Potential of Co-benefit Mercury Control for Coal-Fired Power Plants and Industrial Boilers in China

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CONTENTS

Executive Summary

Using a new technology-based probabilistic emission factor model, to reduce the range of uncertainties versus previous efforts, we estimated mercury emissions from coal-fired power plants (CFPPs) and coal-fired industrial boilers (CFIBs). For the year 2010, the median estimate for mercury emissions from CFPPs is 100 t, and from CFIBs is 72.5 t.

We then evaluated the mercury emission reduction co-benefit associated with actions already required to comply with the Action Plan for Prevention and Control of Air Pollution ("Ten Measures"), the existing emission standards for CFPPs and CFIBs, and various coal consumption scenarios developed by experts in this area. Compared to the projected emissions that would be expected if none of these actions occurred, by 2017 mercury emissions will be reduced by 46.3 t for CFPPs and 45.7 t for CFIBs. These reductions are higher than "actual" reductions due to the growth of coal consumption and possible non-compliance with the control measures over this period of time.

We project <u>actual</u> mercury emissions reductions for CFPPs by 2020 of about 25% on average (over the various control and energy consumption scenarios evaluated), versus 2010 emissions. By 2030, higher reductions are anticipated, ranging from 35–77%, largely depending upon the energy consumption scenario. For CFIBs, we project <u>actual</u> emissions reductions for CFIBs by 2020 of about 44% on average versus 2010. By 2030, reductions will range between 29–79%, again largely depending upon the energy scenario. Together, under an aggressive but feasible control strategy, up to 133 t of mercury emission reductions can be achieved from these two source categories.

The overall uncertainty levels for mercury emissions from CFPPs and CFIBs in 2010 were evaluated to be (−35%, +45%) and (−45%, +47%), respectively. The uncertainties of mercury concentration in coals from major coal producing provinces, such as Shanxi and Inner Mongolia, and the uncertainties of mercury removal efficiencies major air pollution control devices contributed most to the overall uncertainties. The future projections by 2020 and 2030 have even larger uncertainties due to the extra uncertainties from energy and control scenarios.

However, on the basis of these estimates, China can establish a national mercury reduction target for CFPPs of 25% by 2020, and 50–70% by 2030, versus 2010 emissions. For CFIBs, China can establish a 30–50% reduction target by 2020, and a 50–70% reduction target by 2030, compared to 2010 emissions.

In addition, we evaluated the emission levels achievable at the source level, based upon our estimation of mercury concentrations in exhausted flue gases from CFPPs and CFIBs in China, after considering the mercury content in Chinese coals and the removal efficiency of typical APCD combinations, and the variation of mercury removal efficiency. We find most CFPPs can currently meet an emission standard of 15 $\mu g/m^3$, as compared to the existing standard of 30 $\mu g/m^3$, and most CFIBs can meet 20 $\mu g/m^3$ as opposed to the current standard of 50 $\mu g/m^3$. A possible exception may be some southwestern regions in China consuming coals with high mercury content.

To allow for the consumption of high mercury coal in some instances, we propose China consider adopting a combination of an emission limit and a mercury removal efficiency when revising the mercury emission standards for these sources, so that the regulatory agency/source could choose between which component of the standard it chooses to apply due to its site-specific circumstances. The combinative standard for CFPPs by 2020 could be an alternative between a concentration emission limit of 8 $\mu g/m^3$ or a mercury removal efficiency of 75%, and the combinative standard for CFIBs by 2020 could be an alternative between an emission limit of 10 $\mu g/m^3$ or a removal efficiency of 70%. The concentration limits for 2020 are about half of the limits determined achievable by most plants for 2010 in this study.

Based on the same methodology, the combinative standard for CFPPs by 2030 could be an alternative between a concentration limit of 5 $\mu g/m^3$ or a mercury removal efficiency of 85%, and the combinative standard for CFIBs by 2030 could be an alternative between an emission limit of 7 $\mu g/m^3$ or a removal efficiency of 75%.

1. Introduction

Mercury (Hg) is a trace heavy metal, attracting global attention due to its toxicity, persistence, long range transport and bioaccumulation in the environment. Because of the regional and global atmospheric circulation, mercury can travel for a long distance and deposit far away from emission sources, causing the elevation of mercury or methyl-mercury level in organisms and subsequent losses of human and ecological health and properties. The burden of disease of mercury, and the global threats it poses to human health and the environment are well-recognized by governments and efforts to confront the threat posed by mercury to human health and the environment have grown over the last decades. In 2013, a legally binding international treaty, the Minamata Convention on Mercury, was agreed. The Convention aims to protect human health and the environment from anthropogenic mercury emissions and releases. China signed the Convention on October 10, 2013. As of February 2016, 128 countries have signed the Convention and 23 countries have ratified it.

The most significant releases of mercury emission are to the air. The total anthropogenic emissions of mercury to the atmosphere in 2010 are estimated at 1,960 tonnes (UNEP, 2013). Mercury in the atmosphere mainly exists in the gaseous form (Sprovieri et al., 2010). Atmospheric mercury can be divided into total gaseous mercury (TGM) and particle-bound mercury (PBM) in physical forms. TGM is further divided into gaseous elemental mercury (GEM) and reactive gaseous mercury (RGM) in chemical forms (Ci et al., 2012). The three mercury species exhibit very different atmospheric behaviors. RGM and to some extent PBM have a high surface reactivity and water solubility and are readily scavenged from atmosphere through wet and dry deposition. However, GEM, the predominant form of atmospheric Hg (>90% of the total mercury in the atmosphere), is fairly stable in the lower atmosphere with a residence time of several months to over one year (Fu et al., 2012). Under normal atmospheric condition, it disperses globally before it is oxidized by atmospheric oxidants (such as Br, OH, O_3, BrO, etc.) to RGM. Large amounts of mainly inorganic mercury have accumulated in the environment, in particular in surface soils and in the oceans.

China is the largest contributor of anthropogenic mercury to the atmosphere. China's National Implementation Plan (NIP) for implementation of the Minamata Convention is under preparation in order to fulfill its commitment to mercury control and reduction. The predominant mercury emission sources in China are coal combustion, non-ferrous metal smelting and cement production, contributing 47%, 22% and 18% to the total mercury emissions in China in 2010 based on the most recent estimation (Zhang et al., 2015). These sources were listed as the top priorities of mercury emission control in the Convention. Coal-fired power plants (CFPPs) and coal-fired industrial boilers (CFIBs) are the largest contributors in the coal combustion sector. CFPPs are often the first sector for pilot activities because they are better supervised for early actions. In 2011, the Ministry of Environmental Protection initiated the pilot project on mercury monitoring and control for 16 coal-fired power plants in China. CFIBs, on the other hand, are more widely spread and difficult to supervise and manage. Since most of the CFIBs have small scale and low-efficiency air pollution control devices (APCDs), the total amount of mercury emission from CFIBs may be equivalent to the amounts of emissions from large point sources.

The Minamata Convention requires fundamental information on both the inventory of atmospheric mercury emissions from CFPPs and CFIBs in China, and also the effectiveness of existing air pollution control measures on mercury emission control. Among all the existing air pollution control measures implemented in China for both conventional pollutants (PM, SO_2, NO_x) and mercury, the Action Plan for Prevention and Control of Air Pollution ("Ten Measures") has the most relevant and important potential co-benefit impacts on the mercury emission control for CFPPs and CFIBs in China. Therefore, the purpose of this study is to develop the mercury emission inventories for CFPPs and CFIBs in China and to evaluate the potential of co-benefit mercury control for these two sectors during 2012–2017, based on existing or project domestic Chinese air pollution control programs. Future scenarios for 2020 and 2030 are also developed to consider the possible additional requirements of the Minamata Convention for BAT/BEP adoption for CFPPs and CFIBs. The outcome of this study will to a certain extent fulfill the information gap of the coal combustion sector in China, relevant to the Minamata Convention.

2. Methods for the development of mercury emission inventories

2.1. Model description

Most of the existing mercury emission inventories for China (Streets et al., 2005; UNEP, 2013) were based on a deterministic emission factor approach, which can be described by **Equation 1**. Mean values were used for all the parameters.

$$E = \sum_i \sum_j \left[M_i \cdot A_{ij} \cdot (1 - Q \cdot w) \cdot R_j \cdot \left(1 - \sum_k P_{ijk} \cdot \eta_{jk} \right) \right] \quad \textbf{(E1)}$$

where *E* is the mercury emission from coal-fired power plants, t/yr; *M* is the mercury content of coal as burned, mg/kg; *A* is the amount of coal consumption, Mt/yr; *Q* is the percentage of washed coal in the power plants; *w* is the mercury removal efficiency of coal washing; *R* is the release factor of mercury from boiler; *P* is the application rate of a certain combination of APCDs; η 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.

This study adopted a technology-based probabilistic emission factor model to assess the mercury emissions from coal-fired power plants and industrial boilers in China by province. Based on the detailed data collected or investigated in this study, statistical distribution functions are built into the model to address the uncertainties of key parameters (e.g., mercury content of coal, mercury removal efficiency of APCDs, etc.). This model can be described by **Equation 2**:

$$E(x_i, y_{jk}) = \sum_i \sum_j \left[M_i(x_i) \cdot A_{ij} \cdot (1 - Q \cdot w) \cdot R_j \cdot \left(1 - \sum_k P_{ijk} \cdot \eta_{jk}(y_{jk}) \right) \right] \quad \textbf{(E2)}$$

where $E(x,y)$ is the probability distribution of the mercury emission from coal-fired power plants; $M(x)$ is the probability distribution of the mercury content of coal as burned; $\eta(y)$ is the probability distribution of the mercury removal efficiency of APCD combinations.

The model incorporates 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 mercury content of coal and the mercury removal efficiency of APCDs are the two most variable parameters in the equation. Therefore, they were chosen to be considered as probability distribution functions. Crystal Ball ™ was employed to accomplish the calculation. To get reliable output, the sampling number for the Monte Carlo simulation was set to 10,000.

Core input parameters such as mercury concentration in coal and mercury removal efficiency by APCDs fit the skewed distribution (e.g. lognormal distribution and Weibull distribution). Therefore, the arithmetic mean values used in deterministic models were not able to reflect the best guesses of these key parameters, which could probably result in overestimation or in rare cases underestimation of the mercury emissions from given sectors. The calculations in this model for the coal combustion sector were all technology-based and the APCD categorization was more detailed and updated. With the adoption of the novel methodology and the consideration of uncertainty levels of key parameters for the estimation of the coal combustion sector, the depiction of mercury emission inventories for China was significantly improved in this study. More detailed information on the methodology can be found in our recent papers (Zhang et al., 2012; Zhang et al., 2015).

Coal quality has significant influence on the mercury removal efficiency of APCDs. Considerable amount of on-site measurements in CFPPs have been conducted in previous studies, based on which we developed a sub-model for power plants in the inventory model. This sub-model mainly describes the effect of coal quality, primarily chlorine content, on the mercury speciation, transformation and removal in flue gas across APCDs in power plants. In general, high halogen content will yield greater mercury removal, but there is lack of data to quantify the influence bromine content in coal. With the sub-model integrated, **Equation 2** can be modified as:

$$E(x_i, z_i) = \sum_i \sum_j \left[M_i(x_i) \cdot A_{ij} \cdot (1 - Q \cdot w) \cdot R_j \cdot \left(1 - \sum_k P_{ijk} \cdot \eta_{jk}(x_i, z_i) \right) \right] \quad \textbf{(E3)}$$

$$\eta_{jk}(x_i, z_i) = f_{\eta_{jk}} \left(M_i(x_i), C_i(z_i), H_i \right) \quad \textbf{(E4)}$$

where $E(x,z)$ is the probability distribution of the mercury emission from coal-fired power plants; $M(x)$ is the probability distribution of the mercury content of coal as burned; $C(z)$ is the probability distribution of the chlorine content of coal as burned; H is the ash content of coal as burned; $\eta(x,z)$ is a function of $M(x)$, $C(z)$ and H.

The sub-model is an empirical model based on the results from on-site measurements, linking coal quality to the mercury behavior in the flue gas across each APCD in power plants. It starts from the mercury speciation out of the boiler considering the mercury content, the chlorine content and the ash content of coal, followed by evaluating the removal efficiencies of different mercury species according to the proportions of the three species before each APCD. Details of the sub-model can be found in our previous paper (Zhang et al., 2012).

2.2. Key parameters for inventory development

2.2.1. Mercury content of coal

The database of mercury coal content used in this study was based on Zhang et al. (2012) and USGS (2004), covering almost all the large coal basins in China (**Table 1**). Shanxi and Inner Mongolia, the largest two coal producers in China, have 88 and 46 samples respectively. For other large coal producers, such as Shaanxi, Henan, Shandong, Anhui and Heilongjiang, over 20 samples were obtained. The number of samples was mainly based on the amount of coal production in each province. The variability of mercury content of coal was also taken into consideration when deciding on the number of samples. Guizhou, considered as the province with the largest variability in the mercury content of coal, has 46 samples. For other provinces with a large variation in the range of coal mercury content, such as Yunnan, Sichuan and Hebei, over 15 samples were taken.

Table 1. Number of coal samples in the database by province

Province	**Zhang et al. (2012)**	**USGS (2004)**	**Total**	**Province**	**Zhang et al. (2012)**	**USGS (2004)**	**Total**
Anhui	9	11	20	Jiangxi	–	7	7
Beijing	–	1	1	Jilin	–	5	5
Chongqing	5	7	12	Liaoning	10	9	19
Fujian	–	3	3	Ningxia	–	4	4
Gansu	2	5	7	Qinghai	–	1	1
Guangdong	–	2	2	Shaanxi	17	11	28
Guangxi	–	5	5	Shandong	14	19	33
Guizhou	30	16	46	Shanghai	–	–	–
Hainan	–	–	–	Shanxi	–	88	88
Hebei	9	15	24	Sichuan	4	11	15
Heilongjiang	10	10	20	Tianjin	–	–	–
Henan	10	27	37	Xinjiang	12	6	18
Hubei	–	3	3	Xizang	–	–	–
Hunan	–	10	10	Yunnan	10	7	17
Inner Mongolia	30	16	46	Zhejiang	–	–	–
Jiangsu	5	6	11	**National**	**177**	**305**	**482**

Table 2 shows the comparison with previous studies, and **Table 3** shows the comparison with other countries/regions in the world.

The provinces with large coal consumption are not the same as the provinces with large coal production due to the inter-provincial coal transport. The mercury content of coal in **Equation 2** is for the coal as consumed, while the original mercury content information is for the raw coal. Therefore, the mercury content of coal as consumed by province is a linear combination of the mercury content of raw coal by province. A coal transport matrix was developed in this study to link the two datasets. The coal transport matrix can be described as follows:

$$\mathbf{m}_c = \mathbf{A}\mathbf{m}_p \qquad \textbf{(E5)}$$

$$\mathbf{m}_c = [m_{c1}, m_{c2}, \cdots, m_{cn}]^{\mathrm{T}}$$
$$\mathbf{A} = \{a_{ij}\}_{n \times n}$$
$$\mathbf{m}_p = [m_{p1}, m_{p2}, \cdots, m_{pn}]^{\mathrm{T}}$$

where vector $\mathbf{m}_c$ is the mercury content of coal as consumed in all the provinces; $\mathbf{m}_p$ is the mercury content of coal as produced in all the provinces; **A** is the coal transport matrix, and a_{ij} is the percentage of the amount of coal transported from province j to province i; n is the number of provinces.

Table 2. Mercury content of raw coals by province in different studies (mg/kg)

Province	Zheng et al. (2007)	Ren et al. (2006)	Streets et al. (2005)	USGS (2004)	Huang et al. (2002)	Wang et al. (2000)
Anhui	0.21	0.46(50)	0.26	0.19(11)	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)	–	–
Gansu	–	1.35(1)	0.05	0.05(5)	–	–
Guangdong	–	0.10(1)	0.15	0.06(2)	–	–
Guangxi	–	–	0.30	0.35(5)	–	–
Guizhou	1.14	0.70(133)	0.52	0.20(16)	0.52	–
Hainan	–	–	0.15	–	–	–
Hebei	0.46	0.16(33)	0.14	0.14(15)	0.80	0.13
Heilongjiang	0.13	0.12(14)	0.09	0.06(10)	0.14	0.12
Henan	0.17	0.14(115)	0.25	0.21(27)	0.17	0.30
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	0.17(14)	0.22	0.16(16)	0.02	0.28
Jiangsu	0.09	0.18(10)	0.16	0.35(6)	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	0.14(16)	0.17	0.19(9)	0.13	0.20
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)	0.08	0.16
Shandong	0.28	0.18(11)	0.18	0.13(19)	0.21	0.17
Shanghai	–	–	–	–	–	–
Shanxi	0.08	0.17(79)	0.16	0.15(88)	0.20	0.22
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)	–	0.03
Xizang	–	–	–	–	–	–
Yunnan	0.30	0.32(56)	0.29	0.14(7)	0.34	–
Zhejiang	–	0.75(2)	0.35	–	–	–
National	0.19	0.33(619)	0.19	0.16(305)	0.15	0.22

Table 3. Mercury content of raw coals from different countries/regions (mg/kg)

Country/region	Coal rank	Average	Range	Reference
Australia	Bituminous	–	0.03–0.4	Pirrone et al. (2001)
Argentina	Bituminous	0.10(2)	0.03–0.18	Finkelman (2004)
Botswana	Bituminous	0.09(11)	0.04–0.15	Finkelman (2004)
Brazil	Bituminous	0.19(4)	0.04–0.67	Finkelman (2004)
Columbia	Subbituminous	0.04(16)	0.02–0.17	Finkelman (2004)
Czech	Bituminous	0.25(24)	0.02–0.73	Finkelman (2003)
Egypt	Bituminous	0.12(14)	0.04–0.36	Finkelman (2003)
Germany	Bituminous	–	0.7–1.4	Pirrone et al. (2001)
Indonesia	Lignite	0.11(8)	0.02–0.19	Finkelman (2003)
Indonesia	Subbituminous	0.03(78)	0.01–0.05	US EPA (2002)
Japan	Bituminous	–	0.03–0.1	Pirrone et al. (2001)
New Zealand	Bituminous	–	0.02–0.6	Pirrone et al. (2001)
Peru	Anthracite/Bituminous	0.27(15)	0.04–0.63	Finkelman (2004)
Philippines	Subbituminous	0.04	0.04–0.1	Finkelman (2004)
Poland	Bituminous	–	0.01–1.0	Pirrone et al. (2001)
Romania	Lignite/Subbituminous	0.21(11)	0.07–0.46	Finkelman (2004)
Russia	Bituminous	0.11(23)	0.02–0.84	Finkelman (2003)
Slovakia	Bituminous	0.08(7)	0.03–0.13	Finkelman (2004)
South Africa	Bituminous	–	0.01–1.0	Pirrone et al. (2001)
South America	Bituminous	0.08(269)	0.01–0.95	US EPA (2002)
South Korea	Anthracite	0.30(11)	0.02–0.88	Finkelman (2003)
Tanzania	Bituminous	0.12(15)	0.04–0.22	Finkelman (2004)
Thailand	Lignite	0.12(11)	0.02–0.57	Finkelman (2003)
Turkey	Lignite	0.11(143)	0.03–0.66	Finkelman (2004)
Ukraine	Bituminous	0.07(12)	0.02–0.19	Finkelman (2003)
UK	Bituminous	–	0.2–0.7	Pirrone et al. (2001)
USA	Subbituminous	0.10(640)	0.01–8.0	US EPA (1997)
USA	Lignite	0.15(183)	0.03–1.0	US EPA (1997)
USA	Bituminous	0.21(3527)	0.01–3.3	US EPA (1997)
USA	Anthracite	0.23(52)	0.16–0.30	US EPA (1997)
Vietnam	Anthracite	0.28(3)	0.02–0.74	Finkelman (2004)
Yugoslavia	Lignite	0.11(3)	0.07–0.14	Finkelman (2004)
Zambia	Bituminous	0.60(12)	0.03–3.6	Finkelman (2004)
Zimbabwe	Bituminous	0.08(3)	0.03–0.5	Finkelman (2004)

2.2.2. Mercury removal efficiency by APCDs

Besides the mercury content of coal, the mercury removal efficiency of air pollution control devices (APCDs) is another key parameter in the model. Results of the 118 on-site measurements from existing studies were summarized and analyzed to achieve a comprehensive understanding of mercury removal across APCDs. Most of these test results were from China and the United States, and some also came from Canada, Japan, South Korea, the Netherlands and Australia. **Table 4** shows the average mercury removal efficiencies of 18 different APCD combinations (including boiler type) for both CFPPs and CFIBs. Cyclones (CYC) barely have any mercury removal efficiency (Streets et al., 2005) and are thus not included in **Table 4**.

The combination of pulverized coal boiler (PC boiler), electrostatic precipitator (ESP) and wet flue gas desulfurization (WFGD) is the most commonly used APCD combination for CFPPs in China in 2010 with an average mercury removal efficiency of 62%. With the increase of the application of selective catalytic reduction system (SCR), PC+SCR+ESP+WFGD will be the most widely used combination in the near future for CFPPs, the mercury removal efficiency of which averages 69%. There are 63 observations for PC+ESP and 19 for PC+ESP+WFGD, and we developed a sub-model for these two combinations based on the sufficient database (as described in Section 2.1). Data for the combination of PC boiler and fabric filter (FF) are not enough for the sub-model, so we use the batch fit function in Crystal Ball ™ to perform a probabilistic distribution fitting. As a result, the mercury removal efficiency of PC+FF fits the Weibull distribution and corresponding parameters are acquired based on field measurement data. The probabilistic distribution of the mercury removal efficiency of PC+FF was directly used in the inventory model as described in **Equation 2**.

The combination of stoker fired boiler (SF boiler) and wet scrubber (WS) is widespread for CFIBs in China in 2010 with an average mercury removal efficiency of 23%. Similar to the combination of PC+FF for CFPPs, the mercury removal efficiency of the combination of SF+WS for CFIBs also fits the Weibull distribution, and corresponding parameters are acquired based on field measurement data. The probabilistic distribution of the mercury removal efficiency of SF+WS was directly used in the inventory model as described in **Equation 2**. Integrated marble scrubber (IMS) is a special type of WS for concurrent PM and SO_2 removal, which is more and more widely adopted by CFIBs in China due to its technological economy. The average mercury removal efficiency is 38%, higher than that of WS. IMS uses $Ca(OH)_2$ or NaOH as the sorbent to capture SO_2, which has co-benefit on enhancing mercury removal. However, different alkali addition rate will result in different mercury removal efficiencies. Some CFIBs, especially large-scale boilers, have the same APCD configurations as CFPPs, such as FF+WFGD. Although the scale of these devices for CFIBs are usually smaller than those for CFPPs, no significant discrepancy is found for the mercury removal efficiency and the mean value (86%) is used for FF+WFGD with either PC boiler or SF boiler.

The mercury removal efficiencies of APCD combinations other than PC+ESP, PC+ESP+WFGD, PC+FF and SF+WS do not have enough data to perform a probabilistic distribution fitting. Therefore, mean values are used in the calculation of mercury emission inventories.

Table 4. Average mercury removal efficiencies of air pollution control devices (%)

	Overall	Bituminous	Anthracite	Lignite	Sub-bit
PC+ESP	29 (63)	29 (42)	22 (4)	38 (6)	27 (11)
PC+ESP+WFGD	62 (19)	63 (14)	81 (1)	65 (1)	50 (3)
PC+FF	67 (10)	66 (8)	–	–	73 (2)
PC+SCR+ESP+WFGD	69 (4)	69 (4)	–	–	–
PC+FF+WFGD	86 (3)	90 (2)	79 (1)	–	–
PC+SCR+FF+WFGD	93 (2)	93 (2)	–	–	–
PC+SDA+FF	59 (3)	99 (1)	–	66 (1)	13 (1)
PC+SDA+ESP	70 (1)	–	–	–	70 (1)
PC+ESP+CFB–FGD+FF	68 (1)	68 (1)	–	–	–
PC+SCR+SDA+FF	98 (2)	98 (2)	–	–	–
PC+NID+ESP	90 (1)	–	90 (1)	–	–
PC+SNCR+ESP	83 (1)	83 (1)	–	–	–
SF+WS	23 (8)	23 (8)	–	–	–
SF+IMS	38 (2)	17 (1)	59 (1)	–	–
SF+FF+WFGD	86 (3)	90 (2)	79 (1)	–	–
CFB+ESP	74 (3)	99 (1)	–	66 (2)	–
CFB+FF	86 (3)	100 (2)	–	59 (1)	–
CFB+SNCR+FF	84 (2)	89 (1)	–	–	79 (1)

Note: the numbers in brackets are number of onsite measurements. PC – pulverized coal boiler; SF – stoker fired boiler; CFB – circulating fluidized bed boiler; ESP – electrostatic precipitator; FF – fabric filter; WS – wet scrubber; IMS – integrated marble scrubber; WFGD – wet flue gas desulfurization; CFB-FGD – circulating fluidized bed flue gas desulfurization; NID – novel integrated desulfurization; SDA – spray dryer absorber; SCR – selective catalytic reduction; SNCR – selective non-catalytic reduction.

2.2.3. Activity levels and APCD installation rates for the baseline year (2010)

(1) Coal-fired power plants (CFPPs)

In 2010, the total capacity of thermal power plants in China is 710 GW, 92% of which is CFPPs. The total amount of electricity production from thermal power plants is 3417 TWh in 2010, and the standard coal consumption is 333 gce/kWh averagely. According to China Energy Statistical Yearbook, the total coal consumption in the power sector is 1545 million tonnes in 2010. Inner Mongolia, Shandong and Jiangsu are the three provinces with the biggest coal consumption for power generation, all exceeding 100 million tonnes in 2010. Pulverized coal (PC) boiler is the most widely used type of boiler in the power sector, accounting for 88% of the total capacity. The rest of the power plants use circulating fluidized bed (CFB) boiler. Only 2.1% of the coal for power use is washed in 2010.

For particulate matter (PM) control, electrostatic precipitators (ESP) are installed in 93% of all the CFPPs, and the remaining plants use fabric filter (FF) or the combination of ESP and FF. In 2010, the total PM emission from CFPPs is about 3 million tonnes with an intensity of less than 1.0 g/kWh. A capacity of 560 GW installs SO_2 control devices, accounting for 86% of the total capacity. Wet flue gas desulfurization (WFGD) using limestone is the most popular technology (92%), and the rest are WFGD using seawater or ammonia or CFB-FGD. In 2010, the total SO_2 emission from CFPPs is 9.26 million tonnes with an intensity of 2.7 g/kWh, even lower than that of the USA in 2009 (3.4 g/kWh). Only 14% of the total capacity installs NO_x control devices in 2010. Over 95% uses selective catalytic reduction system (SCR), and the rest uses selective non-catalytic reduction system (SNCR).

(2) Coal-fired industrial boilers (CFIBs)

Industrial boilers are those boilers which provide manufacturing and mining industries (e.g. chemical industry, heating supply, iron and steel production, coal mining, etc.) with steam or hot water to satisfy the needs of production, power, heating and so on. There are over 600,000 industrial boilers in service in China with a capacity of 2.3 million tonnes of steam per hour (t/h). Over 80% of the industrial boilers use coal as fuel, while others use natural gas, oil, biofuel or waste heat. In 2010, approximately 730 million tonnes of coal was burned in CFIBs in China. Given that the average mercury content of coal in China is 0.17 mg/kg, over 124 tonnes of mercury was released from CFIBs to flue gases, a large percentage of which was emitted to the atmosphere eventually due to outdated APCDs for CFIBs in China. Based on the National Investigation of Pollution Sources in China, most of the industrial boilers in China (70% by unit) are in small scale with a capacity of less than 10 t/h. Large-scale boilers (>35 t/h) only accounted 7% of the total by unit but contribute to 52% by capacity.

According to combustion mode, industrial boilers can be divided into stoker fired (SF) boiler, chamber combustion (CC) boiler, and circulating fluidized bed (CFB) boiler. SF boiler is the most widely used boiler type, accounting for over 90% of the capacity of small- and medium-scale boilers, and 70% of large-scale boilers. As discussed below, most CFIBs in China only have low-efficiency PM control devices including cyclone (CYC) and wet scrubber (WS), whose co-benefit mercury removal efficiency is also low. WS has an average mercury removal rate of 23%, while CYC has almost no co-benefit on mercury capture. High-efficiency PM control devices, including electrostatic precipitator (ESP) and fabric filter (FF), have not yet been widely adopted for CFIBs in China.

Most of the small- and medium-scale CFIBs (95% of the total capacity) are equipped with wet scrubbers (WS) to reduce PM emissions. Large-scale CFIBs also have a WS installation rate of over 80%. A small proportion (<20%) of large-scale CFIBs are equipped with FF and WFGD, the combination of which have a high mercury removal efficiency of 86%. NO_x control devices have not yet been applied to CFIBs. No dedicated mercury control devices are used in this sector either.

2.3. Method for uncertainty analysis

Streets et al. (2005) analyzed the uncertainties of Hg emission inventory of anthropogenic sources in China with a semi-quantitative approach by grading all the parameters in Hg emission factors. It was only applicable to the deterministic emission factor model and had relatively lower reliability than the quantitative method. Wu et al. (2010) used the P10–P90 confidence interval of the statistical distribution of Hg emission as the uncertainty range, where P10/P90 value represents a probability of 10%/90% that the actual result would be equal to or below the P10/P90 value. However, this uncertainty range was even larger than the result from the study of Streets et al., because these two methods were not comparable. Therefore, a new approach was developed in our recent study to determine the uncertainty range of a general skewed distribution for the model. The calculating method is shown as **Equation 6**:

$$u^{\pm} = \frac{\mathrm{Mo} - \sqrt{\sigma_s^{\pm}\sigma_k^{\pm}}}{\mathrm{P50}} - 1 \qquad \textbf{(E6)}$$

where u is the uncertainty; Mo is the mode; P50 is the value at which there is a probability of 50% the actual result would be equal to or below; σ_s^- and σ_s^+ are the distances between Mo and the values where the probability equal to $f(\mathrm{Mo})/2$; σ_k^- and σ_k^+ are the distances between Mo and P20 or P80.

The uncertainty range of a normal distribution is described by the relative standard deviation (RSD). The approach for uncertainty analysis in this study extended the use of the RSD in a normal distribution case to a general skewed distribution case. The uncertainty range yielded from this quantitative approach reflects both the span and the kurtosis of the skewed distribution, which is more reasonable and distinguished from a confidence interval. This approach is better to compare with previous studies, e.g. Streets et al. (2005). P10/P90 ranges from the study of Wu et al. (2010) can be better referred as the confidence interval with a confidence degree of 80%. More details can be found in our recent study (Zhang et al., 2015).

3. Projection of mercury emission control scenarios

3.1. Identification of air pollution control requirements for coal combustion

3.1.1. Action Plan for Prevention and Control of Air Pollution ("Ten Measures")

The Action Plan for Prevention and Control of Air Pollution ("Ten Measures") was released by the State Council of China in June 2013. The goal of "Ten Measures" is to improve the nation air quality and significantly reduce the heavy pollution episodes, especially for the Beijing-Tianjin-Hebei (BTH) region, the Yangtze River Delta (YRD) region and the Pearl River Delta (PRD) region. The specific objective of "Ten Measures" is to achieve a 10% reduction of PM_{10} concentration in all cities in China from 2012 to 2017, and 25%, 20% and 15% reduction of $PM_{2.5}$ concentrations respectively in the BTH, YRD and PRD regions during this period, with a $PM_{2.5}$ concentration threshold of 60 μg/m^3 for Beijing in 2017. These air pollution control measures will have co-benefits on atmospheric mercury abatement. There are four major actions in "Ten Measures" for the coal combustion sector:

(1) Shutting down small-scale boilers and promoting centralized heat supply

- Coal-fired industrial boilers with a capacity of less than 10 t/h in urban area need to be eliminated;
- New constructions of coal-fired industrial boilers with a capacity of less than 20 t/h in urban area are strictly forbidden;
- New constructions of coal-fired industrial boilers with a capacity of less than 10 t/h in other area are strictly forbidden.

(2) Accelerating the construction of high-efficiency PM, SO_2 and NO_x control devices

- All the coal-fired power plants are required to install SO_2 control devices before 2017;
- All the coal-fired power plants are required to install NO_x control devices except for those with circulating fluidized bed (CFB) boilers before 2017;
- All the coal-fired industrial boilers with a capacity of over 20 t/h are required to install SO_2 control devices before 2017.

(3) Controlling the total amount of coal consumption

- The proportion of coal consumption in the total energy consumption is reduced to less than 65%;
- The total amounts of coal consumption in the BTH, YRD and PRD regions decrease from 2012 to 2017.

(4) Promoting coal washing

- Newly built coal mines are required to equip with coal washing devices;
- The proportion of coal washing needs to be higher than 70% by 2017.

3.1.2. Emission Standard of Air Pollutants for Thermal Power Plants (GB 13223-2011)

Emission Standard of Air Pollutants for Thermal Power Plants (GB 13223-2011) was released in July 2011 in replacement of GB 13223-2003. The emission thresholds for PM, SO_2 and NO_x concentrations in the new standard were implemented on January 1, 2012 for newly built coal-fired power plants and on July 1, 2014 for existing CFPPs. The tightening of the standards for conventional air pollutants will accelerate the construction of high-efficiency PM, SO_2 and NO_x control devices, which will have co-benefit on mercury emission control. The emission threshold for Hg concentration in the exhausted flue gas from CFPPs in China was, for the first time, put forward and was implemented on January 1, 2015. All the emission thresholds for PM, SO_2, NO_x and Hg concentrations are listed in **Table 5**. The emission threshold for atmospheric mercury emission from thermal power plants was for the first time adopted (0.03 mg/m^3).

3.1.3. Emission Standard of Air Pollutants for Boilers (GB 13271-2014)

Emission Standard of Air Pollutants for Boilers (GB 13271-2014) was released in May 2014 to replace GB 13271-2001. The tightening of the standards for conventional air pollutants will also accelerate the construction of high-efficiency PM, SO_2 and NO_x control devices, which will have co-benefit on mercury emission control. All the emission thresholds for PM, SO_2, NO_x and Hg concentrations are listed in **Table 6**. The emission thresholds for PM, SO_2, NO_x and Hg concentrations in the new standard became effective on July 1, 2014 for newly built coal-fired industrial boilers, became effective on October 1, 2015 for existing coal-fired industrial boilers with a capacity of over 10 t/h or 7 MW, and on July 1, 2016 will be effective for existing coal-fired industrial boilers with a capacity of less than 10 t/h or 7 MW. The emission threshold for Hg concentration in the exhausted flue gas from coal-fired industrial boilers in China was for the first time adopted (0.05 mg/m^3).

Table 5. New emission thresholds for coal-fired power plants in China (mg/m^3)

	Threshold for newly built power plants	Threshold for existing power plants	Special threshold for key regions
PM	30	30	20
SO_2	100 200 [a)]	200 400 [a)]	50
NO_x	100 200 [b)]	100 200 [b)]	100
Hg	0.03	0.03	0.03

Notes: a) for coal-fired power plants in Guangxi, Chongqing, Sichuan and Guizhou; b) for coal-fired power plants with W-shape flame boilers and CFB boilers or built before December 31, 2003.

Table 6. New emission thresholds for coal-fired industrial boilers in China (mg/m^3)

	Threshold for newly built industrial boilers	Threshold for existing industrial boilers	Special threshold for key regions
PM	50	80	30
SO_2	300	400 550 [a)]	200
NO_x	300	400	200
Hg	0.05	0.05	0.05

Notes: a) for coal-fired power plants in Guangxi, Chongqing, Sichuan and Guizhou.

3.2. Projection of the 2017 scenarios

The “Ten Measures” is the most stringent emission control strategy among the three initiatives in Section 3.1, although it is not mercury-specific. However, the requirement of the “Ten Measures” is in the form of air quality ($PM_{2.5}$ concentration threshold) instead of emission concentration threshold or emission quantity cap. Chemical transport models (CTMs) are the only viable tools for evaluating the response of air pollutant concentrations to certain control measures. One of the most widely used CTMs is the Community Multi-scale Air Quality (CMAQ) model, developed by the US EPA (Byun and Schere, 2006). The overall modeling domain covers almost all of China with a 36 km × 36 km horizontal grid resolution, and three sub-domains with a 12 km × 12 km grid resolution cover the three heavily polluted regions as specifically required in the “Ten Measures”, the BTH, YRD and PRD regions. The CMAQ model links the emissions of different air pollutants to the air quality. This model is especially necessary for $PM_{2.5}$ because it has not only primary emissions from anthropogenic and natural sources but also secondary formation from precursors such as SO_2, NO_x and VOCs. However, due to the computational costs and the complication of the required emission inputs and processing, using CMAQ models and still meeting time constraints of policy analysis present a difficult challenge. A promising tool for addressing this challenge, Response Surface Model (RSM), has been developed by using advanced statistical techniques to characterize the relationship between input parameters (i.e., emission changes) and model outputs (i.e., air quality responses) in a highly efficient and economical manner (US EPA, 2006). RSM is a meta-model of air quality modeling, in other words, a reduced form of the prediction model using statistical correlation structures to approximate model functions through the design of complex multi-dimension experiments.

Based on the CMAQ/RSM model, the 2017 scenario was established in this study to meet with the $PM_{2.5}$ concentration requirement of the “Ten Measures”. The 2017 scenario is divided into two parts: Energy Scenario and Control Scenario. Energy Scenario refers to the coal consumption in CFPPs and CFIBs, and Control Scenario refers to the APCD applications. **Table 7** shows the coal consumption in CFPPs and CFIBs by province in 2012 and 2017. To meet with the requirements of “Ten Measures”, the coal consumption in CFPPs will decrease from 1860 million tonnes in 2012 to 1747 million tonnes in 2017, and that in CFIBs will be reduced from 787 million tonnes in 2012 to 716 million tonnes in 2017. The coal consumption of key regions will be highly restrained. Just like the “Ten measures”, the Energy Scenario for 2017 is ambitious. The 2017 scenario is in accordance with the Policy Control scenario in the China Coal Cap Project.

Table 7. Coal consumption in CFPPs and CFIBs by province in 2012 and 2017

Province	CFPPs		CFIBs	
	2012	2017	2012	2017
	Benchmark	Control	Benchmark	Control
Anhui	72.97	70.02	20.61	18.74
Beijing	12.38	3.85	7.29	6.63
Chongqing	17.35	16.03	18.70	17.00
Fujian	57.30	59.87	15.98	14.53
Gansu	37.50	37.94	9.11	8.28
Guangdong	132.57	123.58	30.18	27.44
Guangxi	27.12	25.29	16.73	15.21
Guizhou	49.71	45.92	23.23	21.12
Hainan	7.67	7.02	0.42	0.39
Hebei	90.27	81.77	50.19	45.63
Heilongjiang	47.60	42.04	31.17	28.34
Henan	128.46	118.05	41.25	37.50
Hubei	47.60	46.87	52.76	47.97
Hunan	42.43	42.53	34.05	30.96
Inner Mongolia	143.90	140.67	41.51	37.73
Jiangsu	157.66	142.65	43.63	39.66
Jiangxi	32.15	31.87	10.84	9.86
Jilin	34.20	32.48	33.77	30.70
Liaoning	71.13	66.29	37.31	33.92
Ningxia	37.96	39.00	6.84	6.22
Qinghai	4.92	4.21	2.57	2.34
Shaanxi	57.34	59.68	18.88	17.17
Shandong	159.23	146.98	99.96	90.88
Shanghai	46.33	41.92	7.36	6.69
Shanxi	107.96	104.78	29.69	26.99
Sichuan	31.18	28.58	29.91	27.20
Tianjin	28.46	25.75	11.66	10.60
Xinjiang	27.83	24.69	21.24	19.31
Xizang	0.26	0.30	0.00	0.00
Yunnan	28.53	27.80	12.32	11.20
Zhejiang	120.24	108.79	28.02	25.47
National	**1860.21**	**1747.22**	**787.20**	**715.63**

Notes: the unit is million tonnes.

Figure 1 shows the application of different APCD combinations (including PM, SO_2 and NO_x control devices) in CFPPs and CFIBs by province in 2012 and 2017.

Figure 1. Application of different APCD combinations in China by province
(a: CFPPs-2012; b: CFPPs-2017; c: CFIBs-2012; d: CFIBs-2017)

From 2012 to 2017, WFGD will be fully installed in CFPPs in China and the application rate of SCR will increase from 34% to 82% based on the national total amount control of SO_2 and NO_x emissions and the thresholds of SO_2 and NO_x in the Emission Standard of Air Pollutants for Thermal Power Plants (GB 13223-2011). The requirement of $PM_{2.5}$ were more stringent in the “Ten Measures”, under which the retrofit from ESP to FF would be necessary. The BTH, YRD and PRD regions will be the priority control regions for $PM_{2.5}$, and thus the FF adoption rates for Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang and Guangdong will be higher than those for the other provinces. SCR+ESP+WFGD and SCR+FF+WFGD will be the dominant APCD combinations in CFPPs in 2017. For CFIBs in China, the rapid increase of FF+WFGD will be a result from the stringent $PM_{2.5}$ and SO_2 control demand for CFIBs under the “Ten Measures”. The application rates for CFIBs of FF+WFGD in the BTH, YRD and PRD regions are expected to be 50% to 60% by 2017.

Coal washing is another important measure in the “Ten Measures”. The overall coal washing rate needs to reach 70% by 2017. Currently most washed coal goes to the coking sector. The proportion of washed coal in the power sector was only 1.5% in 2012, and the proportion for CFIBs was only about 10% (NESA, 2013). To fulfill the requirement of the “Ten Measures”, the proportion of coal washing will reach about 50% and 60% respectively for CFPPs and CFIBs by 2017, and 100% of the coal use in the coking sector will be washed coal.

3.3. Projection of 2020 and 2030 scenarios

China is likely to ratify Minamata Convention by 2016 or 2017. Therefore, the period of 2017-2030 will be the time when dedicated mercury control measures are put into practice. Under the requirement of Minamata Convention, China will need to adopt best available techniques or best environmental practices (BAT/BEP) in the coal combustion sector. There is much larger uncertainty in the projection of the 2020 and 2030 scenarios than the 2017 scenario. Therefore, we adopted multi-scenario analysis to reflect the uncertainty level and evaluate the effectiveness of mercury emission control measures. Three energy scenarios were developed respectively for CFPPs and CFIBs in 2020 and 2030, referred to as 0, 1 and 2. Energy Scenarios 0 and 2 were established according to the Benchmark and Coal Cap Scenarios in NRDC’s China Coal Cap Project, and Energy Scenario 1 was developed in this study by Tsinghua Team. Energy Scenario 2 was an extension of the 2017 energy scenario based on the “Ten Measures”.

3.3.1. Energy scenarios

Future projection of coal consumption, i.e., the energy scenarios for CFPPs and CFIBs, are shown in **Figure 2**. The electricity demand will continue to increase, more aggressively during 2010-2020 than during 2020-2030, while the coal share in the energy structure will gradually decrease. For CFPPs, a significant increase of coal consumption from 1.52 billion tonnes to 2.03 billion tonnes is expected during 2010-2020 under ES0, and a decrease by 157 million tonnes will take place from 2020 to 2030; the power coal consumption will reduce by 196 million tonnes during 2020-2030 under ES1; the peak value by 2020 will be only 1.87 billion tonnes under ES2 which is the mildest scenario for the growth of coal consumption, and the total amount will be 1.61 billion tonnes by 2030. The coal consumption for CFIBs has similar situations to that for CFPPs under different energy scenarios expect for ES2, under which the total amount will have slight decrease continuously from 2010 to 2030.

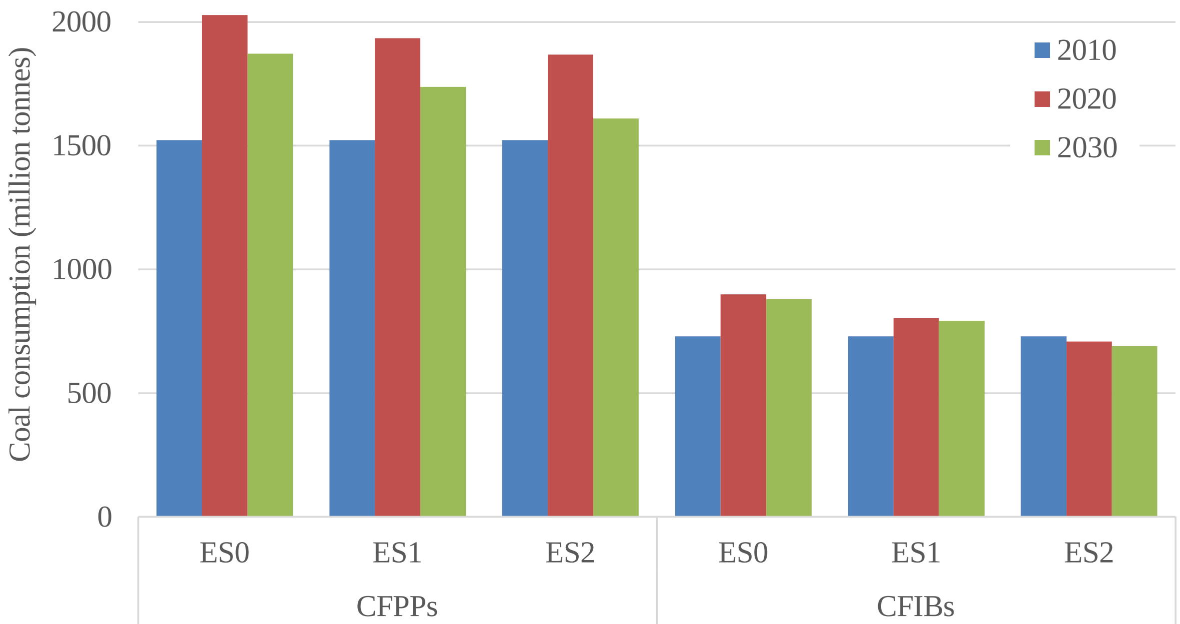

Figure 2. Future projections of coal consumption for CFPPs and CFIBs (2010-2030)

3.3.2. Control scenarios

The Minamata Convention will have more influence on the control scenarios, as shown in **Figure 3**. Three control scenarios, namely business as usual (BAU) scenario, extended emission control (EEC) scenario and accelerated control technology (ACT) scenario, were considered in this study. The BAU scenario assumes that the air pollution control will basically follow policies and regulations by 2010.

The EEC scenario assumes more advanced air pollution control technologies will gradually spread out based on the policies implemented after 2010 and those with the potential to be implemented in future. The ACT scenario speeds up the implementation of all the air pollution control technologies to comply with more stringent requirements from the Minamata Convention.

(1) CFPPs

For PM control, only ESP and FF were considered in the three scenarios for 2020 and 2030. Wet particulate scrubbers are no longer applied in CFPPs in China. In 2010, 93% of the power plants were equipped with ESP. However, the requirement of PM control is becoming more and more stringent, which implies that the removal efficiency for finer particulate matter (i.e., $PM_{2.5}$ or PM_1) is likely to be improved in the near future. The new emission standard of air pollutants for power plants released in July 2011 set a threshold of 30 mg/m^3 for the total suspended particulate (TSP). This threshold can be attained by combining ESP with FGD for coal with lower ash content. For coal with higher ash content, FF has to be installed to attain the emission limit. However, FF is more expensive, especially for the replacement of ESP in existing plants. Considering the implementation limits, the installed capacity with FF is assumed to take up 10–20% by 2020 and 20–35% by 2030 in various scenarios.

For SO_2 control, 81% of the units had been equipped with FGD by the end of 2010. Based on the new standard for air pollutant emissions from power plants, the FGD installation rate will reach 100%. Chinese legislation requires power plants operate FGD no less than 95% of the electricity generating hours. Considering the maintenance of FGD, we assume that 90–100% of the units will use FGD by 2020. In the EEC and ACT scenarios for 2030, the FGD application rate is assumed to reach 100%. Wet FGD is the most cost-effective SO_2 control technology and the only technology that can fit the new SO_2 emission standard. Therefore, all the FGDs applied in CFPPs are assumed to be wet FGDs.

For NO_x control, the Chinese government aims to reduce the total anthropogenic NO_x emissions by 10% during the 12th five-year period (2011–2015), and power plants are regarded as the key sector for NO_x emission reduction. The BAU scenario is in line with the total NO_x emission control in the 12th Five-Year Plan. As a result, 45% and 60% of the power units will be equipped with SCR by 2020 and 2030, respectively. The new emission standard is even more aggressive than the total NO_x emission control plan, which requires most power plants to be equipped with flue gas denitration technology. The EEC scenario and the ACT scenario are based on the new emission standard. By 2020, 85% and 95% of the units will install SCR in the two scenarios respectively. By 2030, 95% of the units will be applied with SCR and the rest 5% with SNCR in both the EEC and ACT scenarios.

The ratification of the Minamata Convention might set up a more challenging target for atmospheric mercury emission reduction. Therefore, specific mercury control (SMC) technologies, such as bromide injection into the furnace (BIF) or activated carbon injection (ACI), will be used besides the existing APCDs. It will take several years to demonstrate and evaluate the best available technologies on mercury, so there will be no SMC applications before 2020. However, SMC will be gradually applied in CFPPs from 2020 to 2030 with an application rate of 10–50%. United States Environmental Protection Agency (US EPA) has recently issued a new standard for mercury control in power plants. Based on this new standard the average mercury removal efficiency in US power plants will be 91%. Our control scenario projection is based on this new standard. In the ACT scenario by 2030, the average mercury removal efficiency in Chinese power plants will reach 90%.

Coal washing is an effective way to reduce multi-pollutants. In China, the overall coal washing rate is 18% in 2010 (NESA, 2011). Over 70% of the washed coal went to the coking sector in 2010. The application rate of coal washing in the power sector in 2010 was only 2.1% due to high price and inapplicability to existing boilers. In the ACT scenario, coal washing will follow the assumption of the 2017 scenario. Therefore, the application rates of coal washing for CFPPs are assumed to be 30–50% by 2020 and 40–70% by 2030 in the three control scenarios.

(2) CFIBs

For PM control, more or less 90% of the CFIBs in China were equipped with WS or IMS in 2010, and only 10% installed FF. To meet with the requirement of the "Ten Measures" and the new emission thresholds for CFIBs, more FFs will be applied for fine PM control. Under the BAU scenario in 2020, one fourth of the CFIBs will have FF installed, while 50% and 65% installation rates are expected under the EEC and ACT scenarios, respectively. By 2030, the FF installation rates will reach 35%, 60% and 80% under the BAU, EEC and ACT scenarios, respectively. ESP is not considered for CFIBs since it is not often used for industrial boilers because the scale of industrial boilers is usually much smaller than utility boiler used in CFPPs and ESP is not very economical.

For SO_2 control, IMS is a type of APCDs that reduces both PM and SO_2 emissions. However, the SO_2 removal efficiency of IMS is not enough to meet with the new SO_2 emission standard for CFIBs in China. More and more widespread use of WFGD is required in the near future. In this study, we assume that all the CFIBs equipped with FF in 2020 or 2030 are also going to have WFGD by then. Aside from WFGDs with limestone slurry ($CaCO_3$), MgO slurry is also an option for WFGD equipped for industrial boilers.

For NO_x control, no SCR or SNCR was installed for industrial boilers in 2010. To fulfill the target of total NO_x emission control in the 12th Five-Year Plan and the requirement of the new NO_x emission standard for CFIBs, NO_x control devices will be gradually popularized. SCR is assumed to be applied to most large-scale boilers. As a result, the overall application rate of SCR will be 5–35% under the three different scenarios by 2020. By 2030, the SCR application rate will reach 10%, 30% and 60% under the BAU, EEC and ACT scenarios, respectively.

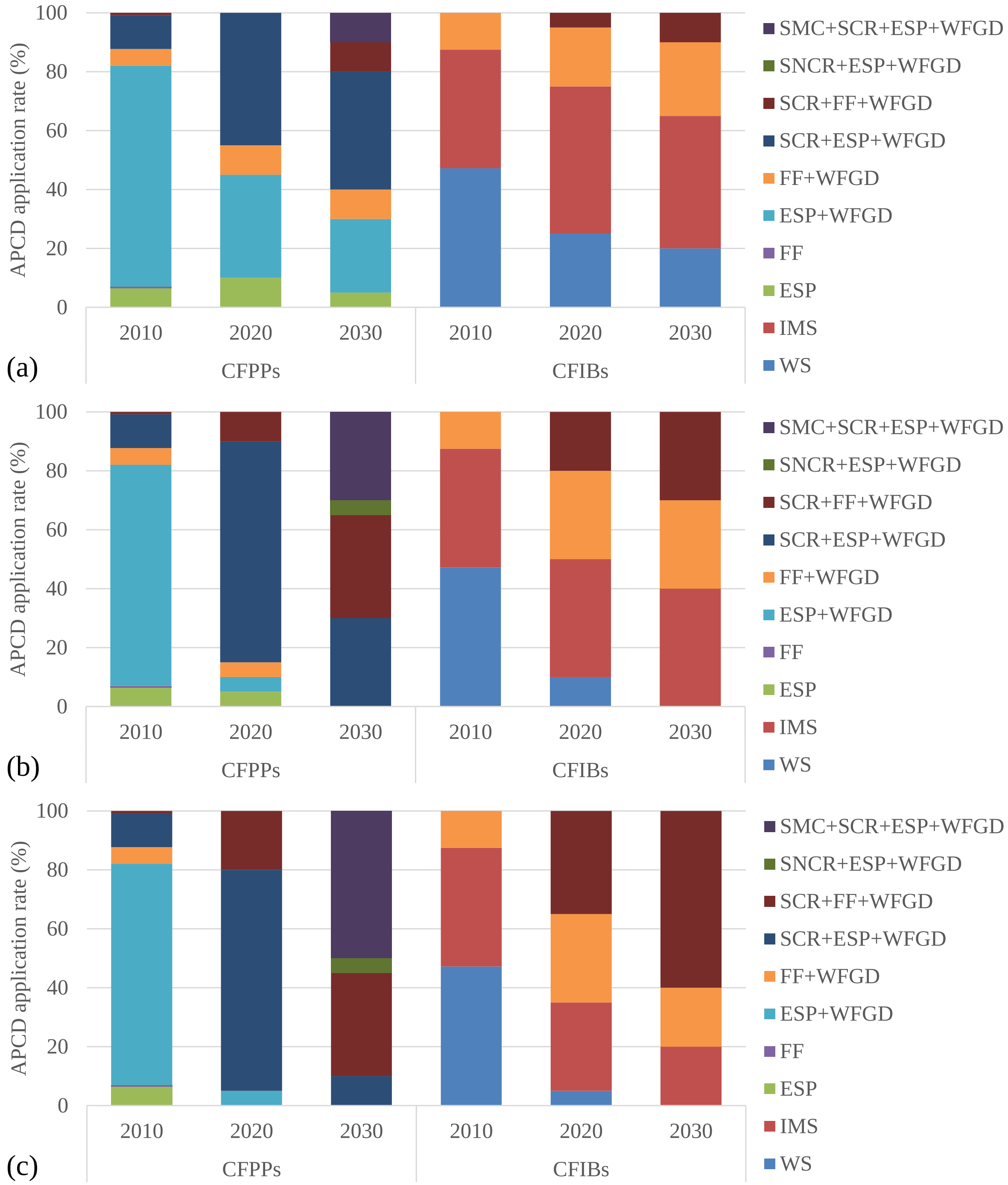

Figure 3. Application of different APCD combinations for CFPPs and CFIBs from 2010 to 2030 (a: BAU scenario; b: EEC scenario; c: ACT scenario)

The application rate of coal washing for CFIBs in 2010 was only about 10% due to high price and inapplicability to existing boilers. In the ACT scenario, coal washing will follow the assumption of the 2017 scenario. Therefore, the application rates of coal washing for CFIBs are assumed to be 40–60% by 2020 and 50–80% by 2030 in the three control scenarios.

4. Potential of co-benefit mercury control for CFPPs in China

The inventory of atmospheric mercury emissions from CFPPs in 2010 was first established to set a baseline. The effectiveness of control measures including the “Ten Measures” and the new emission standard on co-benefit mercury removal was then evaluated for the period of 2012-2017. Potential of co-benefit mercury control for CFPPs by 2020 and 2030 was assessed based on scenario projection.

4.1. Inventory of mercury emissions from CFPPs in 2010

Information on mercury content of coal and mercury removal efficiencies of APCDs were combined with the coal consumption data for power plants in China in 2010 to calculate the mercury emission inventory for CFPPs in China. The atmospheric mercury emissions from CFPPs in China by province are shown in **Figure 4**. The median estimate for mercury emissions from CFPPs in China was 100 t (P50) in 2010. From **Figure 4** we can see that Jiangsu, Shandong and Henan province were the top three emitters in the coal power sector in China in 2010. The top ten emitters contributed 66% of the total mercury emission from the power sector in China.

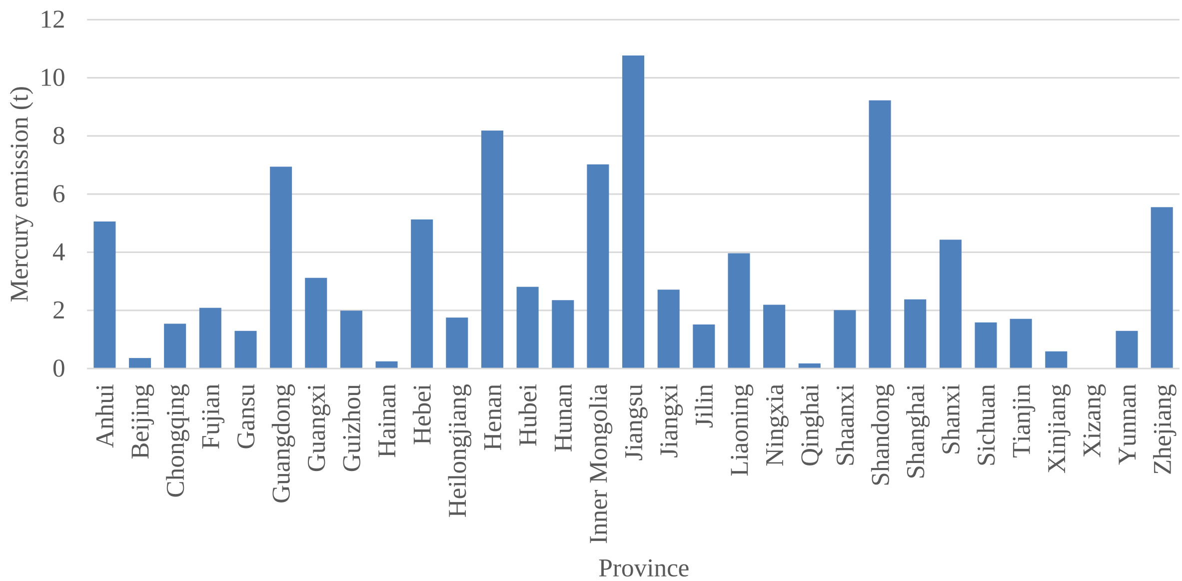

Figure 4. Median atmospheric mercury emission from CFPPs in 2010 by province

4.2. Effectiveness of measures on mercury removal from CFPPs during 2012–2017

Based on the PM_{10} and $PM_{2.5}$ concentration thresholds in the "Ten Measures" for both the whole China and the three key regions, the CMAQ/RSM model yielded fairly ambitious control scenarios for 2017. Not only the advanced APCDs for PM, SO_2 and NO_x control need a rapid growth, but the coal consumption also requires aggressive restraint. As a result, the total atmospheric mercury emission from CFPPs in China will be reduced from 93.8 t in 2012 to 58.1 t in 2017. **Figure 5** shows the total mercury emission from CFPPs by province during 2012–2017. Inner Mongolia, Jiangsu, Shandong, Henan and Guangdong will remain the top five emitters, but the total emissions of these provinces will decrease by 36–43% from 2012 to 2017. Due to the most stringent control measures to be conducted in Beijing, the mercury emission from CFPPs in Beijing will be reduced by 76%.

The extended North China Plain region (including Inner Mongolia, Hebei, Beijing, Tianjin, Henan and Shandong), the YRD region (Jiangsu, Zhejiang and Shanghai) and the PRD region (mostly Guangdong) will have significant co-benefits of mercury removal in CFPPs from the "Ten Measures". The 2017 scenario for CFPPs is quite ambitious, consistent with the 2020-ACT scenario (the most stringent one) which will be discussed in Section 4.3. The main purpose of this scenario is to evaluate the effect of the "Ten Measures" on mercury emission control. The overall proportion of mercury reduction for CFPPs during 2012–2017 is 38%. The proportions for Shanxi, Shaanxi and Anhui will be below the national average, which needs extra attention in the future.

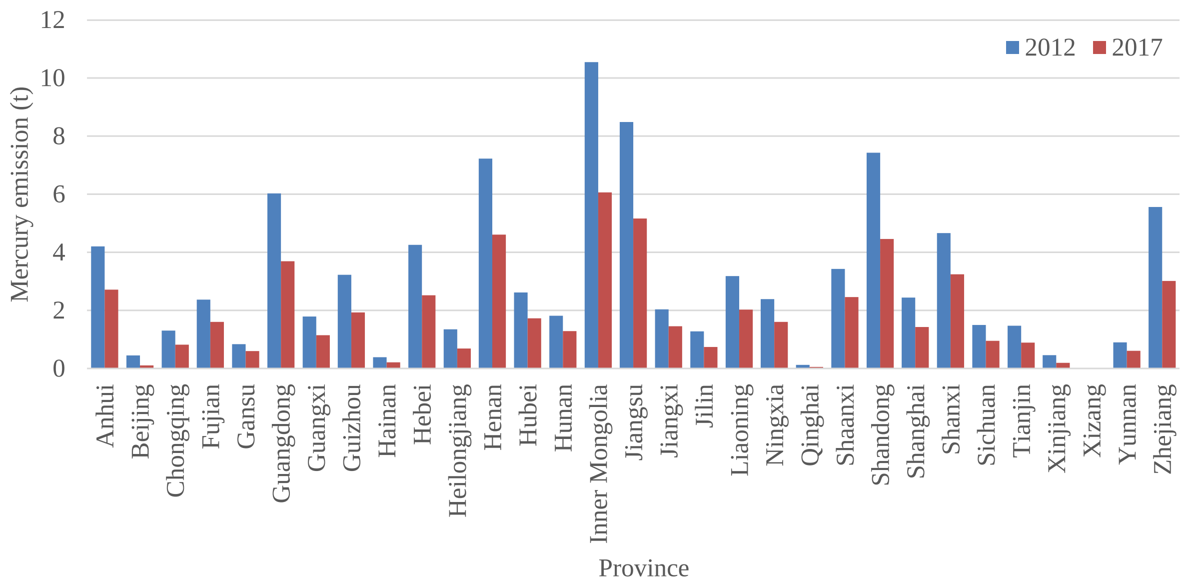

Figure 5. Atmospheric mercury emission from CFPPs by province during 2012–2017

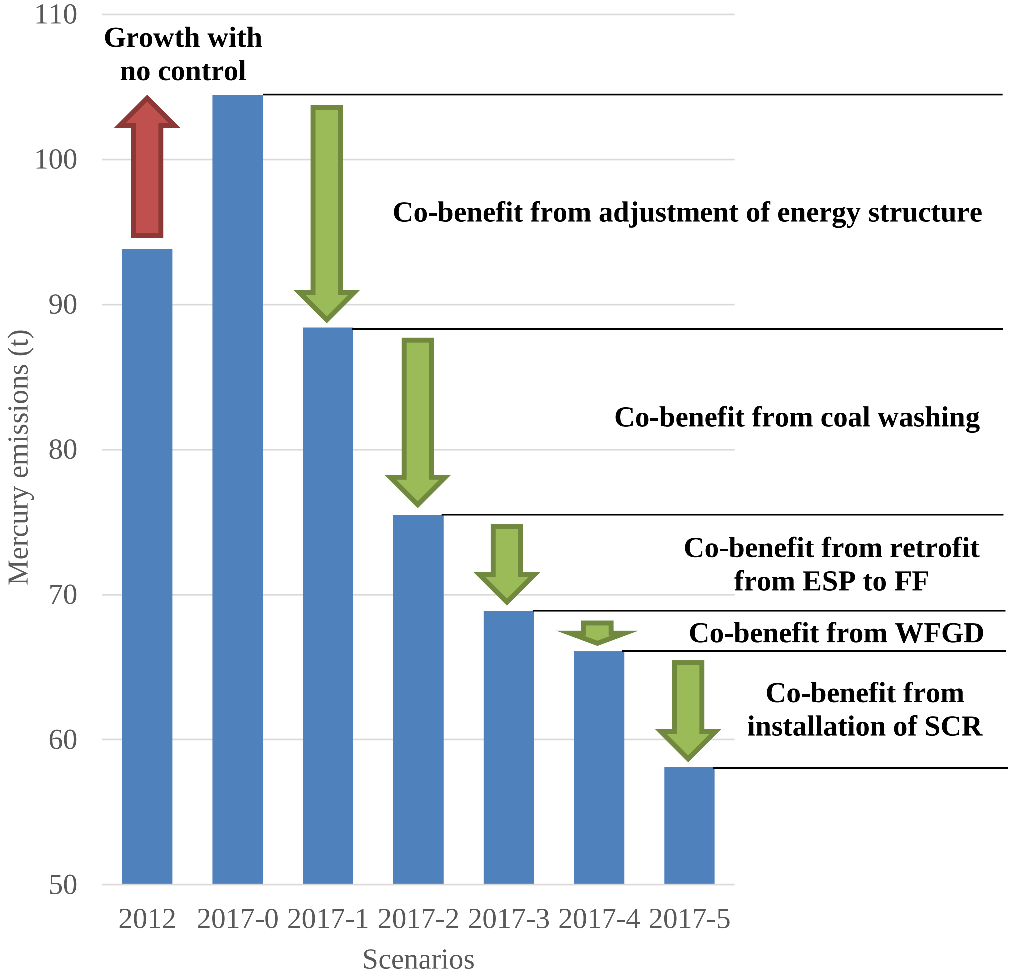

Figure 6. Co-benefit of mercury removal in CFPPs from control measures from 2012 to 2017

The overall co-benefit of mercury removal in CFPPs from the "Ten Measures" will be achieved by the adjustment of energy structure, the increasing application of coal washing and the widespread adoption of more advanced APCDs including FF, WFGD and SCR for PM, SO_2 and NO_x control, respectively. **Figure 6** shows the co-benefit of mercury removal in CFPPs from different measures from 2012 to 2017. Without any control measures, the total mercury emission from CFPPs in China will grow from 93.8 t to 104.4 t during this period due to the growth of electricity demand. Therefore, the overall co-benefit of mercury removal will be 46.3 t. The adjustment of energy structure, in other words, the decrease of coal power share will contribute a reduction of 16.0 t. The tremendous increase of coal washing can offer 12.9 t of mercury removal.

ESP can remove almost all the particulate-bound mercury (Hg_p), but has almost no removal efficiency on gaseous elemental mercury (Hg^0) and gaseous oxidized mercury (Hg^{2+}). FF can remove not only all the Hg_p but also a large proportion of Hg^{2+} at the filter cake, resulting in the high removal efficiency of FF (67% averagely) compared to that of ESP (29%). Therefore, the retrofit of PM control devices from ESP to FF for fine particle control in CFPPs will lead to 6.6 t of mercury removal. The application of FGD has been spread out in Chinese CFPPs during the 11th Five-Year Plan period (2005–2010). The further increase of WFGD installation rate can provide 2.8 t of mercury removal. NO_x control is the focus in the 12th and 13th Five-Year Plan periods. The SCR adoption rate will be growing rapidly during 2012–2017, contributing to 8.0 t of mercury removal in Chinese coal-fired power sector. Therefore, in the aggregate, APCD improvements will yield an estimated 17.4 t of mercury emission reductions.

4.3. Potential of co-benefit mercury control for CFPPs by 2020 and 2030

Base on the projections of both the coal consumption in CFPPs in China and application of the emission control technologies, the future trends of mercury emissions from CFPPs were calculated with the probabilistic mercury emission factor model, as shown in **Figure 7**. All the values are the median estimates (P50). From 2010 to 2020, the mercury emissions will decrease by 11%, 21% and 30% respectively under the BAU0, EEC0 and ACT0 scenarios. Under the energy scenario developed in this study, the mercury emissions under the BAU1, EEC1 and ACT1 scenarios will decrease by 15%, 25% and 34% respectively in 2020, compared with that in 2010. The high growth rates of the installation of WFGD and SCR will play an important role during this period. Under the coal control energy scenario from China Coal Cap Project extending from the 2017 energy scenario based on the "Ten Measures", the BAU2, EEC2 and ACT2 scenarios will have 18%, 27% and 36% mercury reduction respectively during 2010–2020. Averagely the mercury emission from CFPPs in 2020 will be about 25% lower than that of 2010, due to influence of both the increase of electricity demand and the implementation of APCDs. It indicates that the co-benefit of mercury removal from the accelerated control measures for PM and NO_x in the period of 2010–2020 will conquer the enhancement of mercury emission brought by the increase of electricity demand. All the scenarios for 2030 will be much lower than the corresponding ones for 2020. The decreasing trend in the period of 2020–2030 will be sharper than that during 2010–2020. Under the BAU0, EEC0 and ACT0 scenarios for 2030, the mercury emission will decrease by 35%, 60% and 73% compared with that in 2010. The reduction proportion for the ES1 series (i.e., BAU1, EEC1 and ACT1 scenarios) will be 40%, 63% and 75% respectively during 2010–2030. Under the most stringent scenario (ACT2) in 2030, the total mercury emission will be only 23.1 t, 77% lower than that of 2010. This shows the significant mitigation potential of mercury emissions from CFPPs in China in the future. The mercury emissions under the ES1 series scenarios are 5% and 7% lower than those under the ES0 series scenarios in 2020 and 2030 respectively, while the differences between ES1 series and ES2 series are 3% and 7% for 2020 and 2030 respectively. This reveals the uncertainty of mercury reduction potential as a result of energy restructuring in the two decades. The mercury emission under the EEC1 scenario is 11% lower than the BAU1 scenario in 2020, which is mainly contributed by the widespread application of SCR. The difference between EEC1 and ACT1 scenarios for 2020 is 12%. This is due to the increase of FF applications. Comparing the EEC1 scenario with the ACT1 scenario for 2030, the mercury emission in the ACT scenario is 33% lower, which is mainly due to the enhancement of SMC applications.

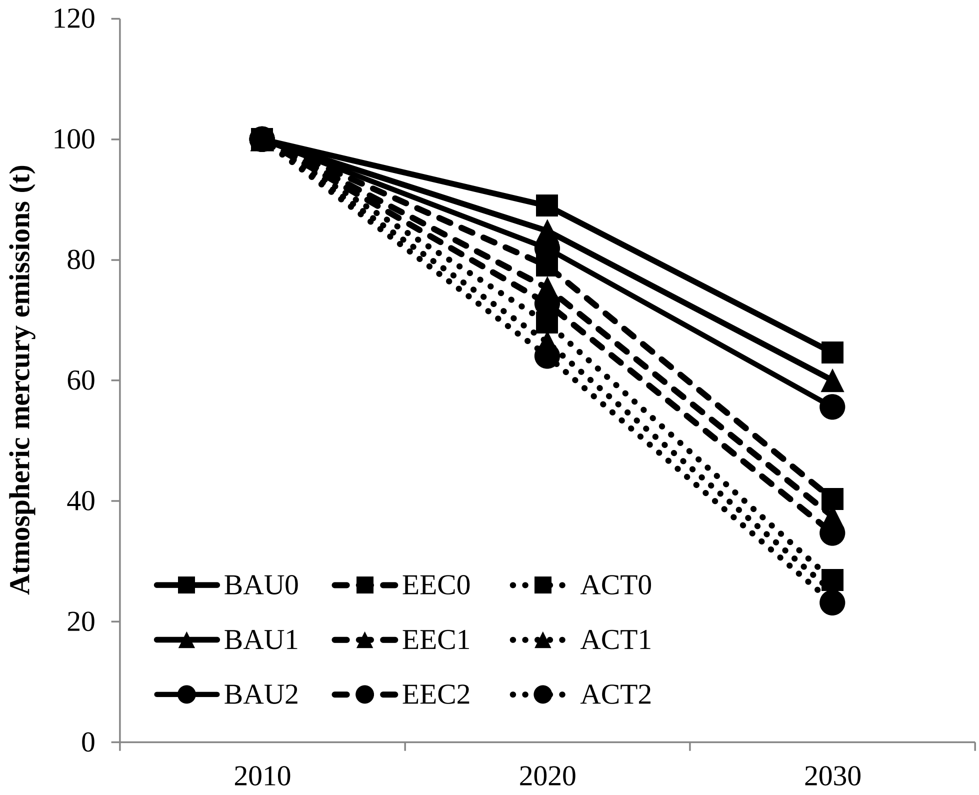

Figure 7. Scenario projections of total mercury emission from CFPPs during 2010–2030

5. Potential of co-benefit mercury control for CFIBs in China

The inventory of atmospheric mercury emissions from CFIBs in 2010 was first established to set a baseline. The effectiveness of control measures including the "Ten Measures" and the emission standard on co-benefit mercury removal was then evaluated for the period of 2012–2017. Potential of co-benefit mercury control for CFIBs by 2020 and 2030 was assessed based on scenario projection.

5.1. Inventory of mercury emissions from CFIBs in 2010

The atmospheric mercury emissions from CFIBs in China by province are shown in **Figure 8**. The median estimate for mercury emissions from CFIBs in China was 72.5 t (P50) in 2010. From **Figure 8** we can see that Shandong, Henan, Hubei, Jiangsu, Hebei, Inner Mongolia, Liaoning, Guangdong, Anhui and Zhejiang were the top ten emitters in the CFIB sector in China in 2010, accounting for 62% of the total mercury emission from CFIBs in China.

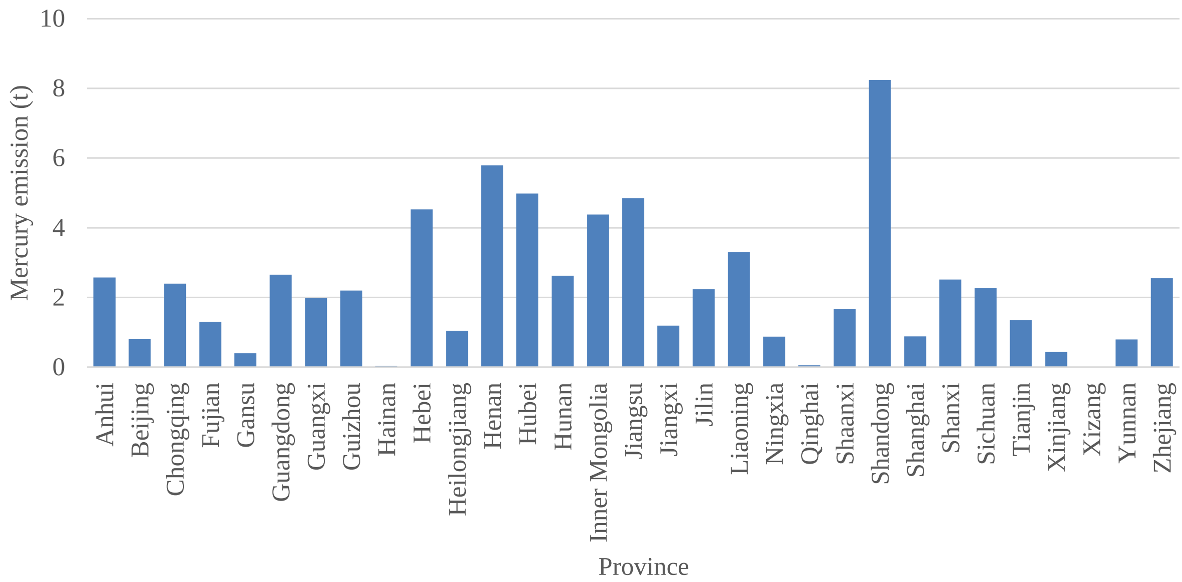

Figure 8. Atmospheric mercury emission from CFIBs in 2010 by province

5.2. Effectiveness of measures on mercury removal for CFIBs during 2012–2017

Based on the PM_{10} and $PM_{2.5}$ concentration thresholds in the "Ten Measures" for both the whole China and the three key regions, the CMAQ/RSM model yielded fairly ambitious control scenarios for 2017. Not only the advanced APCDs for PM, SO_2 and NO_x control need a rapid growth, but the coal consumption also requires aggressive restraint. As a result, the total atmospheric mercury emission from CFIBs in China will be reduced from 75.7 t in 2012 to 40.5 t in 2017. **Figure 9** shows the total mercury emission from CFIBs by province during 2012–2017. Shandong, Hubei and Inner Mongolia will remain the top three emitters, but the total emissions of these provinces will decrease by over 40% from 2012 to 2017. Due to the stringent control measures to be conducted in key regions, the mercury emission from CFIBs in Beijing, Tianjin, Hebei, Jiangsu, Zhejiang, Shanghai and Guangdong will be reduced by 64–73%.

The extended North China Plain region (including Shandong, Inner Mongolia, Hebei, Beijing, Tianjin and Henan), the YRD region (including Shanghai, Jiangsu and Zhejiang) and the PRD region (mostly Guangdong) will have significant co-benefits of mercury removal in CFIBs from the "Ten Measures". The 2017 scenario for CFIBs is quite ambitious, consistent with the 2020-ACT scenario (the most stringent one) which will be discussed in Section 5.3. The main purpose of this scenario is to evaluate the effect of the "Ten Measures" on mercury emission control.

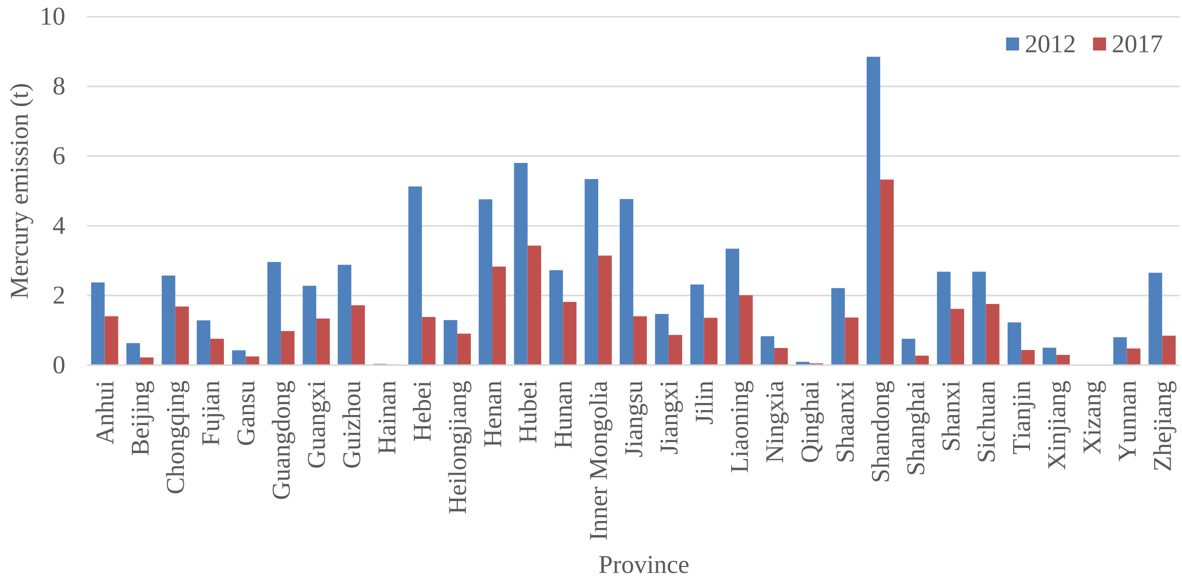

Figure 9. Atmospheric mercury emission from CFIBs by province during 2012–2017

The overall co-benefit of mercury removal in CFIBs from the "Ten Measures" will be contributed by the adjustment of energy structure, the increasing application of coal washing and the widespread adoption of more advanced APCDs including FF, WFGD and SCR for PM, SO_2 and NO_x control, respectively. **Figure 10** shows the co-benefit of mercury removal in CFIBs from different measures from 2012 to 2017. Without any control measures, the total mercury emission from CFIBs in China will grow from 75.7 t to 86.1 t during this period due to the growth of electricity demand. Therefore, the overall co-benefit of mercury removal will be 45.7 t, almost the same as the co-benefit from the coal-fired power sector. The adjustment of energy structure, in other words, the decrease of coal use in industrial boilers will contribute to the most co-benefit of mercury removal (17.3 t). The tremendous increase of coal washing can offer 10.8 t of mercury removal.

WS and IMS can only capture most of the particulate-bound mercury (Hg_p) and a small part of gaseous oxidized mercury (Hg^{2+}), but they have almost no removal efficiency on gaseous elemental mercury (Hg^0). Moreover, the SO_3^{2-} in the slurry can even reduce Hg^{2+} to Hg^0, resulting in Hg^0 re-volatilization. FF can removal not only all the Hg_p but also a large proportion of Hg^{2+} at the filter cake, resulting in the high removal efficiency of FF (67% averagely) compared to that of WS (23%)

and that of IMS (38%). Therefore, the retrofit of PM control devices from WS or IMS to FF for fine PM control in CFIBs will lead to 12.0 t of mercury removal. The growth of WFGD installation rate can provide 5.2 t of mercury removal. The application of SCR can only contribute another 0.3 t of mercury removal due to the already high mercury removal efficiency of FF+WFGD. In the aggregate, APCD improvements yield 17.5 t of mercury emission reductions.

The control measure of shutting down small-scale boilers (with capacity less than 10 t/h) contributes to both the adjustment of energy structure and the retrofit from outdated APCDs to high-efficiency ones. Small boilers are not as energy-efficient as large ones and consume more coal producing the same amount of steam. Replacing them with large ones will reduce the coal consumption. Moreover, high-efficiency APCDs such as FF and WFGD are more economical for large boilers, which will thus accelerate the retrofit. Therefore, although the effectiveness of shutting down small-scale boilers was not evaluated directly in this study, it is a cost-effective measure.

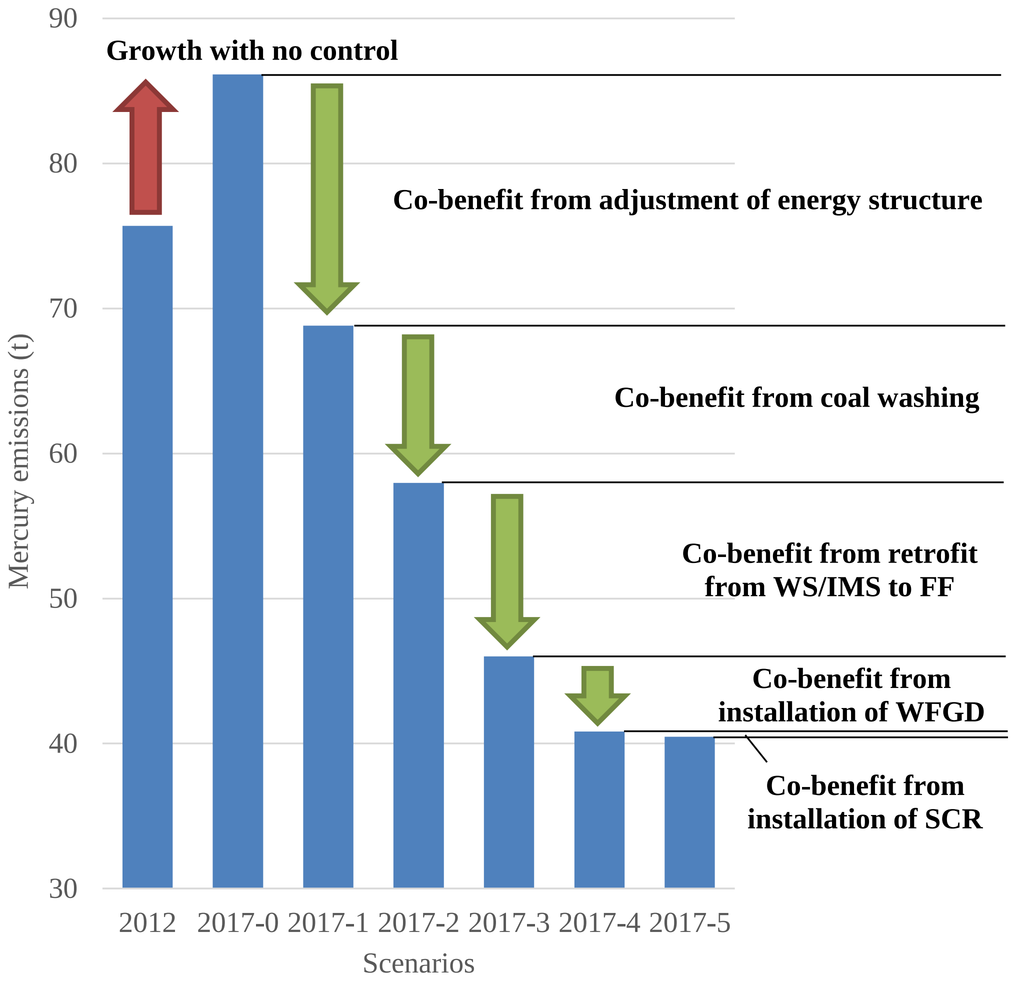

Figure 10. Co-benefit of mercury removal in CFIBs from control measures from 2012 to 2017

5.3. Potential of co-benefit mercury control for CFIBs by 2020 and 2030

Based on the projections of both the coal consumption in CFIBs in China and application of the emission control technologies, the future trends of mercury emissions from CFIBs were calculated with the probabilistic mercury emission factor model, as shown in **Figure 11**. All the values are the median estimates (P50). From 2010 to 2020, the mercury emissions will decrease by 15%, 41% and 57% respectively under the BAU0, EEC0 and ACT0 scenarios. Under the energy scenario developed in this study, the mercury emissions under the BAU1, EEC1 and ACT1 scenarios will decrease by 24%, 48% and 61% respectively in 2020, compared with that in 2010. The high growth rates of the installation of FF and WFGD will play an important role during this period. Under the coal control energy scenario from China Coal Cap Project extending from the 2017 energy scenario based on the “Ten Measures”, the BAU2, EEC2 and ACT2 scenarios will have 33%, 54% and 66% mercury reduction respectively during 2010–2020. Averagely the mercury emission from CFIBs in 2020 will be 44% lower than that of 2010.The retrofit from WS/IMS to FF and the adoption of WFGD have a significant mercury control co-benefit. All the scenarios for 2030 will be much lower than the corresponding ones for 2020. The decreasing trend in the period of 2020–2030 will be milder than that during 2010–2020. This indicates the co-benefit of mercury control measures for CFIBs in the first decade. Under the BAU0, EEC0 and ACT0 scenarios for 2030, the mercury emission will decrease by 29%, 56% and 74% compared with that in 2010. The reduction proportion for the BAU1, EEC1 and ACT1 scenarios will be 36%, 60% and 76% respectively during 2010–2030. Under the ACT2 scenario for 2030, the mercury emission can be reduced by 79% from that of 2010.

The mercury emissions under the ES1 series scenarios are 11% and 10% lower than those under the ES0 series scenarios in 2020 and 2030 respectively, while the differences between ES1 series and ES2 series are 12% and 13% for 2020 and 2030 respectively. This reveals the uncertainty of mercury reduction potential as a result of energy restructuring in the two decades. As the share of coal use for CFIBs decreases, the mercury emission will be significantly reduced. The mercury emission under the EEC1 scenario is 31% lower than the BAU1 scenario in 2020, which is mainly contributed by more and more widespread application of FF, WFGD and SCR. The difference between EEC1 and ACT1 scenarios for 2020 is 26%. This is mainly due to the further increase of advanced APCD applications. Comparing the EEC1 scenario with the ACT1 scenario for 2030, the mercury emission in the ACT1 scenario is 41% lower, which is mainly due to the aggressive enhancement of SCR applications. The ACT2 scenario represents the maximum potential of mercury emission control for the coal combustion sector in China. The mercury control measures for CFPPs and CFIBs together can achieve totally 133 t of mercury reduction from 2010 to 2030.

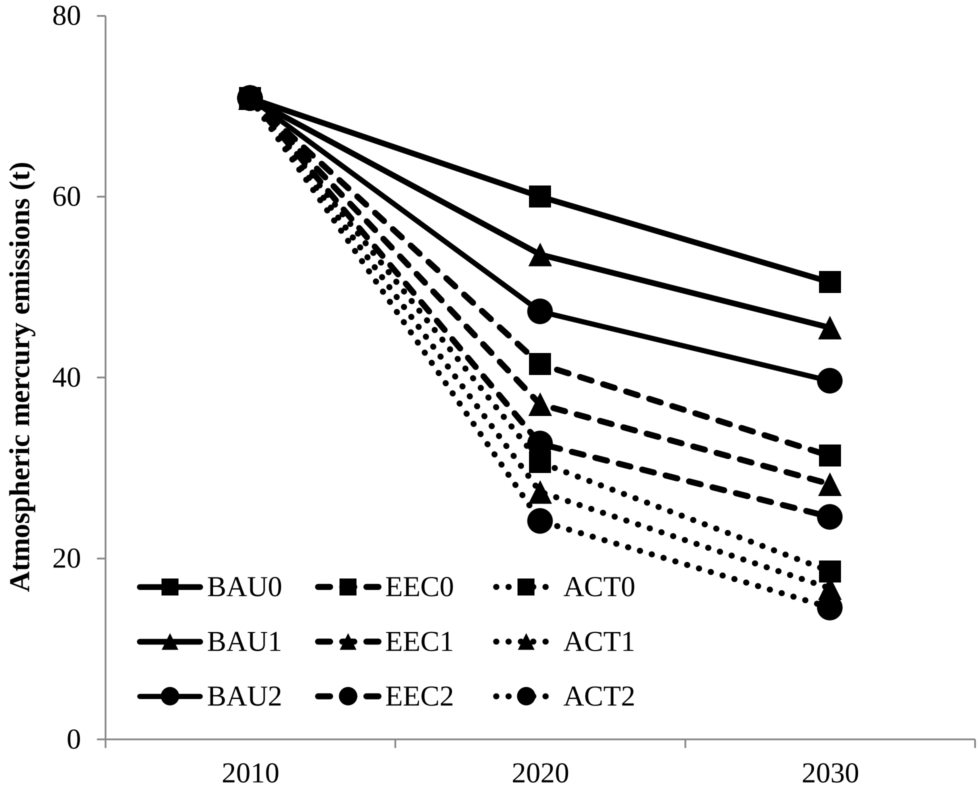

Figure 11. Scenario projections of total mercury emission from CFIBs during 2010–2030

6. Implications and policy recommendations

6.1. Uncertainties and implications

Based on the uncertainty analysis method for probabilistic mercury emission factor model described in Section 2.3, the overall ranges of uncertainties of mercury emissions from CFPPs and CFIBs in 2010 were evaluated to be (−35%, +45%) and (−45%, +47%), respectively. The overall uncertainties originate from model parameters (e.g., mercury content of coal, mercury removal efficiency of APCDs, etc.) and model inputs (e.g., coal consumption, application rates of APCDs, etc.). The uncertainties of model parameters are usually related to data availability and model structure, while the uncertainties of model inputs are linked to the statistical errors. The uncertainties for future years are also reflected by the differences between different scenarios. Detailed uncertainty analysis is described as follows.

6.1.1. Uncertainty of mercury content of coal

The stochastic simulation method adopted in the probabilistic model can provide sensitivity analysis for each parameter and quantify the influence of each parameter on the overall uncertainty. **Figure 12** shows the contribution of model parameters to the overall uncertainties for mercury emissions from CFPPs and CFIBs in 2010. Mercury content of coal from major coal producing provinces, such as Shanxi and Inner Mongolia, has the most significant influence on the mercury emission inventories. Some provinces in Southwest China, such as Guizhou and Chongqing, have high coal mercury values due to the geological conditions during the coal formation periods, resulting in the high uncertainty of mercury in coal. However, the information on mercury contents of Chinese coal is still very limited compared to the huge amount of coal mines in China. On the other hand, the inventory model is at the provincial level, which is an interior restriction to further reduce the uncertainties from the mercury content of coals from different provinces.

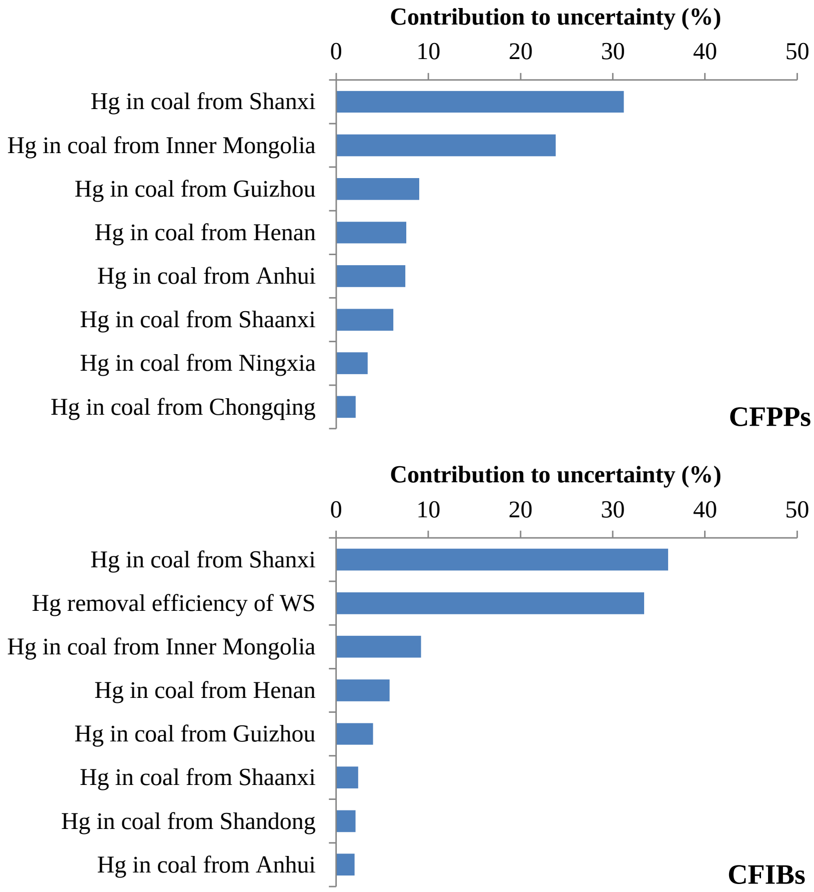

Figure 12. Contribution of model parameters to overall uncertainties for 2010 inventories

The newer coal mining is towards the deep layer and the western parts of China. Both these changes will certainly affect the mercury content of coal. However, the influence of coal seam depth and coal mine layout on the mercury content of coal are still controversial, which adds more uncertainties to the forecast of mercury emission from the coal combustion sector. Aside from the uncertainty of mercury content in raw coal, the uncertainty of mercury content in coal as burned is related to inter-provincial coal transport as well. The import and transportation of coal among province directly influence the mercury contents of coal as burned in each province.

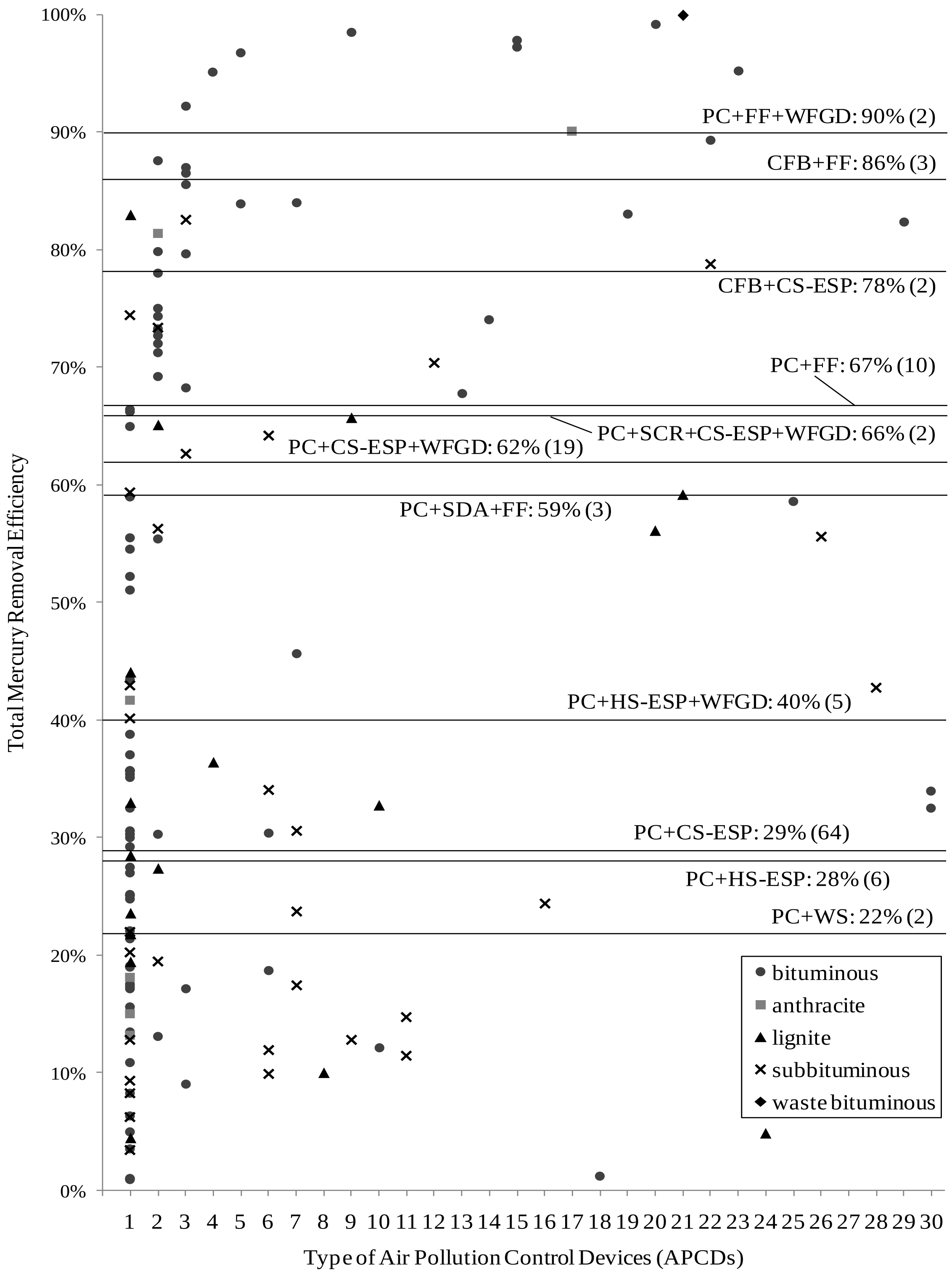

Figure 13. Onsite test results for total mercury removal efficiency by APCDs

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.

6.1.2. Uncertainty of mercury removal efficiency of APCDs

As shown in **Figure 12**, mercury removal efficiency of WS is also a significant parameter for the uncertainty of mercury emissions from CFIBs in China. The mercury removal efficiencies of APCDs used in CFPPs are not reflected in the results of uncertainty analysis, because they are linked to coal quality with the sub-model described in Section 2.1. Data of mercury removal efficiencies from on-site measurements for different APCD combinations are summarized as **Figure 13**. Significant variation is shown for combinations like PC+ESP and PC+ESP+WFGD under the influence of different coal qualities and operational conditions. Although they are not directly used in the model, the uncertainty level can be revealed here. The mercury removal efficiencies for other combinations not only show significant variation but also lack sufficient data, which makes the uncertainty ever larger. The uncertainty of mercury removal rate of coal washing did not contribute much to the uncertainty of the 2010 inventory because the application rate of coal washing is very low in 2010. However, based on the "Ten Measures", coal washing will be more and more widely adopted, which will cause larger uncertainty in this aspect.

6.1.3. Uncertainty of energy scenarios

If the proportion of coal power and the standard coal consumption rate remain constant, the total electricity demand has a positive relationship with the coal consumption in CFPPs. Similar case also applies to CFIBs. The total coal consumption 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 energy consumption per capita. As a fast growing economy and also an economy in transition, there are significant uncertainties to forecast the future economy of China. This can be reflected in different energy scenarios. In this study, taking the EEC scenario for example, the mercury emission estimate for CFPPs and CFIBs together under the EEC0 scenario by 2030 is 71.6 t, while the emission under the EEC2 scenario by 2030 is 59.3 t, 17% lower than the EEC0 case. The uncertainty of the energy demand will significantly affect the trend of mercury emissions in the future. The energy structure is under adjustment in China. The development of renewable energy will be emphasized in the next two decades. 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 ongoing. Therefore, the extent of coal power dependence is very uncertain.

6.1.4. Uncertainty of control scenarios

Control scenarios are based both on the current and the future potential control policies, regulations and standards. For the current measures, there is large uncertainty in the implementation. For example, at the early stage of the widespread WFGD application for SO_2 control, the in-service rate of WFGD is low, not to mention the limestone slurry spraying rate. With the enforcement of monitoring and supervision, including the real-time monitoring of SO_2 concentration at the provincial environmental protection bureau (EPB) level for key sources, the operation-in-optimal-condition rate has been greatly improved. The targets of some control measures will also bring uncertainties. The PM concentration thresholds in the "Ten Measures" are typical examples. We can only use some comprehensive model such as the CMAQ/RSM model to simulate the circumstances, but these models often have very high uncertainties, which will contribute to the uncertainty of control scenarios.

6.2. Recommendations on control policies and emission standards

Based on the analysis of current control policies, regulation and standards and the mercury emission inventories for CFPPs and CFIBs from this study, we propose the following recommendations to meet the requirements from the Minamata Convention.

6.2.1. Best available technique (BAT) adoption

Best available techniques (BATs) and best environmental practices (BEPs) are anticipated control options for key sources identified by Minamata Convention, although other mechanisms are theoretically available for existing facilities. BAT adoption is much easier for supervision than emission thresholds and total emission cap, especially under the current situation that CFPPs and CFIBs in China have not equipped with continuous emission monitoring systems (CEMS) for mercury yet. In our recent study (Ancora et al., 2015), based on mercury removal efficiencies and costs of different APCD combinations we ranked the most popular co-benefit APCDs installed in CFPPs in China and identified the most promising dedicated mercury APCDs and practices. Six primary decision factors that influence the BAT adoption paths were identified: 1) occurrence form of mercury in coal; 2) existing PM control device; 3) existing SO_2 control device; 4) existing NO_x control device; 5) coal rank; and 6) mercury removal rate requirement. A decision tree based (see **Figure 14**) on this

BAT adoption model was provided to offer guidance for the BAT options to reduce mercury emissions and comply with potential mercury emission targets necessary to meet China's obligations under the Minamata Convention (Ancora et al., 2016).

Occurrence form of mercury in coal determines the mercury removal efficiency of coal washing. Pyrite-bond mercury is more easily removed during the coal washing process than organic mercury. Once established the options for pre-combustion mitigation efforts to control mercury emissions, the decision analysis continues looking at the APCDs installed to reduce conventional air pollutants (i.e., PM, SO_2 and NO_x). The retrofit from ESPs to FFs for the control of fine particulates is the most cost-effective for co-benefit mercury removal. Coal rank is the key factor influencing the enhancement measures of co-benefit mercury control technologies. Coal blending/switching is a direct embodiment of the impact of coal rank. Switching from lignite or sub-bituminous coal to bituminous coal results in a 5% increase of mercury removal on average. Halogen injection (HI) has better performance in enhancing mercury removal for bituminous coal. The ultimate decision of using dedicated mercury control technologies (i.e., ACI) depends on the requirements of mercury removal efficiencies.

6.2.2. National mercury emission reduction target

According to the experience on SO_2 and NO_x control in the 11th and 12th Five-Year Plan periods, to set a national mercury emission reduction target for CFPPs and CFIBs in China could be useful to fulfill the requirement of the Minamata Convention. Above all, accurate mercury emission inventories are necessary for this "National Cap" policy.

Based on the scenario projections in this study, the national mercury emission reduction target for CFPPs in China by 2020 could be 25% compared to 2010, and the reduction target for CFPPs by 2030 could be 50–70% compared to 2010. The 25% target by 2020 can be achieved without any dedicated mercury control technologies (e.g., ACI). However, to achieve the 2030 target, over 30% installation rate of dedicated mercury control technologies is necessary.

For CFIBs, the target by 2020 could be 30–50%, more room for reduction than CFPPs due to the current outdated APCD installation for CFIBs. The reduction target for CFIBs by 2030 could be even more aggressive, 50–70% compared to 2010. Both the 2020 and 2030 reduction targets could be achieved without any dedicated mercury control technologies. The retrofit from WS/IMS to FF and the wide application of WFGD will be quite effective, not to mention the contribution of coal washing.

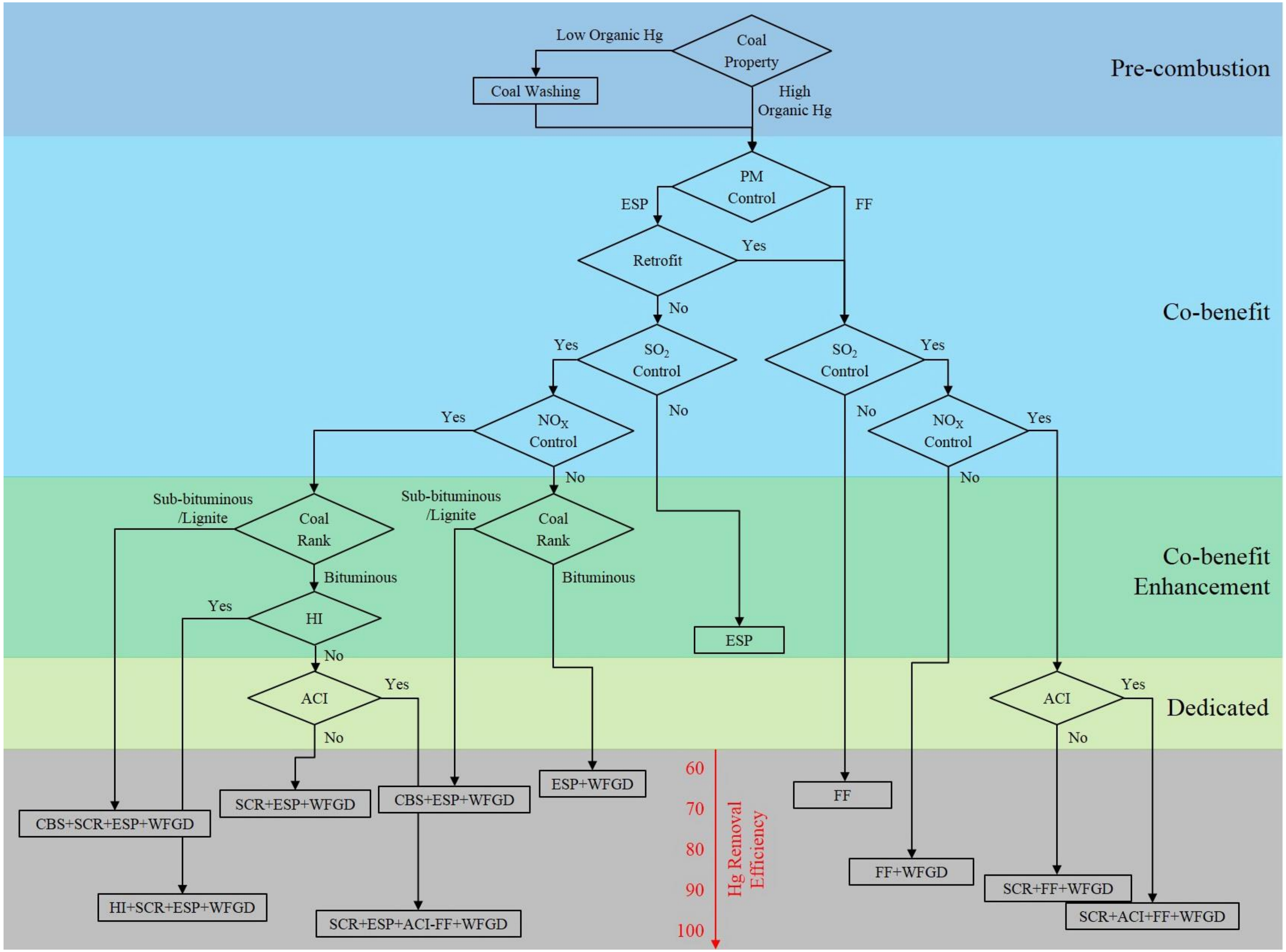

Figure 14. Best available technique (BAT) adoption paths for mercury control technologies

6.2.3. Combination of concentration and efficiency-oriented emission standards

China usually uses concentration-oriented emission standards (e.g., the 30 μg/m^3 mercury emission threshold for CFPPs and the 50 μg/m^3 one for CFIBs in the new standards). However, the concentration-oriented standard has its limitation, especially for mercury emission control in China. The threshold value is key to this type of emission standards. **Figure 15** shows the results of mercury concentrations in the flue gases before and after APCDs during our previous on-site measurements in China (Zhang, 2012). Although the number of tested CFPPs and CFIBs is quite limited compared to the huge number of CFPPs and CFIBs in China, the selection of installed capacity, located province, APCD combination and coal type is relatively representative for the current situation in China. The average mercury concentrations before APCDs at tested emission sources were all below 30 μg/m^3. The mercury concentrations in exhausted flue gases from tested CFPPs were all below 10 μg/m^3 and those for CFIBs were all below 15 μg/m^3. According to our estimation of mercury concentrations in exhausted flue gases from CFPPs and CFIBs in China based on the mercury content in Chinese coals and the removal efficiency of typical APCD combinations, also considering the variation of mercury removal efficiency, a threshold of 15 μg/m^3 and a threshold of 20 μg/m^3 are more reasonable for most CFPPs and CFIBs in China respectively under current situation with exception of some southwestern regions in China consuming coals with high mercury content.

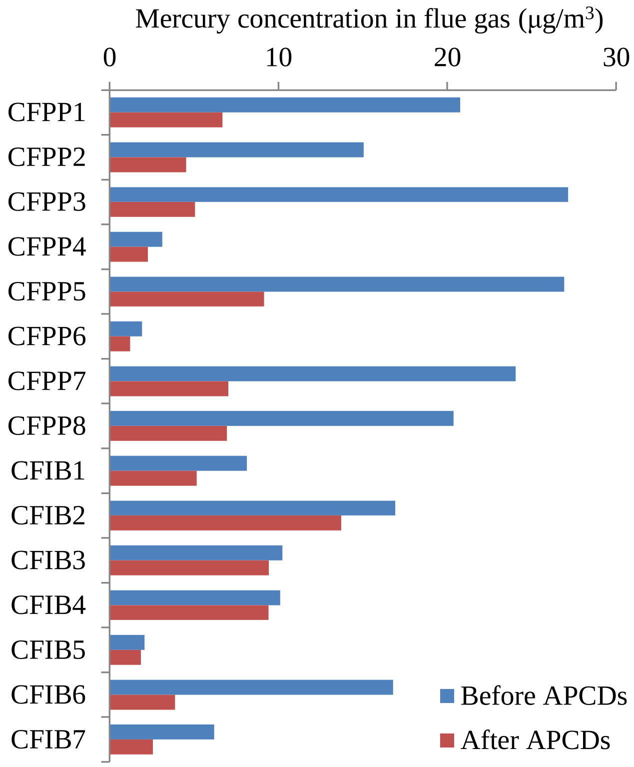

Figure 15. Mercury concentrations in flue gases from on-site measurements in China

Efficiency-oriented standards are more and more widely adopted by many developed countries and regions. The Mercury and Air Toxics Standards (MATS) rule in the US requires approximately 90% mercury removal efficiency for coal-fired power plants beginning in 2015. The Canada-Wide Standard (CWS) for Mercury Emissions from Coal-Fired Electric Power Generation Plants requires the annual overall mercury control efficiency to be 60% in 2010 and 80% in 2018. The overall mercury removal efficiencies for CFPPs and CFIBs in China were 63% and 43% respectively in 2010. Based on our projections under the EEC scenario, the overall mercury removal efficiencies for CFPPs could reach 74% and 85% respectively by 2020 and 2030, and the efficiencies for CFIBs could reach 68% and 75% respectively by 2020 and 2030.

Concentration-oriented standards are easier for real-time monitoring and encourage the use of coals with low mercury content (usually also low sulfur content), while efficiency-oriented standards offer flexibility to plants consuming coals with high mercury content. Therefore, we propose a combination of these two types of standards, where the regulatory agency/source could choose between which component of the standard it chooses to apply on its site-specific circumstances. Considering 0.2 mg/kg as a critical value for mercury content in coal and assuming approximately 10000 Nm^3 flue gas generation from combustion of one tonne coal, the overall critical mercury concentrations in flue gas at the 2020 efficiency level for CFPPs and CFIBs will be about 5.2 and 6.4 $\mu g/m^3$, respectively. Considering the variation of mercury content in coal and mercury removal efficiency, a coefficient of 1.5 is adopted.

As a result, the combinative standard for CFPPs by 2020 could be an alternative between a concentration emission limit of 8 $\mu g/m^3$ or a mercury removal efficiency of 75%, and the combinative standard for CFIBs by 2020 could be an alternative between an emission limit of 10 $\mu g/m^3$ or a removal efficiency of 70%. The concentration limits for 2020 are about half of the limits determined achievable by most plants for 2010 in this study.

Based on the same methodology, the combinative standard for CFPPs by 2030 could be an alternative between a concentration limit of 5 $\mu g/m^3$ or a mercury removal efficiency of 85%, and the combinative standard for CFIBs by 2030 could be an alternative between an emission limit of 7 $\mu g/m^3$ or a removal efficiency of 75%.

6.2.4. Reinforcement of mercury emission monitoring standard system

The mercury emission monitoring standard system for CFPPs and CFIBs in China is in need of urgent improvement, including on-line and off-line monitoring methods. Consequently the supervision system is still basically blank. The Ministry of Environment Protection (MEP) of China has piloted mercury emission monitoring and control projects at 16 power plants since 2010, fifteen of which are from the five major power groups in China and one from Shenhua Group. Both on-line and off-line mercury monitoring methods are adopted for comparison. However, due to the high costs of imported mercury CEMS and its high maintenance requirements, the continuous on-line method is not widely applied in China so far. In the meanwhile, the standard method (HJ 543-2009) is immature and still under revision.

6.2.5. Development of environmental registration system

The environmental registration system is still under construction in China. The system can not only contribute to the monitoring and supervision for mercury control but also benefit the development of mercury emission inventories which are crucial to China's commitment to the Minamata Convention. This is especially true for CFIBs. There are over half a million CFIBs in China, most of which are only registered to Special Equipment Safety Supervision Bureau of China. Detailed information on the coals burned in boilers and the equipped APCDs is not included in the statistical system in China. To improve the mercury emission control framework in China and keep mercury emission inventories updated, the development of an environmental registration system in China needs to be accelerated.

6.2.6. Improvement of the management system for industrial boilers

The gaps of the CFIB sector in both the information of emission inventory and the implementation of control measures are much more significant than those of the CFPP sector in China. This is largely related to the existing management system for industrial boilers. There are hundreds of thousands of CFIBs in China, affiliated to different types of plants as auxiliary facilities. Due to the huge quantity and the affiliation to different industries, the supervision and management system for industrial boilers is inefficient. Large-scale boilers for centralized heating supply have been widely adopted in China, which can significantly reduce residential coal combustion. This can be as well applied to the whole CFIB sector. Large-scale boilers can be individual companies for centralized steam or hot water supply in industrial parks or certain industrial zones in replacement of small-scale boilers, which will result in a more efficient management system.

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