Anthracite	14	0.085	0.437	0.196
Lignite	8	0.102	0.309	0.221

Table 11 Halogen content of coal sampled from power plants (mg/kg)

Coal type	No.	Cl			Br		
		Min	Max	Mean	Min	Max	Mean
Bituminous	10	90	660	271	59	111	73
Subbituminous	33	30	760	276	51	105	76
Anthracite	14	40	1860	316	41	90	69
Lignite	8	80	590	238	56	95	74

3. Development of Coal-fired Power Plants in China

3.1. Installed capacity and electricity generation

The installed capacity and electricity generation of coal-fired power plants in China are shown in **Table 12**.

Table 12 Installed capacity and electricity generation of coal-fired power plants in China in 2005 and 2008

Province	2005		2008	
	Installed capacity (GW)	Electricity generation (10^9 kWh)	Installed capacity (GW)	Electricity generation (10^9 kWh)
Anhui	11.51	63.6	24.82	107.4
Beijing	3.83	21	4.76	24.3
Chongqing	3.74	18.6	6.66	28.6
Fujian	9.35	48.7	15.43	74.8
Gansu	5.71	34	8.98	46.8
Guangdong	35.18	176.5	45.73	210.7
Guangxi	4.93	25	10.27	34.2
Guizhou	9.63	58.4	17.17	81.3
Hainan	1.53	7.2	2.37	10.7
Hebei	22.33	133.2	29.87	158
Heilongjiang	11.58	58.1	16.57	71.5
Henan	26.27	134.7	42.68	189
Hubei	9.53	47.6	14.21	55.3
Hunan	7.21	40.3	14.43	53.7
Inner Mongolia	19.17	104.2	45.74	200.8
Jiangsu	42.51	211.4	50.68	273.5
Jiangxi	5.91	30.6	9.34	40.5
Jilin	6.36	35.4	8.35	46.4
Liaoning	16	84.5	19.9	108.5
Ningxia	4.64	29.5	7.54	44
Qinghai	0.89	5.6	2	10.7
Shaanxi	9.64	49.6	17.85	71.5
Shandong	37.34	191	55.93	268.9
Shanghai	13.11	72.9	16.78	79.4
Shanxi	22.29	129.2	35.25	176.2
Sichuan	7.5	36.5	12.77	40.1
Tianjin	6.17	36.6	7.49	39.7
Xinjiang	5.05	26.5	8.2	39.7
Xizang	0.032	0.008	0.079	0.013
Yunnan	4.75	27.5	10.03	41.8
Zhejiang	27.68	109.5	40.99	174.8
National	391.38	2047.3	602.86	2803.0

(Data source: China Electricity Council, Annual Development Report for Chinese Electricity

Power Sector, 2006-2009)

In year 2005, the installed capacity of thermal power units reached 391.38 GW and the electricity generation was 2047.3 billion kWh. By the end of 2008, the total installed capacity had increased to 602.86 GW and the electricity generation had grown up to 2803.0 billion kWh. The provinces with large installed capacity and high coal consumptions were North China, Northeast China and East China.

3.2. Status of air pollution control

3.2.1. Particulate matter (PM) control

Although the installed capacity of thermal power plants had increased by 12 times from 1980 to 2008, the PM emissions decreased from 3.99 million tons to 3.30 million tons. The PM emission per unit electricity generation had been decreasing at the same period, which was 1.2 g/kWh in 2008, about 15.3 g/kWh lower than that in 1980. **Figure 4** shows the PM emissions from thermal power plants from 2000 to 2008.

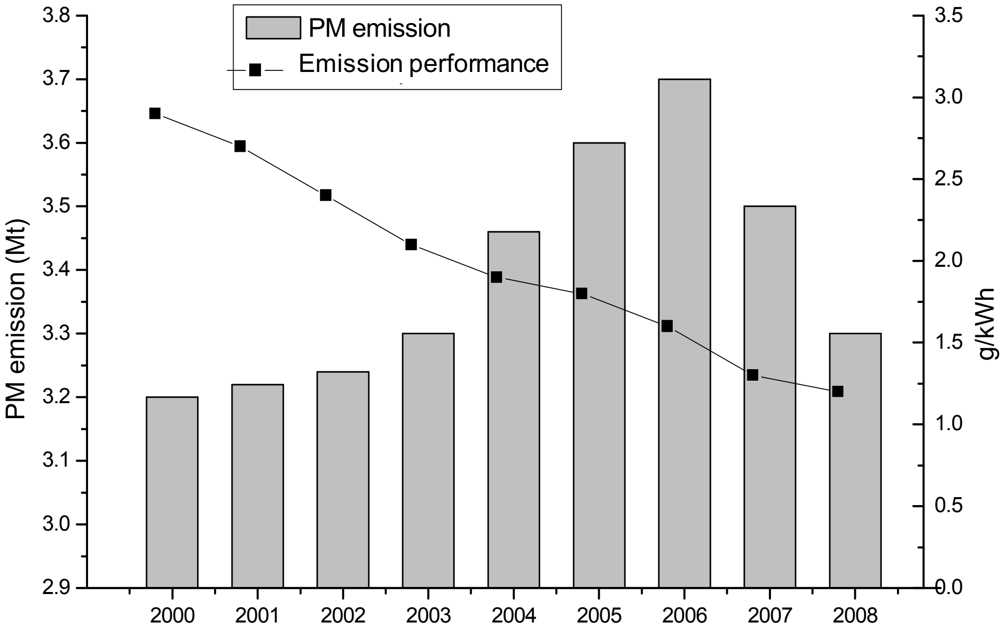

Figure 4 PM emissions from coal-fired power plants in China, 2000~2008

(Data source: China Electricity Council, Annual Development Report for Chinese Electricity Power Sector, 2006-2009)

In China, the PM emission control has been emphasized since 1990s. Since then, the application ESPs in power plant has been increasing and the PM removal efficiency has been significantly improved, shown in **Figure 5**.

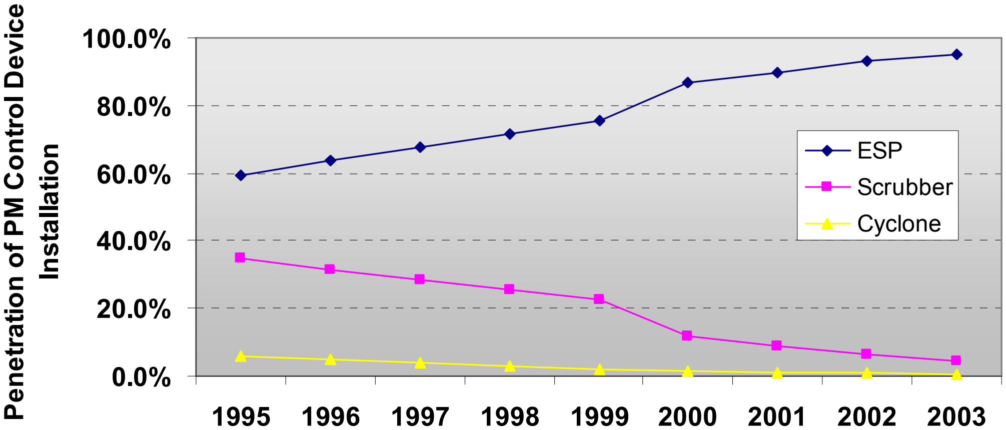

Figure 5 The installation of particulate control devices in thermal power plants in China, 1995~2003

(Data source: China Electricity Council, Annual Development Report for Chinese Electricity Power Sector, 1996-2004)

At the end of 2005, the PM removal efficiency for units with a capacity of 6 MW and above reached to 98.5%, and that for newly-built power plants was over 99%. Since 2003, all newly built units have been designed to meet the new PM emission standard , which requires the PM concentration in flue gas to be less than 50 mg/m^3. Meanwhile, fabric filter has been put into commercial use for the units with a capacity of 600 MW.

Currently most newly built coal-fired power plants have installed ESPs with PM removal efficiency over 99%. By the end of 2008, over 96% of the coal-fired power plants in China have installed ESP, and 3% of them have installed fabric filter.

3.2.2. SO_2 control

Control of SO_2 emissions from coal-fired power plants is one of the priorities of air pollution control in China. Based on the 11th five-year plan, in 2010, the national total SO_2 emissions would be reduced 10% on the basis of that in 2005. By 2008, the units that installed with flue gas desulfurization devices (FGDs) had reached 363 GW. The ratio of installed capacity with FGD had increased from 14% in 2005 to 60% in 2008. The rapid development of FGD installation during 2005–2008 is shown in **Figure 6**.

According to statistics from China Electricity Council (CEC), the total SO_2 emission in power sector in China was 10.5 million tons in 2008. The SO_2 emission from power plants in 2008 had decreased by 19.2% compared to that in 2005. Correspondingly, the SO_2 emission performance had decreased to 3.8 g/kWh.

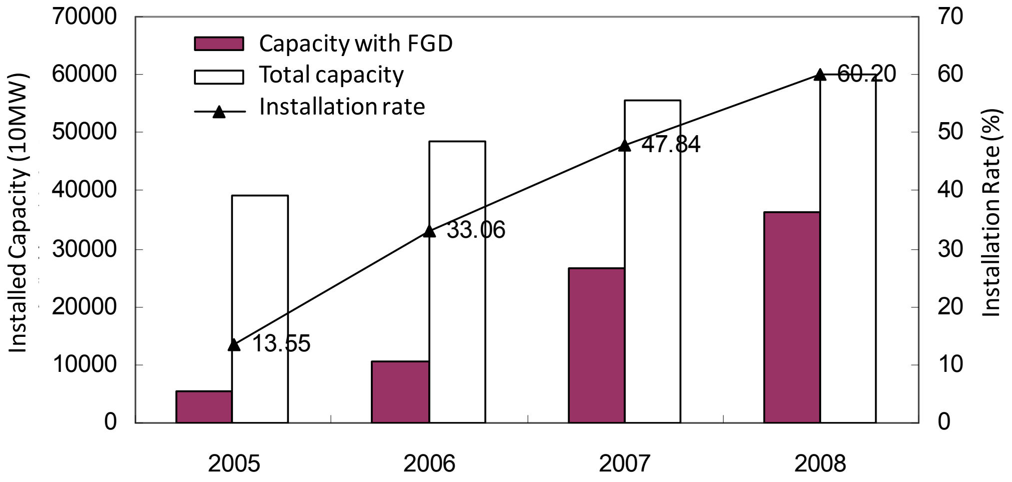

Figure 6 Development of FGD installation (2005–2008)

(Data source: China Electricity Council, Annual Development Report for Chinese Electricity Power Sector, 2006-2009)

Of all the units with FGD installation, 91% used limestone-gypsum wet FGD technology, 3% used seawater FGD technology, 3% used circulating fluidized bed FGD technology, and 3% used other technologies. Under the designed operating conditions, all desulfurization technology can achieve a removal efficiency of over 90%. Limestone-gypsum wet FGD technology, whose removal efficiency can reach 95%, has already been widely used.

3.2.3. NO_x control

According to CEC estimates, NO_x emissions from power plants were approximately 8.55 million tons in 2008. Emissions per unit electricity generation dropped from 3.6 g/kWh to 3.1 g/kWh during 2005–2008.

Owing to its low capital and operation cost, low NOx burner (LNB) has been widely used. The units built in early 1980s usually do not use LNB. Units built in early 1990s mostly have conventional LNB or compact air-staged combustion technology. In the late 1990s, multi-level air-staged burning technology was applied. After the revision and implementation of Emission Standard for Air Pollutants from Thermal Power Plants (GB13223-2003), nearly all units built after 2003 used the advanced LNB technology.

In 2008, the total capacity of the operating units with flue gas denitrification systems was about 20 GW, of which only 1.5 GW applied SNCR, while the rest installed SCR. The NOx removal efficiency of SCR technology is usually 60%~80%, and that of SNCR is usually over 40%. The installation rates of SCR and SNCR during 2005 to 2009 are given in **Figure 7**. The installation rates of SCR and SNCR have increased to 7% and 0.3% by the end of 2009.

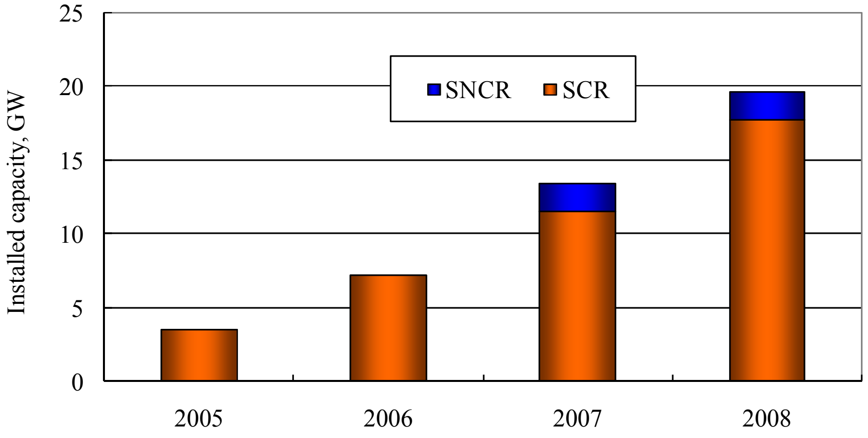

Figure 7 The installation of SCR and SNCR in thermal power plants in China, 2005~2008

(Data source: China Electricity Council, Annual Development Report for Chinese Electricity Power Sector, 2006-2009)

4. Mercury Emission Characteristics

Comprehensive field measurements are needed to understand the mercury emissions and to improve the accuracy of emission inventories. In this study, 124 onsite tests of coal-fired power plants were selected from existing literature to characterize mercury behavior and to calculate mercury emission factor.

The unit capacity, the APCD configuration and the type of coal burned of all the tested power plants are shown in **Table 13**. The installed capacity varies from 50 MW to 700 MW. More than ten types of APCDs were included. Most of the coal burned in the tested plants was bituminous or subbituminous. A considerable number of tests burned with anthracite and lignite coal were also quoted in this study. Among all the measurements, 29 tests were conducted in China, 71 tests were in the United States, and the rest were carried out in Canada, Japan, Spain, Netherlands and Australia.

In all tests, the mercury in flue gas was measured either by the Ontario Hydro Method (OHM) or the continuous mercury emission monitors. More detail information on the 124 plants from the literature was given in the Appendix.

Table 13 General information of the tested coal-fired power plants in literature

No.	Capacity (MW)	Air Pollution Control Devices	Coal Type	Mercury Removal Efficiency (%)	Country	Reference
1	200	PC+CS-ESP+WFGD	Bituminous	6%	China	Wang et al., 2010
2	600	PC+CS-ESP+WFGD	Bituminous	21%	China	Wang et al., 2010
3	300	PC+CS-ESP+WFGD	Anthracite	18%	China	Wang et al., 2010
4	600	PC+CS-ESP+WFGD	Lignite	16%	China	Wang et al., 2010
5	100	PC+CS-ESP+CFB-FGD+FF	Bituminous	13%	China	Wang et al., 2010
6	165	PC+SCR+CS-ESP+WFGD	Lignite	39%	China	Wang et al., 2010
7	220	PC+CS-ESP	Bituminous	36%	China	Chen et al., 2007
8	600	PC+CS-ESP+WFGD	Bituminous	25%	China	Chen et al., 2007
9	600	PC+CS-ESP	Bituminous	27%	China	Chen et al., 2007
10	50	PC+FF	Bituminous	33%	China	Chen et al., 2007

No.	Capacity (MW)	Air Pollution Control Devices	Coal Type	Mercury Removal Efficiency (%)	Country	Reference
11	200	PC+FF	Bituminous	17%	China	Chen et al., 2007
12	135	CFB+CS-ESP	Bituminous	31%	China	Chen et al., 2007
13	300	PC+CS-ESP	Bituminous	19%	China	Zhou et al., 2005
14	600	PC+CS-ESP	Bituminous	1%	China	Zhou et al., 2006
15	300	PC+CS-ESP	Bituminous	25%	China	Zhou et al., 2008
16	600	PC+CS-ESP	Bituminous	30%	China	Wang et al., 2008
17	220	PC+CS-ESP	Bituminous	22%	China	Yang et al., 2007
18	100	PC+CS-ESP	Bituminous	35%	China	Duan et al., 2005
19	50	PC+FF	Bituminous	13%	China	Wang et al., 2009
20	200	PC+FF	Bituminous	15%	China	Wang et al., 2009
21	220	PC+CS-ESP	Bituminous	42%	China	Wang et al., 2009
22	600	PC+CS-ESP	Bituminous	33%	China	Wang et al., 2009
23	600	PC+CS-ESP+WFGD	Bituminous	83%	China	Wang et al., 2009
24	60	PC+NID+CS-ESP	Anthracite	22%	China	Wu et al., 2008
25	300	PC+CS-ESP	Anthracite	19%	China	Guo et al., 2004
26	300	PC+SCR+CS-ESP+SW-FGD	Bituminous	29%	China	Chen et al., 2008
27	200	PC+CS-ESP	Anthracite	6%	China	Tang, 2004
28	350	PC+CS-ESP	Bituminous	13%	China	Chen et al., 2006
29	700	PC+CS-ESP	Bituminous	40%	China	Chen et al., 2006
30	N.R.	PC+CS-ESP+WFGD	Bituminous	43%	USA	Kilgroe et al., 2002
31	100	PC+CS-ESP	Lignite	59%	USA	Kellie et al., 2004
32	100	PC+CS-ESP	Bituminous	3%	USA	Kellie et al., 2004
33	250	PC+CS-ESP	Lignite	74%	USA	He et al., 2007
34	795	PC+SCR+CS-ESP+WFGD	Bituminous	66%	USA	Cheng et al., 2009
35	N.R.	PC+CS-ESP	Bituminous	55%	USA	ICR, 2010

No.	Capacity (MW)	Air Pollution Control Devices	Coal Type	Mercury Removal Efficiency (%)	Country	Reference
36	N.R.	PC+CS-ESP	Bituminous	52%	USA	ICR, 2010
37	N.R.	PC+CS-ESP	Bituminous	44%	USA	ICR, 2010
38	N.R.	PC+CS-ESP	Bituminous	36%	USA	ICR, 2010
39	N.R.	PC+CS-ESP	Bituminous	29%	USA	ICR, 2010
40	N.R.	PC+CS-ESP	Bituminous	27%	USA	ICR, 2010
41	N.R.	PC+CS-ESP	Bituminous	25%	USA	ICR, 2010
42	N.R.	PC+CS-ESP	Bituminous	22%	USA	ICR, 2010
43	N.R.	PC+CS-ESP+WFGD	Bituminous	20%	USA	ICR, 2010
44	N.R.	PC+FF	Bituminous	9%	USA	ICR, 2010
45	N.R.	PC+FF	Bituminous	8%	USA	ICR, 2010
46	N.R.	PC+FF	Bituminous	5%	USA	ICR, 2010
47	N.R.	PC+FF+WFGD	Bituminous	71%	USA	ICR, 2010
48	N.R.	PC+FF+WFGD	Bituminous	74%	USA	ICR, 2010
49	N.R.	PC+HS-ESP	Bituminous	13%	USA	ICR, 2010
50	N.R.	PC+HS-ESP	Bituminous	N.R.	USA	ICR, 2010
51	N.R.	PC+HS-ESP+WFGD	Bituminous	75%	USA	ICR, 2010
52	N.R.	PC+HS-ESP+WFGD	Bituminous	69%	USA	ICR, 2010
53	N.R.	PC+SDA+FF	Bituminous	55%	USA	ICR, 2010
54	N.R.	PC+WS	Bituminous	88%	USA	ICR, 2010
55	N.R.	PC+SCR+SDA+FF	Bituminous	73%	USA	ICR, 2010
56	N.R.	PC+SCR+SDA+FF	Bituminous	30%	USA	ICR, 2010
57	N.R.	PC+SI+CS-ESP	Bituminous	73%	USA	ICR, 2010
58	N.R.	PC+SNCR+CS-ESP	Bituminous	80%	USA	ICR, 2010
59	N.R.	CFB+SNCR+FF	Bituminous	78%	USA	ICR, 2010
60	N.R.	SF+SDA+FF	Bituminous	81%	USA	ICR, 2010
61	N.R.	CYC+CS-ESP+WFGD	Bituminous	27%	USA	ICR, 2010
62	N.R.	TUR+CS-ESP+WFGD	Bituminous	73%	USA	ICR, 2010
63	N.R.	CG	Bituminous	72%	USA	ICR, 2010
64	N.R.	CG	Bituminous	65%	USA	ICR, 2010
65	N.R.	PC+CS-ESP	Lignite	56%	USA	ICR, 2010
66	N.R.	PC+CS-ESP+WFGD	Lignite	19%	USA	ICR, 2010
67	N.R.	PC+CS-ESP+FF	Lignite	80%	USA	ICR, 2010
68	N.R.	PC+SDA+FF	Lignite	17%	USA	ICR, 2010
69	N.R.	PC+WS	Lignite	86%	USA	ICR, 2010
70	N.R.	CFB+CS-ESP	Lignite	9%	USA	ICR, 2010
71	N.R.	CFB+FF	Lignite	87%	USA	ICR, 2010
72	N.R.	CYC+CS-ESP	Lignite	92%	USA	ICR, 2010
73	N.R.	CYC+SDA+FF	Lignite	87%	USA	ICR, 2010
74	N.R.	PC+CS-ESP	Subbituminous	83%	USA	ICR, 2010
75	N.R.	PC+CS-ESP	Subbituminous	68%	USA	ICR, 2010
76	N.R.	PC+CS-ESP	Subbituminous	63%	USA	ICR, 2010

No.	Capacity (MW)	Air Pollution Control Devices	Coal Type	Mercury Removal Efficiency (%)	Country	Reference
77	N.R.	PC+CS-ESP	Subbituminous	36%	USA	ICR, 2010
78	N.R.	PC+CS-ESP	Subbituminous	95%	USA	ICR, 2010
79	N.R.	PC+CS-ESP+WFGD	Subbituminous	10%	USA	ICR, 2010
80	N.R.	PC+CS-ESP+WFGD	Subbituminous	97%	USA	ICR, 2010
81	N.R.	PC+CS-ESP+WFGD	Subbituminous	84%	USA	ICR, 2010
82	N.R.	PC+FF	Subbituminous	64%	USA	ICR, 2010
83	N.R.	PC+FF	Subbituminous	34%	USA	ICR, 2010
84	N.R.	PC+HS-ESP	Subbituminous	30%	USA	ICR, 2010
85	N.R.	PC+HS-ESP	Subbituminous	19%	USA	ICR, 2010
86	N.R.	PC+HS-ESP	Subbituminous	12%	USA	ICR, 2010
87	N.R.	PC+HS-ESP	Subbituminous	10%	USA	ICR, 2010
88	N.R.	PC+HS-ESP+WFGD	Subbituminous	84%	USA	ICR, 2010
89	N.R.	PC+HS-ESP+WFGD	Subbituminous	46%	USA	ICR, 2010
90	N.R.	PC+HS-ESP+WFGD	Subbituminous	31%	USA	ICR, 2010
91	N.R.	PC+SDA+FF	Subbituminous	24%	USA	ICR, 2010
92	N.R.	PC+WS+WFGD	Subbituminous	17%	USA	ICR, 2010
93	N.R.	PC+WS+WFGD	Subbituminous	24%	USA	ICR, 2010
94	N.R.	PC+SDA+CS-ESP	Subbituminous	98%	USA	ICR, 2010
95	N.R.	PC+MC+WS+WFGD	Subbituminous	97%	USA	ICR, 2010
96	N.R.	CFB+SNCR+FF	Subbituminous	70%	USA	ICR, 2010
97	N.R.	CYC+HS-ESP	Subbituminous	99%	USA	ICR, 2010
98	N.R.	CYC+WS+WFGD	Subbituminous	66%	USA	ICR, 2010
99	N.R.	CFB+FF	Waste bituminous	13%	USA	ICR, 2010
100	N.R.	CFB+FF	Waste bituminous	1%	USA	ICR, 2010
101	N.R.	PC+CS-ESP	Subbituminous	83%	Canada	Goodarzi, 2004
102	N.R.	PC+CS-ESP	Subbituminous	33%	Canada	Goodarzi, 2004
103	N.R.	PC+CS-ESP	Subbituminous	12%	Canada	Goodarzi, 2004
104	N.R.	PC+CS-ESP	Subbituminous	15%	Canada	Goodarzi, 2004
105	N.R.	PC+CS-ESP	Subbituminous	11%	Canada	Goodarzi, 2004
106	N.R.	PC+CS-ESP	Subbituminous	95%	Canada	Goodarzi, 2004
107	700	PC+CS-ESP+WFGD	Bituminous	68%	Japan	Yokoyama et al., 2000
108	700	PC+CS-ESP+WFGD	Bituminous	74%	Japan	Yokoyama et al., 2000
109	700	PC+CS-ESP+WFGD	Bituminous	90%	Japan	Yokoyama

No.	Capacity (MW)	Air Pollution Control Devices	Coal Type	Mercury Removal Efficiency (%)	Country	Reference
						et al., 2000
110	1000	PC+CS-ESP+WFGD	Bituminous	99%	Japan	Ito et al., 2006
111	200	PC+CS-ESP	Anthracite	56%	South Korea	Lee et al., 2004
112	500	PC+CS-ESP+WFGD	Bituminous	100%	South Korea	Lee et al., 2004
113	500	PC+CS-ESP+WFGD	Bituminous	100%	South Korea	Lee et al., 2006
114	500	PC+CS-ESP+WFGD	Bituminous	59%	South Korea	Kim et al., 2009
115	350	PC+CS-ESP	Lignite	89%	Spain	Otero-Rey et al., 2003
116	350	PC+CS-ESP	Lignite	79%	Spain	Otero-Rey et al., 2003
117	350	PC+CS-ESP	Lignite	5%	Spain	Otero-Rey et al., 2003
118	N.R.	PC+CS-ESP+WFGD	Bituminous	59%	Netherlands	Meij et al., 2006
119	660	PC+FF	Bituminous	56%	Australia	Shah et al., 2008
120	340	PC+CS-ESP	Bituminous	12%	Australia	Shah et al., 2010
121	850	PC+CS-ESP	Bituminous	43%	Australia	Shah et al., 2010
122	116	PC+CS-ESP	Bituminous	82%	Australia	Shah et al., 2010
123	660	PC+CS-ESP	Bituminous	34%	Australia	Shah et al., 2010
124	254	PC+CS-ESP	Bituminous	33%	Australia	Shah et al., 2010

Notes: PC – pulverized coal boiler; CFB – circulating fluidized bed boiler; SF – stoker-fired boiler; CYC – cyclone-fired boiler; TUR – turbo-fired boiler; CG – coal gasification; ESP – electrostatic precipitator; CS-ESP – cold side ESP; HS-ESP – hot side ESP; FF – fabric filter; WS – wet scrubber; MC – mechanical collector; FGD – flue gas desulfurization; WFGD – wet FGD; CFB-FGD – circulating fluidized bed FGD; SW-FGD – seawater FGD; NID – novel integrated desulfurization; SDA – spray dryer adsorber; SI – sorbent injection; SCR – selective catalytic reduction; SNCR – selective non-catalytic reduction.

4.1. Mercury release rate during coal combustion

Studies show that during coal combustion in PC boilers, 99% of the Hg in coal is released to the flue gas in Hg^0 form. With the existence of Cl, Br, and particles in flue gas, part of the Hg^0 is oxidized into Hg^{2+} either by gas phase oxidation or catalytic oxidation (Galbreath and Zygarlicke, 2000). As the flue gas temperature decreases, part of the Hg^0 and Hg^{2+} in the gas phase condenses on or is adsorbed on fly ash particles.

4.2. Mercury removal efficiencies of APCDs

When passing across APCDs, part of the Hg_p and Hg^{2+} can be removed. As for the mercury removal efficiency of APCDs, in UNEP's toolkit (2005), 36% for PC+ESP, 74% for PC+ESP+WFGD and 90% for PC+FF were quoted from the ICR report.

The mercury removal efficiencies given by literature were summarized in **Figure 8**. The mercury removal efficiencies of the most commonly used APCD combinations, including PC+WS, PC+HS-ESP, PC+CS-ESP, PC+HS-ESP+WFGD, PC+SDA+FF, PC+CS-ESP+WFGD, PC+SCR+CS-ESP+WFGD, PC+FF, CFB+CS-ESP, CFB+FF, and PC+FF+WFGD, are 22%, 28%, 29%, 40%, 59%, 62%, 66%, 67%, 78%, 86%, and 90%. The other APCD combinations have few test data and are not representative enough to be the accordance for mercury inventory.

From **Figure 8**, we can see that the coal type has no significant influence on the mercury removal efficiency of ESP. For other APCDs, there is not enough data. Therefore, coal type is not considered in the inventory development in this study.

4.3. Fate of mercury in coal-fired power plants

The fate of mercury in coal-fired power plants is obtained based on the mass balance of the onsite test results. The raw data is given in the Appendix. **Figure 9** shows the average of the mass balance results for PC+ESP, PC+ESP+WFGD and PC+FF.

Only 1% of mercury remains in the bottom ash, while the rest enters APCDs. No loss of total mercury will occur when the flue gas passes through SCR, if applied. However, the speciation of mercury will change, which leads to more mercury capture in the following WFGD. Averagely 28% of the total mercury goes into the fly ash which is removed by ESP. About 71% of the mercury will emit to the atmosphere through the stack if ESP is the only installed APCD. If WFGD is in use, 35% of the mercury will enter the gypsum and the rest 36% will end up in the stack gas. FF can remove 56% of the total mercury.

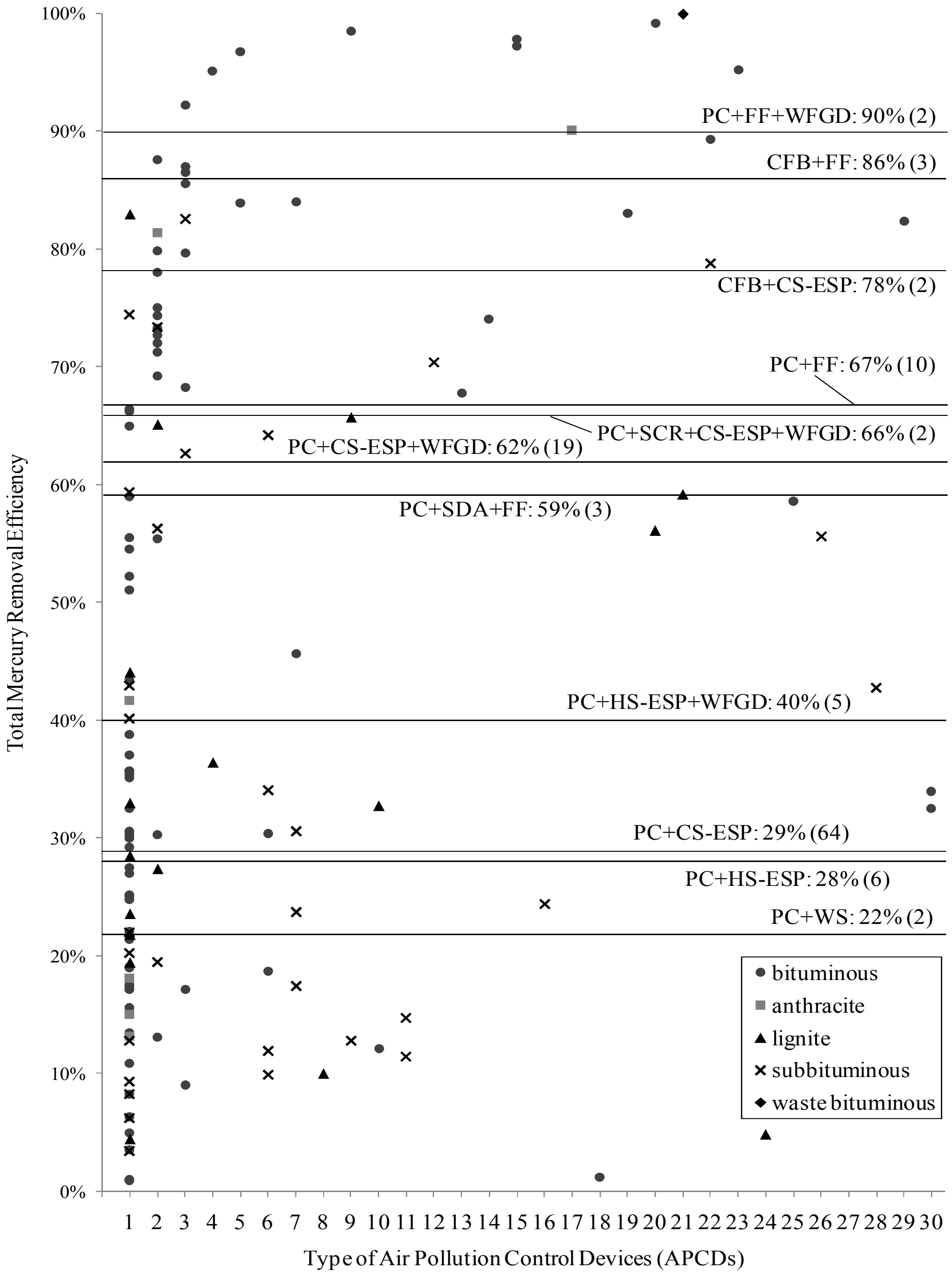

Figure 8 Onsite test results for total mercury removal efficiency by APCDs

Notes: 1 – PC+CS-ESP; 2 – PC+CS-ESP+WFGD; 3 – PC+FF; 4 – PC+SCR+CS-ESP+WFGD; 5 – PC+FF+WFGD; 6 – PC+HS-ESP; 7 – PC+HS-ESP+WFGD; 8 – PC+CS-ESP+FF; 9 – PC+SDA+FF; 10 – PC+WS; 11 – PC+WS+WFGD; 12 – PC+SDA+CS-ESP; 13 – PC+CS-ESP+CFB-FGD+FF; 14 – PC+SCR+CS-ESP+SW-FGD; 15 – PC+SCR+SDA+FF; 16 – PC+MC+WS+WFGD; 17 – PC+NID+CS-ESP; 18 – PC+SI+CS-ESP; 19 – PC+SNCR+CS-ESP; 20 – CFB+CS-ESP; 21 – CFB+FF; 22 – CFB+SNCR+FF; 23 – SF+SDA+FF; 24 – CYC+CS-ESP; 25 – CYC+CS-ESP+WFGD; 26 – CYC+HS-ESP; 27 – CYC+SDA+FF; 28 – CYC+WS+WFGD; 29 – TUR+CS-ESP+WFGD; 30 – CG.

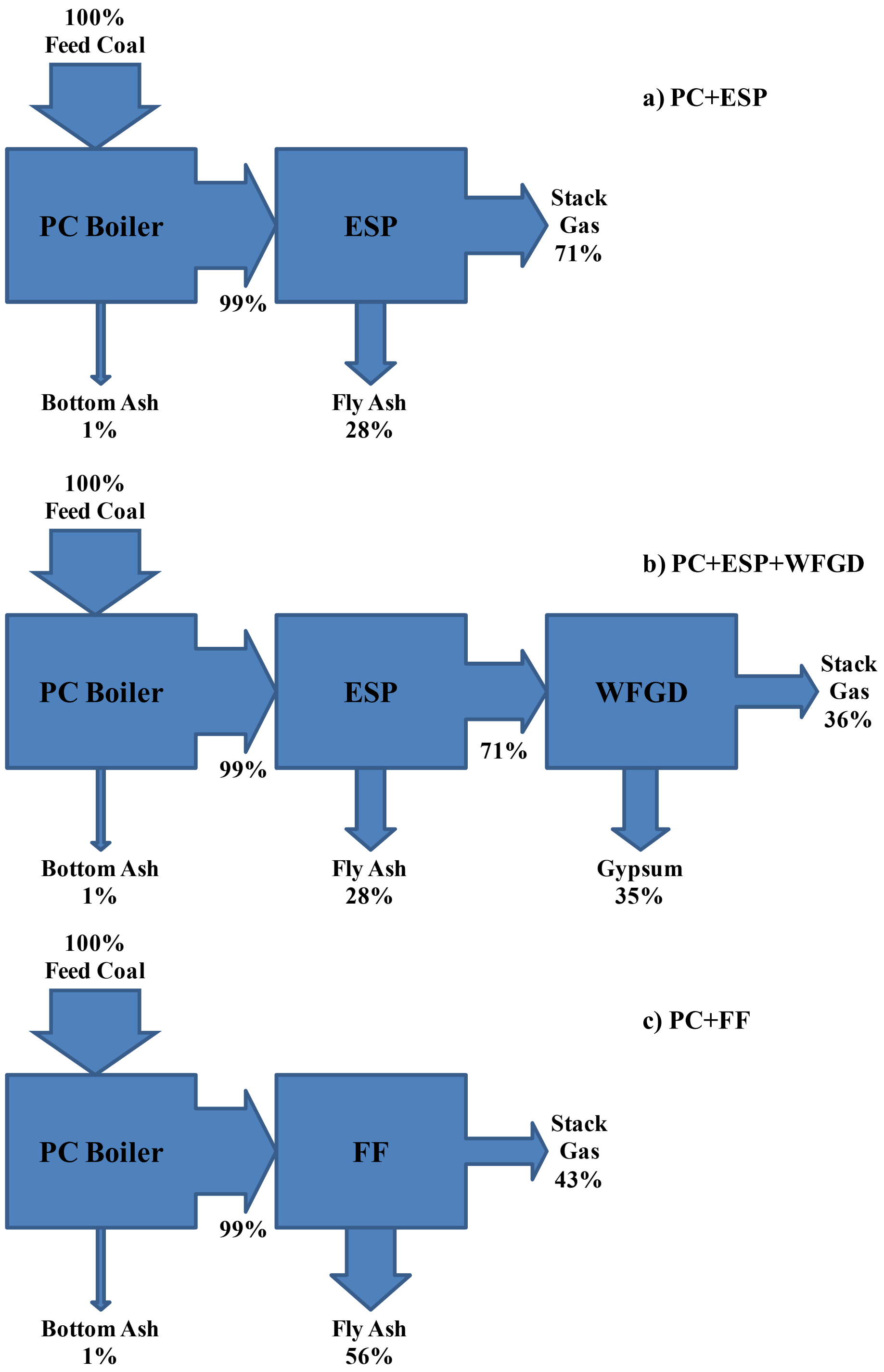

Figure 9 Mass flow of total mercury in coal-fired power plants

5. Mercury Emissions from Coal-fired Power Plants in China

5.1. Methodology

The previous mercury emission inventories were developed using a deterministic emission factor approach. However, as shown in Chapter 3, the mercury removal efficiencies have large variations, which cannot be considered by the deterministic emission factor model. In this study, a detailed probabilistic emission factor model was developed to assess the mercury emission from coal-fired power plants in China.

In this study, information collected in Chapter 2~4 were integrated, including mercury content of coal by province, coal washing and cleaning, coal consumption by province, mercury removal efficiencies by APCDs or technology combinations, and the installation proportion of certain APCD combinations. Probability-based distribution functions are built into the model to address the uncertainties or variations of the key parameters. The model uses Monte Carlo simulations to take into account the probability distributions of key input parameters and produce the mercury emission results in the form of a statistical distribution. All the results are presented as distribution curves or confidence intervals instead of single points.

The model is described as **Equation 1**:

$$E(x_i, y_{j,k}) = \sum_i \sum_j \left[M_i(x_i) \cdot A_{i,j} \cdot (1 - P \cdot w) \cdot R_j \cdot \left(1 - \sum_k C_{j,k} \cdot \eta_{j,k}(y_{j,k}) \right) \right] \qquad \textbf{(E1)}$$

where $E(x,y)$ is probability distribution of the Hg emission; $M(x)$ is the probability distribution of the Hg content of coal as burned; A is the amount of coal consumption; P is the percentage of coal pre-wash in power plants; w is the mercury removal efficiency of coal pre-wash; R is the release factor of mercury from boiler; C is the application rate of a certain combination of APCDs; $\eta(y)$ is the mercury removal efficiency of one combination of APCDs, i is the province; j is the combustor type; and k is the type of APCD combinations.

The probability distributions in this study were discrete, which is suitable for Monte Carlo simulation. We selected the mercury content of coal as burned and the mercury removal efficiency of combinations of APCDs to analyze their probability distribution functions. A statistical software, Crystal Ball^{TM}, was employed for calculation.

In Crystal Ball^{TM}, a mathematical distribution analysis was performed for the two key parameters to describe the characteristics of the dataset. The quality or closeness of each fit is determined by the chi-squared test and Anderson-Darling test. To get reliable outputs, the sampling number of the Monte Carlo simulation was set to be 10,000. Details about this model can be found in our previous paper (Wu et al., 2010).

5.2. Mercury emission factors

The most important factors affecting mercury emissions are the mercury content of coal and the mercury removal efficiency of APCDs.

5.2.1. Mercury content of coal

Based on the results from this study and the USGS database, the mercury content of raw coal in each province was calculated (as shown in **Figure 10**). Statistical distribution fit was performed on the provincial data of mercury content using Crystal Ball^{TM}. The mercury content for most provinces fit the lognormal distribution. **Figure 10** provides the P10, P50 and P90 values for the mercury content of coal in some coal producing provinces. The mercury contents of coal in Shaanxi, Guizhou, Inner Mongolia and Shanxi have large variations. The distributions of these four provinces are shown in **Figure 11**. A notable characteristic for the fit is the "long tail", which is the cause of difference between the P50 value and the mean value.

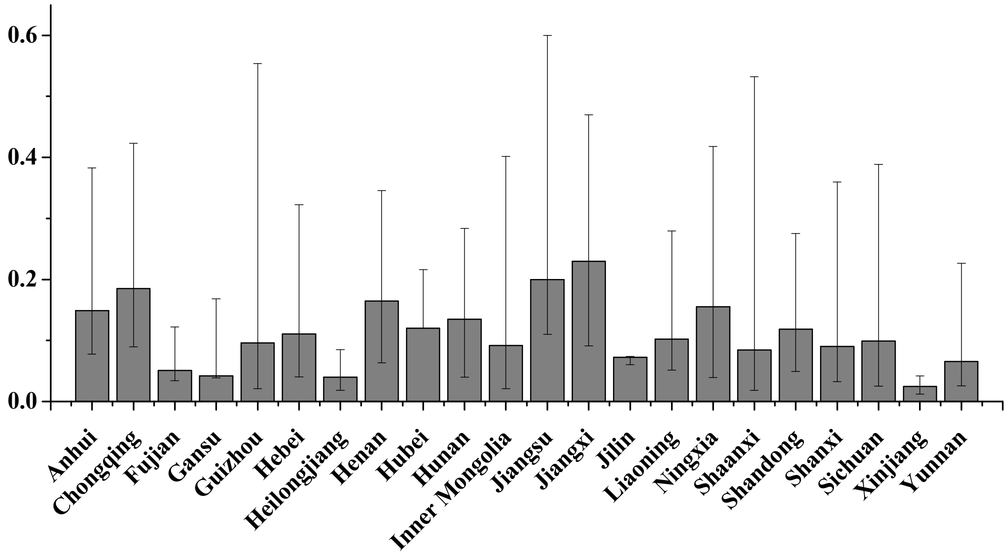

Figure 10 Mercury content of coal in some provinces (mg/kg)

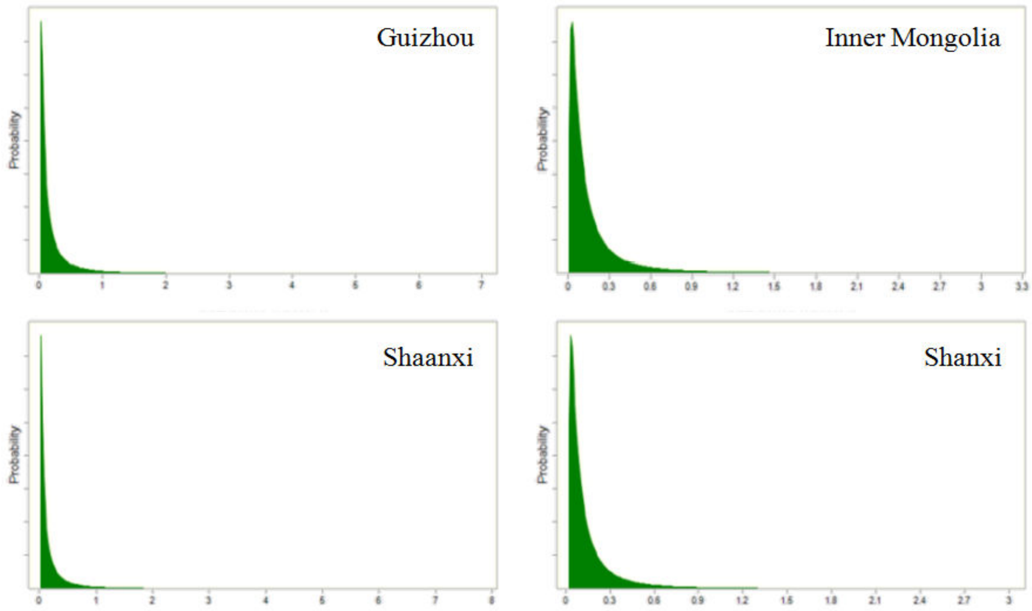

Figure 11 Distribution of mercury content of coal in Guizhou, Inner Mongolia, Shaanxi, and Shanxi

5.2.2. Mercury removal efficiencies of APCDs

The mercury removal efficiencies of APCD combinations also have large uncertainties. The most widely used APCD combinations in China are PC+ESP and PC+ESP+FGD. Data from literature for these two types of APCDs were analyzed using Crystal Ball^{TM}. We assume that the removal efficiency of PC+ESP fits the Weibull distribution. The probability distributions were derived by Crystal BallTM using a Batch Fit function which mainly adopted a stochastic sampling densification method in probability statistics. With probability distributions, we use P10 and P90 value as the confidence interval instead of the standard deviation. The results are given in **Figure 12**. The best estimated value (P50) of mercury removal efficiency by ESP was 26%, lower than the mean value (29%).

Mercury removal efficiencies of PC+ESP+WFGD fit the Weibull distribution as well. The best estimated value (P50) was 65%, higher than the mean value (63%). For PC+FF, there were only 10 test results. We assumed it fit the Weibull distribution and the P50 value was 76%. Mean values were used for other APCD combinations due to the lack of test results.

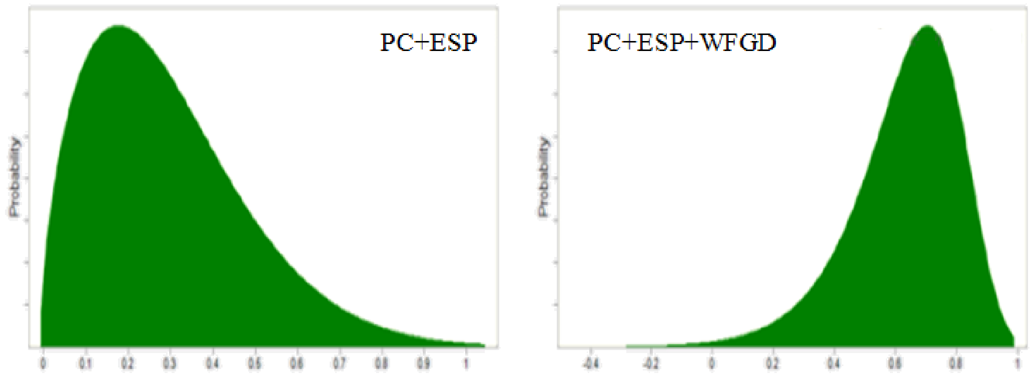

Figure 12 Probabilistic distributions of mercury removal efficiencies of APCD combinations

5.2.3. Mercury speciation in the stack gas

The original data on mercury speciation in the stack gas is summarized in the Appendix. The speciation profile we used in the model was the mean values for each APCD combination, as shown in the following table.

Table 14 Mercury speciation in the flue gas

	Hg^0	Hg^{2+}	Hg_p	Reference
No control	0.56	0.34	0.10	Wu et al., 2006
PC+WS	0.84	0.13	0.03	Wu et al., 2006
PC+ESP	0.57	0.42	0.01	See the Appendix
PC+ESP+WFGD	0.88	0.12	0.00	See the Appendix
PC+FF	0.31	0.58	0.11	See the Appendix

5.3. Mercury emission inventory in 2005

Information on mercury content of coal and mercury removal efficiencies of APCDs, combined with the coal consumption from power plants in China, the mercury emissions from coal-fired power plants in China was established.

Figure 13 presents the output distribution curves of the emission of total Hg, Hg^0, Hg^{2+}, and Hg_p, respectively, from coal-fired power plants in China in 2005. The best estimate for mercury emissions from coal-fired power plants in China was 108.6 t (P50) in 2005, with the confidence interval from 65.2 t (P10) to 195.4 t (P90). In 2005, the best estimate for Hg^0 emissions from coal-fired power plants in China ws 69.6 t, with the confidence interval from 42.9 t (P10) to 125.0 t (P90); the best estimate for Hg^{2+} emissions was 37.5 t, with the confidence interval from 21.1 t (P10) to 68.0 t (P90); and the best estimate for Hg_p emissions was 1.5 t, with the confidence interval from 1.0 t (P10) to 2.7 t (P90). The dominant species of the total mercury was Hg^0, which accounts for 64% of the total emission. Most Hg^{2+} was removed by wet FGD, and thus only accounted for 35% of the total emissions.

The emissions of Hg, Hg^0, Hg^{2+} and Hg_p by province are shown in **Figure 14**. The bar represents the P50 value of emissions, and the short lines superimposed on each bar represent the P10 and P90 value. From **Figure 14** we can see that Jiangsu, Henan and Shandong were the top three emitters in the coal power sector in China in 2005 based on the best estimates. However, the P90 value of Guizhou was high, 569% of its P50 value, due to the high variations of the mercury content of coal. The top ten emitters contributed 54% of the total mercury emission from the power sector in China.

5.4. Co-benefit of SO_2 control on mercury removals

With the increase of electricity demand, the emission for 2008 should have been 20% higher than that for 2005 if no control measures were taken. Because of the phasing-out of small units and installation of FGD, the mercury emission from coal-fired power plants in China decrease to 96 t (P50) in 2008, 11% lower than that for 2005. The co-benefit of SO_2 emission control on mercury removals was 33.9 t (see **Figure 15**), among which 12.8 t were from the FGD installation in the newly built power plants, 13.4 t were from the FGD installation in existing power plants, and 7.7 t were from the phasing-out of small units. The synergetic mercury removal benefited from the SO_2 control measures in the eleventh five-year period was significant. However, the potential of further mercury removals would be limited since 70% of the coal-fired power plants have installed high efficiency ESPs and FGDs.

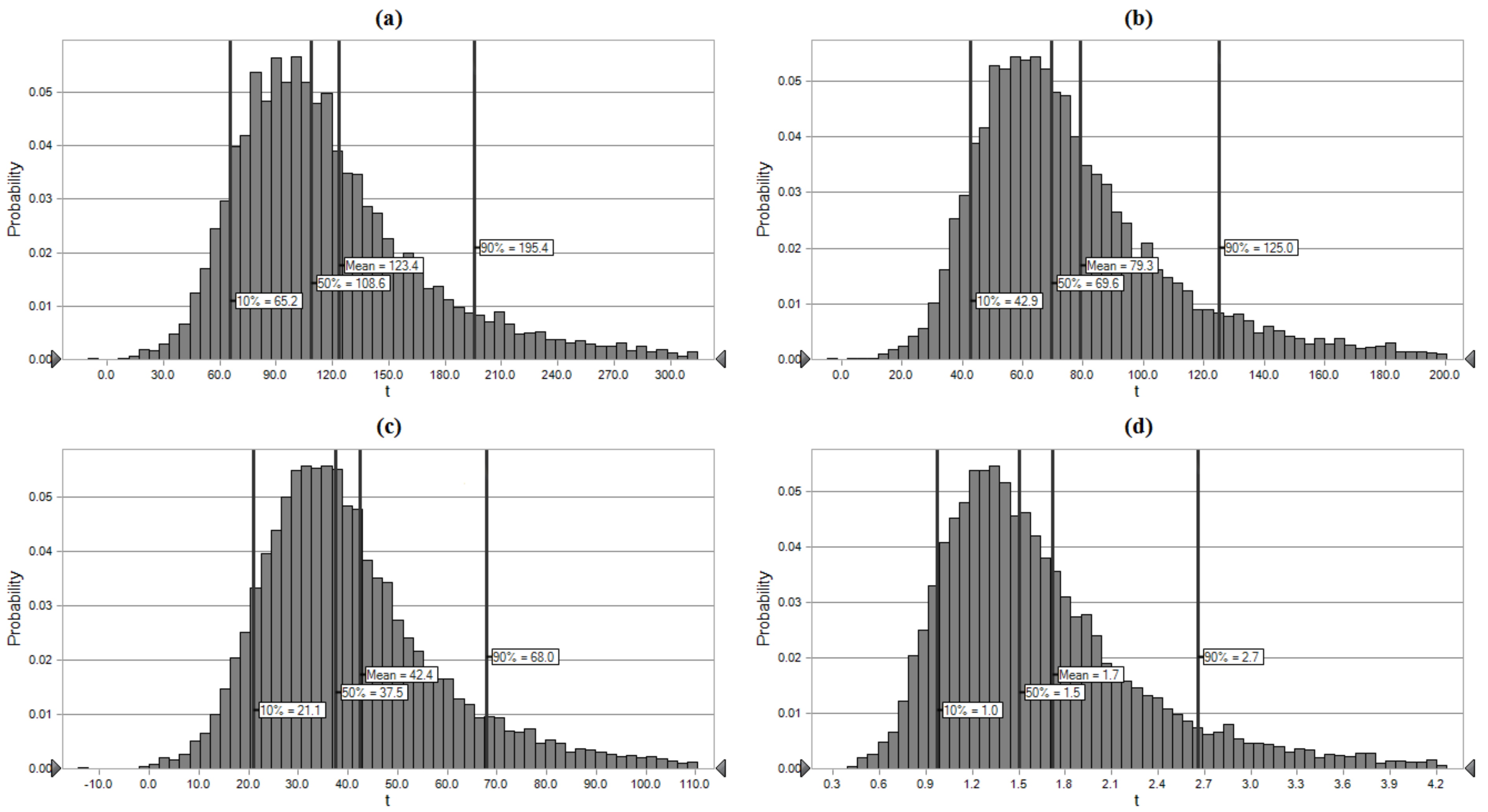

Figure 13 Schematic probabilistic distribution curves for emissions of (a) total Hg, (b) Hg^0, (c) Hg^{2+}, and (d) Hg_p, from coal-fired power plants in China, 2005

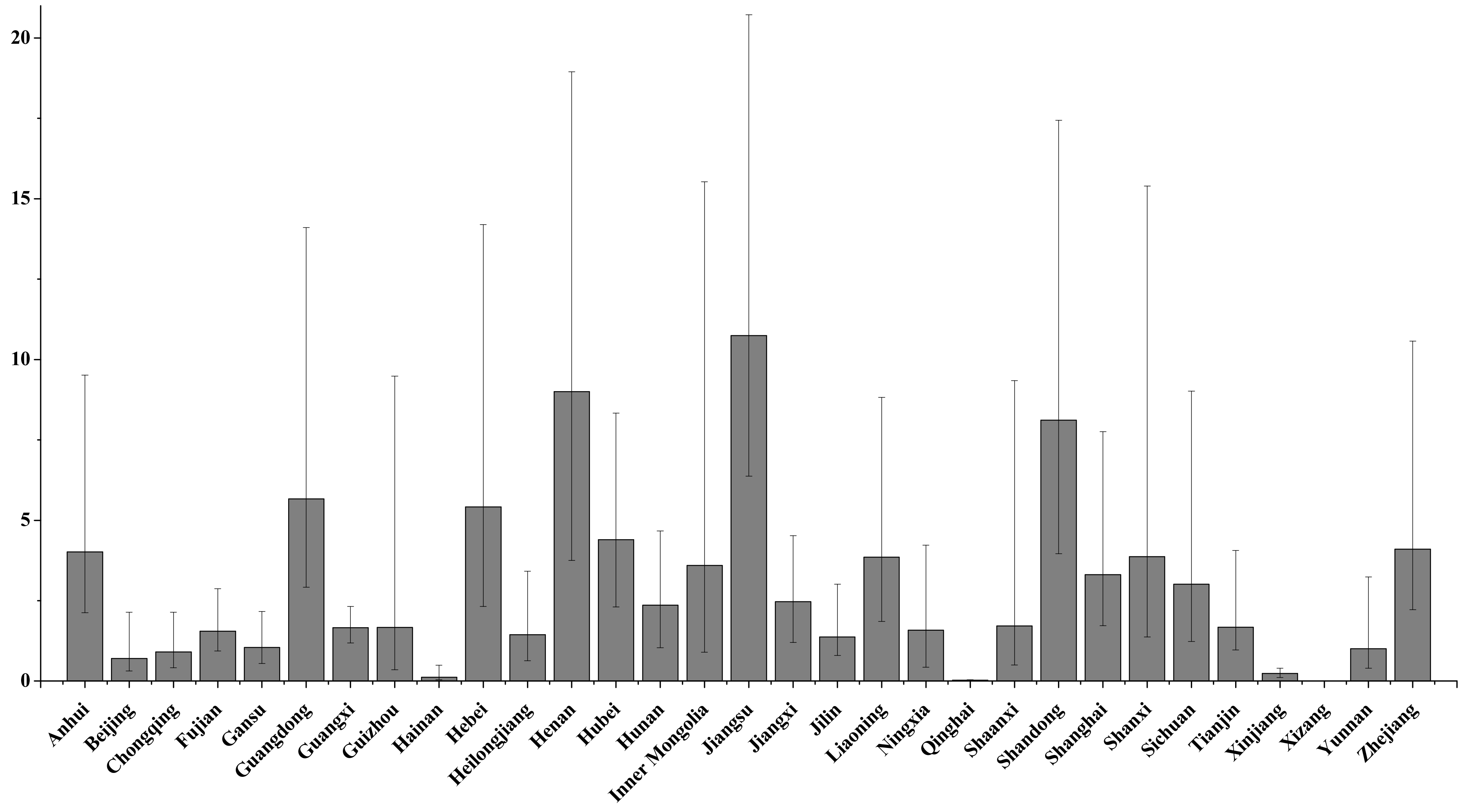

Figure 14 Total mercury emissions and uncertainty ranges for coal-fired power plants by province, 2005

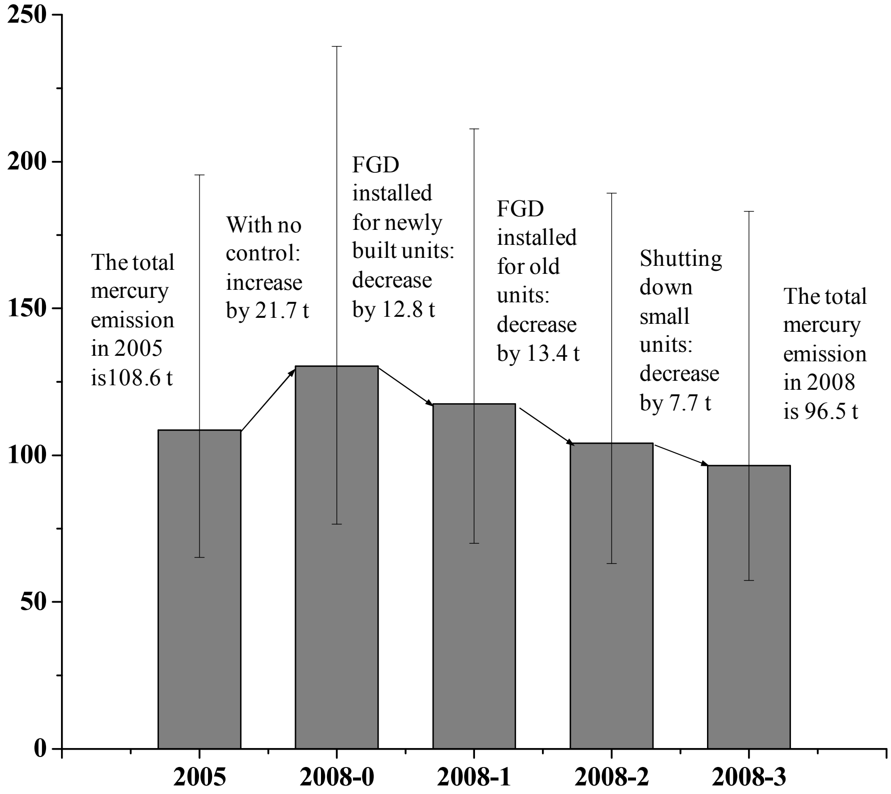

Figure 15 Co-benefit of mercury removal by SO_2 control measures during 2005-2008

6. Future Trends of Mercury Emissions from Coal-fired Power Plants in China

6.1. Trend of coal consumption in coal-fired power plants in China

Based on the economic development, the electricity consumption per capita, and the economic development, the electric power consumption demand and the installed capacity in China in 2020 was forecast, as shown in **Table 15**. From **Table 15**, we can see that the power generation from coal-fired power plants will reach 4.2 to 6.1 billion MWh, which will result in the coal consumption of about 1.84 to 2.69 billion tons in 2020.

Table 15 Prediction of the power consumption and the installed capacity of coal power in China in 2020

Item	High energy scenario	Low energy scenario
Electric power consumption per capita (kWh)	5600	4800
Total power generation (10^{12} kWh)	8.12	6.96
Coal power proportion (%)	75	60
Coal power generation (10^{12} kWh)	6.09	4.18
Hours of power generation (h)	5000	4500
Installed capacity of coal power (GW)	1218	929
Standard coal consumption (gce/kWh)	310-315	310-315
Total coal consumption (10^9 t)	2.69	1.84

6.2. Forecast of emission control policies

Two scenarios, namely, baseline scenario and policy scenario, were developed to describe the air pollution control policies in China. The scenarios are mainly based on two documents: Standard for Air Pollutant Emission from Thermal Power Plant (in revision) and Guidelines to the Implementation of the Joint Prevention and Control of Air Pollution to Improve Regional Air Quality. The baseline scenario assumes the air pollution control follow the current laws and regulations; the policy scenario assumes more advanced air pollution control technologies gradually spread out. The projected application rates of different emission control technologies are showed in **Figure 16**.

Coal-fired power plants are the top priority in SO_2 control in China. The strategies for SO_2 control in both scenarios are similar. In both scenarios, the newly built coal-fired power plants are required to install FGD system. In the policy scenario, all small units with the capacity less than 100 MW will be shut down, whose power generation quota will be accomplished by large-scale units with FGD.

ESP is the most widely used PM control device in Chinese power plants. With the development of emission standards, the installation of fabric filters (FF) has been increasing in the last few years. In the baseline scenario, all the small units using wet scrubber or cyclone will be replaced by large units with ESP and FF gradually increase during 2010~2020. In the policy scenario, the installation ratio of FF will be higher than that in baseline scenario.

The flue gas denitrification is to reduce and decompose the NO_x into N_2 through physical and chemical processes. The typical technologies include SCR and SNCR. The application of flue gas denitrification has just started in China. Power plants in Beijing, Shanghai and some other areas have installed SCR systems. Under the baseline scenario, the SCR application ratio will reach 45%; under the policy scenario, it will reach 55%.

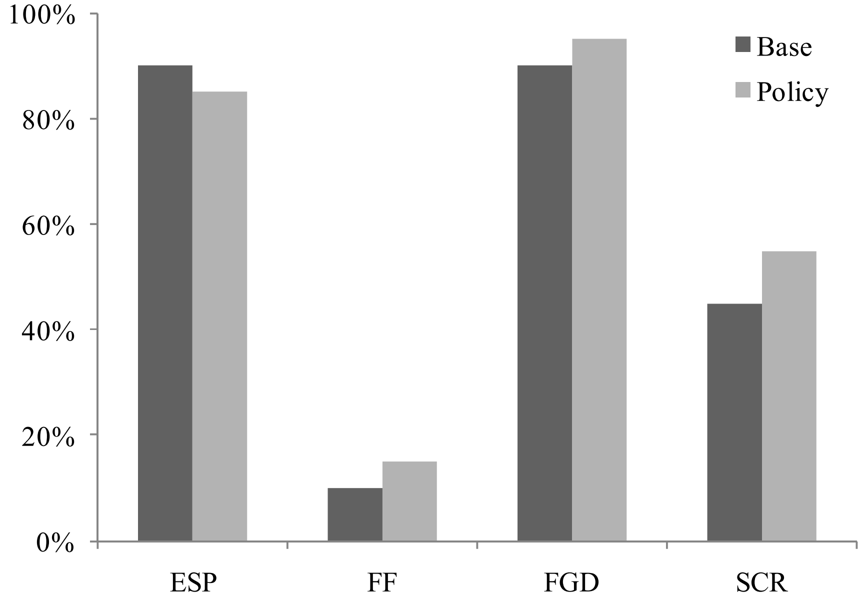

Figure 16 The application rate of emission control technologies in 2020

Coal washing can remove 0~60% of mercury. In the mercury emission projections, the mercury removal efficiency of coal washing is set to be 30%. In the baseline scenario and the policy scenario, the application ratios of coal washing are hypothesized to be 10% and 20%, respectively.

6.3. Future trends of mercury emissions

The probabilistic emission factor method was used to project the future trend of the mercury emissions from coal-fired power plants in China. The two coal consumption scenarios, high energy scenario and low energy scenario, and the two emission control scenarios, baseline scenario and policy scenario, were combined to get four different scenarios in 2020. The results from Crystal Ball^{TM} software was shown in **Figure 17**. With high coal consumption assumptions, the mercury emission would increase to 139 t and 121 t under the baseline scenario and the policy scenario respectively; with low coal consumption assumptions, the mercury emission will decrease to 95 t under the baseline scenario and 83 t under the policy scenario.

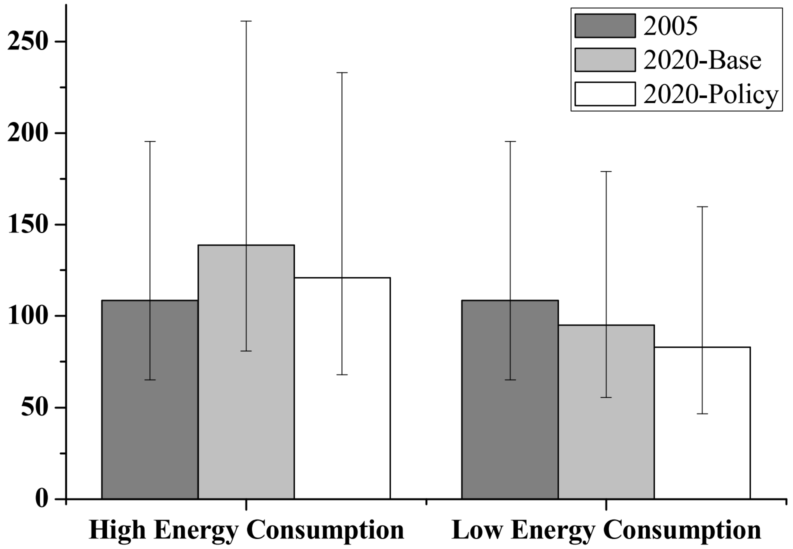

Figure 17 Mercury emissions from coal-fired power plants under different scenarios in 2020, ton

The mercury emission intensity, that is, the ratio of mercury emission to coal consumption, or the ratio of mercury emission to power generation, in 2005 and 2020 were also compared, as shown in **Figure 18**. Under the baseline control scenario, the mercury emission per unit coal consumption and the mercury emission per unit power generation decreased by 49% and 57% respectively, compared with that in 2005. Under the policy control scenario, the mercury emission per unit coal consumption and the mercury emission per unit power generation would decrease by 56% and 63% respectively, compared with that in 2005.

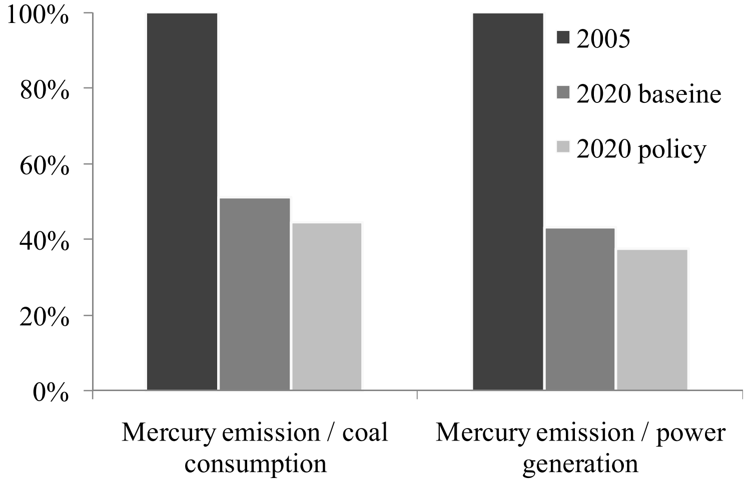

Figure 18 Mercury emission intensities under different scenarios in 2020

7. Uncertainty Analysis of the Mercury Emission

During the calculation of mercury emissions, the uncertainty of each parameter determines the uncertainty of the result.

7.1. Uncertainty of the energy consumption and structure in China

The amount of electricity demand and its structure has significant impact on the mercury emission from coal-fired power plants.

7.1.1. Energy consumption

If the proportion of coal power and standard coal consumption rate remaining constant, the total electricity demand has positive relationship with the coal consumption in power plants. Coal consumption by power plants has the direct influence on the mercury emissions. The forecast of the future energy consumption is based on the development of national economy and the electricity consumption per capita. As a fast growing economy and economy in transition, there are significant uncertainties to forecast the future economy of China.

In this study, taking the policy control scenario for example, the mercury emission estimate under the high energy scenario for 2020 is 121 t, 11% higher than the emission in 2005, while the emission under the low energy scenario for 2020 is 83 t, 24% lower than that in 2005. The emission under the high energy scenario is 46% higher than that under the low energy scenario. The uncertainty of the electricity demand will significantly affect the trend of mercury emissions in the future.

7.1.2. Dependence on coal power

The energy structure is being adjusted in China. The development of renewable energy will be emphasized in the next 20 years. In the same period, the dependence of electricity on coal power will decrease gradually. With the decrease of coal power proportion, coal consumption and mercury emissions from power plants will also change.

However, the development plan on renewable energy is still on-going. Therefore, the extent of coal power dependence is very uncertain. If the energy consumption shifts from high energy scenario to low energy scenario, the coal power proportion decreases from 75% to 60%, which cause 20% mercury emission reduction.

7.2. Uncertainty of mercury content of coal as burned

7.2.1. Mercury content of raw coal

The stochastic simulation method adopted in this study can provide with sensitivity analysis for each parameter and quantify the influence of each parameter on emissions. As shown in **Figure 19**, mercury content of coal from major coal producing provinces, such as Shanxi and Inner Mongolia, has significant influence on the mercury inventory. Therefore, the accurate evaluation of the mercury content of raw coal from major coal producing provinces is necessary to reduce the uncertainty of the inventory. However, the information on mercury contents of Chinese coal is still very limited, which results high uncertainties in the emission estimates.

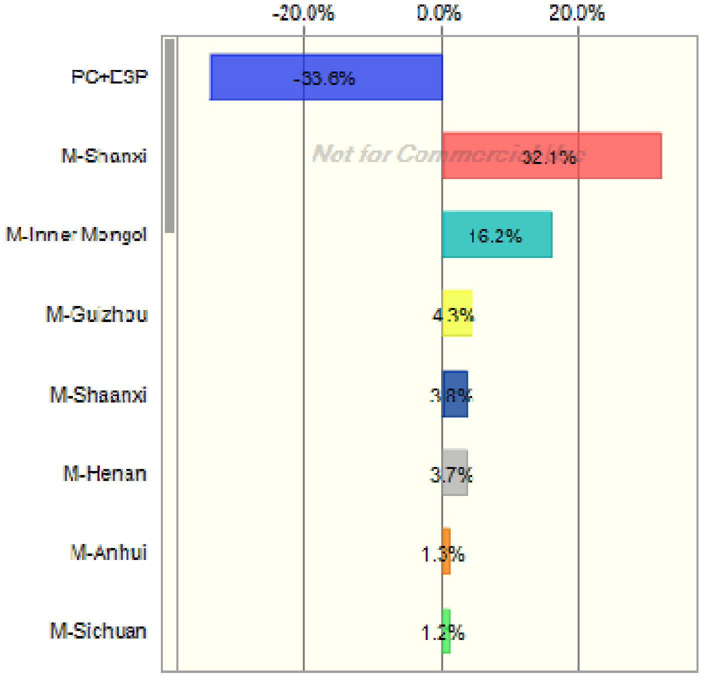

Figure 19 Contributions to variance of total mercury emissions in China (2005)

7.2.2. Trends of coal mining in China

The coal mining is towards the deep layer and the western parts of China. Both these changes will certainly affect the mercury emissions. However, the influence of coal seam depth and coal mine layout on the mercury content of coal are still controversy, which adds more uncertainties to the forecast of mercury emission from coal-fired power plants.

7.2.3. Coal transportation among provinces

The mercury content of power coal is not in accordance with the mercury content of raw coal, due to the inter-provincial coal transport, as shown in **Figure 20**.

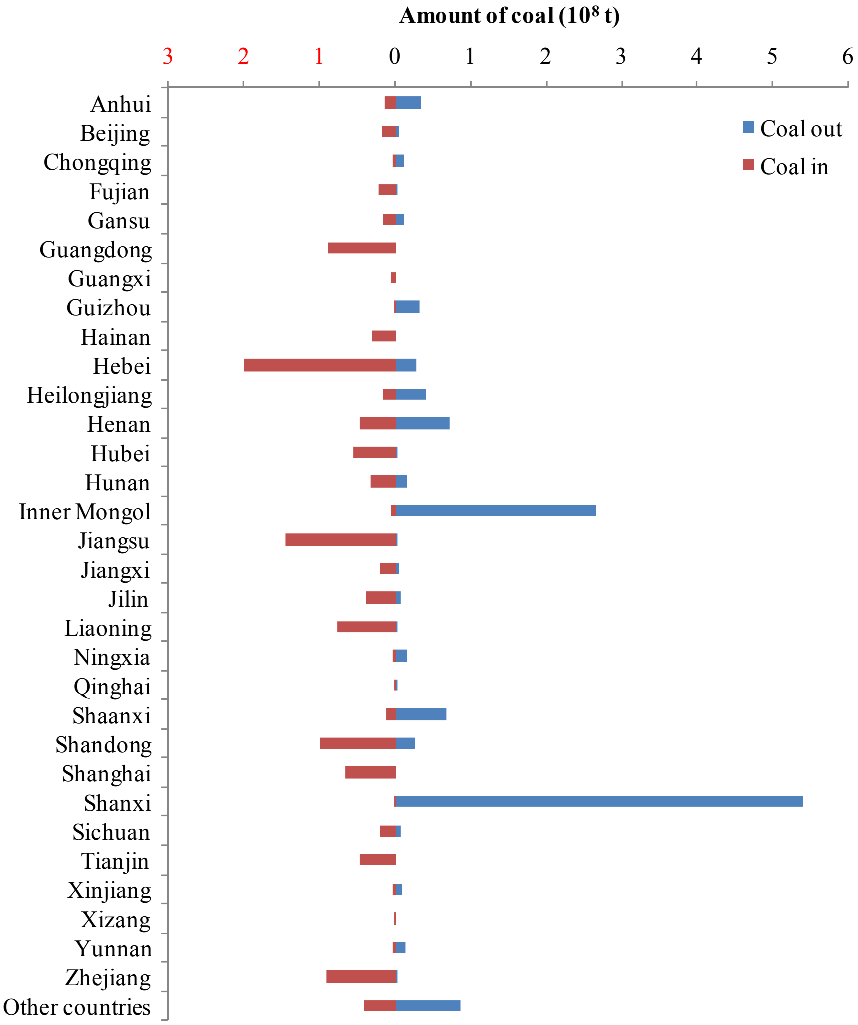

Figure 20 Input and output of raw coal in each province, 2008
(data source: Chinese Coal Statistical Yearbook, 2008)

Shanxi, Inner Mongolia, Henan and Shaanxi are the top four coal supplying provinces, accounting for 78% of the total coal output. Hebei, Jiangsu, Shandong, Zhejiang and Guangdong are the top five coal input provinces, due to their huge energy demand, accounting for 53% of the total coal input.

Besides, China exported 85.98 million tons of coal and imported 40.40 million tons of coal in 2008. The main coal importing countries were Vietnam, Indonesia, Mongolia, and Australia.

The import and transportation of coal among province directly influence the mercury contents of coal as burned in each province. To further reduce the uncertainty of the inventory, it is necessary to collect detail coal transport information.

7.3. Uncertainty of air pollution control strategies

7.3.1. Mercury removal efficiencies of APCDs

From **Figure 21**, we can see that the mercury efficiency of SCR+ESP+WFGD has significant impacts on the mercury emission forecast, because of its high penetration rate in 2020.

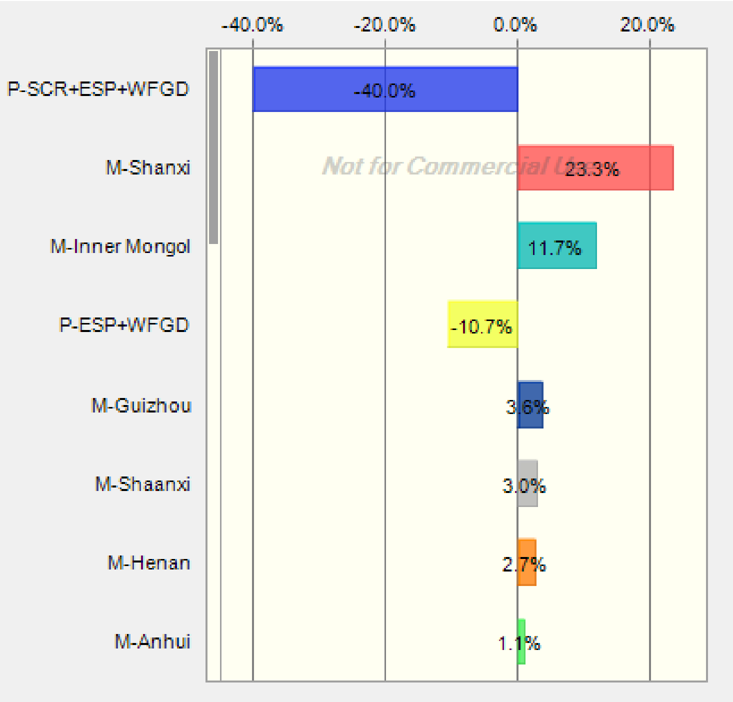

Figure 21 Contribution of different factors to the mercury emission forecast in 2020

The mercury removal efficiencies of SCR+ESP+WFGD and FF+WFGD in this study were derived from literatures and assumed to fit the Weibull distribution. However, there are few test results for these two combinations. Their mercury removal efficiencies have large uncertainty. Under the policy control scenario for 2020, the application rates of SCR and FF will reach 55% and 15% respectively. The uncertainty of mercury removal efficiencies of these two combinations will affect the forecast of the future mercury emission.

7.3.2. Implementation of air pollution control measures

There is significant difference between the two emission control scenarios in this study. Based on the preliminary analysis, the rate of implementation of the control measures can result a 40% difference in mercury emissions. However, the 12th five-year plan for environmental protection has not been introduced and there are even higher uncertainties 2015~2020, which also leads to large uncertainty on future mercury emission esimates.

7.3.3. Coal washing

In the mercury emission inventory in 2005, the application rate of washed coal in the power sector is only 1.5%. In the 2020 mercury emission forecast, we supposed about 20% of coal burned in power plants would be washed, which would reduce mercury emissions. However, there is large uncertainty in the application rate and the mercury removal efficiency of coal washing.

8. Summary

This study conducted literature review on the mercury and chlorine content of coal in China, analyzed the fate of mercury in coal-fired power plants, evaluated the mercury removal efficiencies of PM, SO_2 and NO_x control devices and developed the mercury emission inventory for coal-fired power plants in China in 2005.

Based on the analyses of 177 coal samples, the average mercury content of raw coal samples is 0.17 mg/kg, ranging from 0.01 mg/kg to 2.25 mg/kg. The average chlorine content of raw coal samples is 269 mg/kg, ranging from 30 mg/kg to 3289 mg/kg.

In 2005, the installed capacity of thermal power plants was 391.38 GW and the power generation was 2047.3 billion kWh. By the end of 2008, the total installed capacity had grown up to 602.86 GW and the power generation has reached 2803.0 billion kWh. Of the units with installed capacity over 200 MW, 96% have installed ESP and 4% have installed fabric filter, 60.2% have installed FGD system, and 20GW have installed flue gas denitrification systems.

The test results from 124 coal-fired power plants were collected from literature to analyze the mercury emission characteristics and the mercury removal efficiencies of air pollution control devices. For PC boilers, the mercury removal efficiencies (P50) of the PC+ESP, PC+ESP+WFGD, and PC+FF were 26%, 63%, and 76%, respectively.

Based on the mercury content of coal, the mercury removal efficiencies of APCDs, and amount of coal consumption, the mercury emissions from coal-fired power plants in China was calculated using the probabilistic emission factor model. The best estimate for total mercury emissions from coal-fired power plants in China was 108.6 t (P50) in 2005, with the confidence interval from 65.2 t (P10) to 195.4 t (P90).

Preliminary analysis indicated that the SO_2 emission control policies taken during 2005~2010, including phasing-out of small units and installation of FGDs, had significant co-benefit of mercury reductions. Scenario analysis showed that the power generation from coal-fired power plants might reach 4.2 to 6.1 billion MWh in 2020, which would need to burn 1.84 to 2.69 billion tons of coal.

Two pollution control scenarios, baseline scenario and policy scenario, were developed to forecast the future trend of mercury emissions. With high coal consumption assumptions, the mercury emissions in both emission control scenarios will be higher than that in 2005. With low coal consumption assumptions, the mercury emission in 2020 will slightly decrease compared to that in 2005. Because that over 70% of power plants have installed high efficiency ESPs and FGDs, the mercury emission reduction potential in future is limited.

The uncertainty of each parameter determines the uncertainty of mercury emission estimates. In this study, the uncertainties of electricity demand, dependence on coal power, mercury content of coal as burned, and implementation of air pollution control policies would respectively result in over 46%, 20%, 50%, and 40% uncertainty in the mercury emission estimate. In addition, the trend of coal mining, coal transportation among provinces, and coal washing would also significantly affect the mercury emissions. Therefore, it should be noted that the results from this project are still subject to high uncertainties.

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Appendix

Data of onsite measurement in coal-fired power plants

No.	Country	Capacity	Boiler Type and Control Devices	Coal Type	Hg removal efficiency of ESP	Hg removal efficiency of FF	Hg removal efficiency of FGD	Total Hg removal efficiency	Hg concentration in stack gas	Reference
		MW			%	%	%	%	μg/Nm^3	
1	China	220	PC+CS-ESP	bituminous	6%			6%	1.2	Chen et al., 2007
2	China	600	PC+CS-ESP	bituminous	21%			21%	32.1	Chen et al., 2007
3	China	300	PC+CS-ESP	bituminous	18%			18%	17.0	Zhou et al., 2005
4	China	600	PC+CS-ESP	bituminous	16%			16%	15.0	Zhou et al., 2006
5	China	300	PC+CS-ESP	bituminous	13%			13%		Zhou et al., 2008
6	China	600	PC+CS-ESP	bituminous	39%			39%	22.8	Wang et al., 2008
7	China	220	PC+CS-ESP	bituminous	36%			36%	1.1	Yang et al., 2007
8	China	100	PC+CS-ESP	bituminous	25%			25%	11.6	Duan et al., 2005
9	China	220	PC+CS-ESP	bituminous	27%			27%	0.3	Wang et al., 2009
10	China	600	PC+CS-ESP	bituminous	33%			33%	8.9	Wang et al., 2009
11	China	350	PC+CS-ESP	bituminous	17%			17%		Chen et al., 2006
12	China	700	PC+CS-ESP	bituminous	31%			31%		Chen et al., 2006
13	USA	100	PC+CS-ESP	bituminous	19%			19%	9.5	Kellie et al., 2004
14	Australia	340	PC+CS-ESP	bituminous	1%			1%	2.6	Shah et al., 2010
15	Australia	850	PC+CS-ESP	bituminous	25%			25%	5.6	Shah et al., 2010
16	Australia	116	PC+CS-ESP	bituminous	30%			30%	1.9	Shah et al., 2010
17	Australia	660	PC+CS-ESP	bituminous	22%			22%	1.9	Shah et al., 2010
18	Australia	254	PC+CS-ESP	bituminous	35%			35%	2.4	Shah et al., 2010
19	China	300	PC+CS-ESP	anthracite	13%			13%	16.8	Guo et al., 2004
20	China	200	PC+CS-ESP	anthracite	15%			15%	9.2	Tang, 2004
21	Korea	200	PC+CS-ESP	anthracite	42%			42%	13.7	Lee et al., 2004

22	USA	100	PC+CS-ESP	lignite	33%			33%	11.5	Kellie et al., 2004
23	USA	250	PC+CS-ESP	lignite	83%			83%	1.3	He et al., 2007
24	Spain	350	PC+CS-ESP	lignite	22%			22%		Otero-Rey et al., 2003
25	Spain	350	PC+CS-ESP	lignite	19%			19%		Otero-Rey et al., 2003
26	Spain	350	PC+CS-ESP	lignite	29%			29%		Otero-Rey et al., 2003
27	Canada		PC+CS-ESP	subbituminous	6%			6%	6.6	Goodarzi, 2004
28	Canada		PC+CS-ESP	subbituminous	13%			13%	4.9	Goodarzi, 2004
29	Canada		PC+CS-ESP	subbituminous	40%			40%	4.0	Goodarzi, 2004
30	Canada		PC+CS-ESP	subbituminous	43%			43%	4.2	Goodarzi, 2004
31	Canada		PC+CS-ESP	subbituminous	59%			59%	4.1	Goodarzi, 2004
32	Canada		PC+CS-ESP	subbituminous	3%			3%	6.3	Goodarzi, 2004
33	USA		PC+CS-ESP	subbituminous				74%		ICR, 2010
34	USA		PC+CS-ESP	bituminous				66%		ICR, 2010
35	USA		PC+CS-ESP	bituminous				55%		ICR, 2010
36	USA		PC+CS-ESP	bituminous				52%		ICR, 2010
37	USA		PC+CS-ESP	lignite				44%		ICR, 2010
38	USA		PC+CS-ESP	bituminous				36%		ICR, 2010
39	USA		PC+CS-ESP	bituminous				29%		ICR, 2010
40	USA		PC+CS-ESP	bituminous				27%		ICR, 2010
41	USA		PC+CS-ESP	bituminous				25%		ICR, 2010
42	USA		PC+CS-ESP	subbituminous				22%		ICR, 2010
43	USA		PC+CS-ESP	subbituminous				20%		ICR, 2010
44	USA		PC+CS-ESP	subbituminous				9%		ICR, 2010
45	USA		PC+CS-ESP	subbituminous				8%		ICR, 2010
46	USA		PC+CS-ESP	bituminous				5%		ICR, 2010
47	China	200	PC+CS-ESP+WFGD	bituminous	35%		56%	71%	6.7	Wang et al., 2010
48	China	600	PC+CS-ESP+WFGD	bituminous	43%		55%	74%	4.5	Wang et al., 2010
49	China	600	PC+CS-ESP+WFGD	bituminous	4%		10%	13%	7.4	Chen et al., 2007

50	China	600	PC+CS-ESP+WFGD	bituminous	37%					Wang et al., 2009
51	USA		PC+CS-ESP+WFGD	bituminous				75%		Kilgroe et al., 2002
52	Japan	700	PC+CS-ESP+WFGD	bituminous	55%		31%	69%	1.1	Yokoyama et al., 2000
53	Japan	700	PC+CS-ESP+WFGD	bituminous	8%		51%	55%	0.4	Yokoyama et al., 2000
54	Japan	700	PC+CS-ESP+WFGD	bituminous	17%		85%	88%	0.7	Yokoyama et al., 2000
55	Japan	1000	PC+CS-ESP+WFGD	bituminous	51%		44%	73%	1.4	Ito et al., 2006
56	Korea	500	PC+CS-ESP+WFGD	bituminous	30%			30%	2.3	Lee et al., 2004
57	Korea	500	PC+CS-ESP+WFGD	bituminous	65%		24%	73%		Lee et al., 2006
58	Korea	500	PC+CS-ESP+WFGD	bituminous	66%		40%	80%	1.6	Kim et al., 2009
59	Netherlands		PC+CS-ESP+WFGD	bituminous	59%		48%	78%		Meij et al., 2006
60	China	300	PC+CS-ESP+WFGD	anthracite	18%		77%	81%	5.1	Wang et al., 2010
61	China	600	PC+CS-ESP+WFGD	lignite	4%		24%	27%	2.3	Wang et al., 2010
62	USA		PC+CS-ESP+WFGD	subbituminous				73%		ICR, 2010
63	USA		PC+CS-ESP+WFGD	bituminous				72%		ICR, 2010
64	USA		PC+CS-ESP+WFGD	lignite				65%		ICR, 2010
65	USA		PC+CS-ESP+WFGD	subbituminous				56%		ICR, 2010
66	USA		PC+CS-ESP+WFGD	subbituminous				19%		ICR, 2010
67	China	50	PC+FF	bituminous		80%		80%	11.5	Chen et al., 2007
68	China	200	PC+FF	bituminous		17%		17%	39.1	Chen et al., 2007
69	China	50	PC+FF	bituminous		86%		86%	2.2	Wang et al., 2009
70	China	200	PC+FF	bituminous		9%		9%	7.4	Wang et al., 2009
71	Australia	660	PC+FF	bituminous		87%		87%	0.5	Shah et al., 2008
72	USA		PC+FF	bituminous				92%		ICR, 2010
73	USA		PC+FF	bituminous				87%		ICR, 2010
74	USA		PC+FF	subbituminous				83%		ICR, 2010
75	USA		PC+FF	bituminous				68%		ICR, 2010
76	USA		PC+FF	subbituminous				63%		ICR, 2010
77	China	165	PC+SCR+CS-ESP+WFGD	lignite	24%		17%	36%	1.2	Wang et al., 2010

78	USA	795	PC+SCR+CS-ESP+WFGD	bituminous	19%		94%	95%	0.5	Cheng et al., 2009
79	USA		PC+CS-ESP+FF	lignite				10%		ICR, 2010
80	USA		PC+FF+WFGD	bituminous				97%		ICR, 2010
81	USA		PC+FF+WFGD	bituminous				84%		ICR, 2010
82	USA		PC+HS-ESP	subbituminous				64%		ICR, 2010
83	USA		PC+HS-ESP	subbituminous				34%		ICR, 2010
84	USA		PC+HS-ESP	bituminous				30%		ICR, 2010
85	USA		PC+HS-ESP	bituminous				19%		ICR, 2010
86	USA		PC+HS-ESP	subbituminous				12%		ICR, 2010
87	USA		PC+HS-ESP	subbituminous				10%		ICR, 2010
88	USA		PC+HS-ESP+WFGD	bituminous				84%		ICR, 2010
89	USA		PC+HS-ESP+WFGD	bituminous				46%		ICR, 2010
90	USA		PC+HS-ESP+WFGD	subbituminous				31%		ICR, 2010
91	USA		PC+HS-ESP+WFGD	subbituminous				24%		ICR, 2010
92	USA		PC+HS-ESP+WFGD	subbituminous				17%		ICR, 2010
93	USA		PC+MC+WS+WFGD	subbituminous				24%		ICR, 2010
94	USA		PC+SCR+SDA+FF	bituminous				98%		ICR, 2010
95	USA		PC+SCR+SDA+FF	bituminous				97%		ICR, 2010
96	USA		PC+SDA+CS-ESP	subbituminous				70%		ICR, 2010
97	USA		PC+SDA+FF	bituminous				99%		ICR, 2010
98	USA		PC+SDA+FF	lignite				66%		ICR, 2010
99	USA		PC+SDA+FF	subbituminous				13%		ICR, 2010
100	USA		PC+SI+CS-ESP	bituminous				1%		ICR, 2010
101	USA		PC+SNCR+CS-ESP	bituminous				83%		ICR, 2010
102	USA		PC+WS	lignite				33%		ICR, 2010
103	USA		PC+WS	bituminous				12%		ICR, 2010
104	USA		PC+WS+WFGD	subbituminous				15%		ICR, 2010
105	USA		PC+WS+WFGD	subbituminous				11%		ICR, 2010

106	USA		SF+SDA+FF	bituminous				95%		ICR, 2010
107	China	100	PC+CS-ESP+CFB-FGD+FF	bituminous	11%	64%		68%	9.2	Wang et al., 2010
108	China	300	PC+SCR+CS-ESP+SW-FGD	bituminous	1%		74%	74%	4.1	Chen et al., 2008
109	China	60	PC+NID+CS-ESP	anthracite	90%			90%	2.8	Wu et al., 2008
110	China	135	CFB+CS-ESP	bituminous	99%			99%	0.2	Chen et al., 2007
111	USA		CFB+CS-ESP	lignite				56%		ICR, 2010
112	USA		CFB+FF	waste bituminous				100%		ICR, 2010
113	USA		CFB+FF	waste bituminous				100%		ICR, 2010
114	USA		CFB+FF	lignite				59%		ICR, 2010
115	USA		CFB+SNCR+FF	bituminous				89%		ICR, 2010
116	USA		CFB+SNCR+FF	subbituminous				79%		ICR, 2010
117	USA		CYC+CS-ESP	lignite				5%		ICR, 2010
118	USA		CYC+CS-ESP+WFGD	bituminous				59%		ICR, 2010
119	USA		CYC+HS-ESP	subbituminous				56%		ICR, 2010
120	USA		CYC+SDA+FF	lignite				12%		ICR, 2010
121	USA		CYC+WS+WFGD	subbituminous				43%		ICR, 2010
122	USA		TUR+CS-ESP+WFGD	bituminous				82%		ICR, 2010
123	USA		CG	bituminous				34%		ICR, 2010
124	USA		CG	bituminous				33%		ICR, 2010