JOURNAL OF ENVIRONMENTAL SCIENCES 33 (2015) 125–134

Available online at www.sciencedirect.com

ScienceDirect

www.journals.elsevier.com/journal-of-environmental-sciences

JOURNAL OF ENVIRONMENTAL SCIENCES

www.jesc.ac.cn

Economic analysis of atmospheric mercury emission control for coal-fired power plants in China

Maria Pia Ancora[1,3], *Lei Zhang*[1,3], *Shuxiao Wang*[1,2,3,*], *Jeremy Schreifels*[1], *Jiming Hao*[1,2]

1. *State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China*
2. *State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing 100084, China*
3. *Collaborative Innovation Center for Regional Environmental Quality, Tsinghua University, Beijing 100084, China*

ARTICLE INFO

Article history:
Received 31 October 2014
Revised 3 February 2015
Accepted 4 February 2015
Available online 5 May 2015

Keywords:
Atmospheric mercury
Coal-fired power plants
China
Cost-effectiveness
Activated carbon and halogen injection

ABSTRACT

Coal combustion and mercury pollution are closely linked, and this relationship is particularly relevant in China, the world's largest coal consumer. This paper begins with a summary of recent China-specific studies on mercury removal by air pollution control technologies and then provides an economic analysis of mercury abatement from these emission control technologies at coal-fired power plants in China. This includes a cost-effectiveness analysis at the enterprise and sector level in China using 2010 as a baseline and projecting out to 2020 and 2030. Of the control technologies evaluated, the most cost-effective is a fabric filter installed upstream of the wet flue gas desulfurization system (FF + WFGD). Halogen injection (HI) is also a cost-effective mercury-specific control strategy, although it has not yet reached commercial maturity. The sector-level analysis shows that 193 tons of mercury was removed in 2010 in China's coal-fired power sector, with annualized mercury emission control costs of 2.7 billion Chinese Yuan. Under a projected 2030 Emission Control (EC) scenario with stringent mercury limits compared to Business As Usual (BAU) scenario, the increase of selective catalytic reduction systems (SCR) and the use of HI could contribute to 39 tons of mercury removal at a cost of 3.8 billion CNY. The economic analysis presented in this paper offers insights on air pollution control technologies and practices for enhancing atmospheric mercury control that can aid decision-making in policy design and private-sector investments.

Introduction

Recent global estimates of the United Nations Environment Programme (UNEP) indicate that coal-fired power plants were one of the largest sources of anthropogenic mercury emission globally in 2010 (UNEP, 2013). China's mercury emissions from coal-fired power plants peaked at an estimate of 108.6 tons in 2005 (Wang et al., 2012), but declined shortly thereafter due to wide-spread application of wet flue gas desulfurization (WFGD) technology to reduce sulfur dioxide (SO_2) emissions, but with significant co-benefit mercury abatement impact (Wang et al., 2012; Tian et al., 2012). Because it is cheap, abundant, and offers a stable and secure energy source, it is likely that coal, which is currently about 78% of primary energy production in China, will remain an important source of China's energy mix long into the future, and therefore it is important to consolidate information on how to reduce the resulting mercury emissions in a cost-effective way. China has already adopted a host of legal, technical, economic and administrative measures to address mercury pollution and will need to scale up its control when the 2013 Minamata Convention on Mercury is ratified.

* Corresponding author. E-mail: shxwang@tsinghua.edu.cn (Shuxiao Wang).

http://dx.doi.org/10.1016/j.jes.2015.02.003

Mercury is bound to coal organically or as a mineral associated with pyrite and other sulfides. Once coal is combusted, the bound mercury is volatized in the form of gaseous elemental mercury (Hg^0), some of which is converted to gaseous oxidized mercury (Hg^{2+}) or particulate-bound mercury (Hg_p). This conversion depends on coal properties (*e.g.*, mercury, chlorine, bromine, and ash content), combustion characteristics (*e.g.*, time/temperature profile), flue gas compositions, and fly ash characteristics (Wang et al., 2010; Zhang et al., 2012). Mercury speciation profiles are plant-specific and will strongly influence the efficiency of mercury capture by so-called clean coal technologies. In general, observations show that: (1) Hg^{2+} and Hg_p are much easier to control than Hg^0; (2) a high content of chlorine in the coal will enhance the oxidation of mercury (*i.e.*, its transformation from Hg^0 into Hg^{2+}), but high levels of sulfur in the coal will produce more SO_2 in the flue gas, which limits the ability of chlorine to oxidize the Hg^0; (3) fly ash with high unburned carbon content – as often results during bituminous coal combustion in China – will increase the average proportion of Hg_p relative to Hg^0 in total Hg emissions from coal-fired power plants.

There are broadly four categories of clean coal technologies that have the potential to reduce mercury: (1) pre-combustion technologies used to clean the coal before it is burned (*e.g.*, washing and chemical cleaning of coal to remove sulfur, ash, and pyrite); (2) combustion technologies used to reduce the formation of emissions inside the furnace where coal is burned (*e.g.*, fluidized-bed combustion and low-NO_x burners); (3) post-combustion technologies used after the coal is burned to reduce emissions before they exit the stack; and (4) fuel conversion technologies to turn coal into a gas or liquid that is cleaned before it is used. Given that the effectiveness of pre-combustion, combustion and fuel conversion technologies in terms of mercury control is lower compared to post-combustion technologies and that there are no China-specific data available, this study focuses on the cost-effectiveness of post-combustion technologies, including co-benefit and dedicated mercury control technologies.

There are only limited studies on the cost-effectiveness of different mercury abatement measures, and even fewer for China. Brown et al. (2000) examined for the first time the costs of sorbent injection technologies, which were being tested by the US Department of Energy as a control option for mercury emissions in power plants in the US. They looked at annual cost and performance of five different combinations of activated carbon injection (ACI) practices. Pacyna et al. (2010) explored the cost and effectiveness of control technologies for mercury emissions from several sectors, including coal-fired power plants, at the global level. Their findings demonstrate that the costs associated with achieving higher capture efficiency with air pollution control device (APCD) combinations or lower mercury content in coal were greater because, in both cases, lower mercury concentrations reduce the additional mercury capture potential from additional APCDs. Tian et al. (2012) analyzed the trends of atmospheric mercury emission from power plants in China from 2000 to 2007, focusing on co-benefit mercury control strategies. Wu et al. (2011) performed the first economic analysis for mercury emission control in China and aimed to identify the least-cost strategy for controlling mercury emissions from coal-fired power plants in China. The study was based on global mercury removal efficiencies for APCDs and costs were based on technologies that were not yet commercially mature in China. Sun et al. (2014) developed a comprehensive set of costs, divided into capital and operation and maintenance (O&M) costs, of APCDs for multi-pollutant abatement in the power sector in China from 2010 to 2014. They designed a linear programming algorithm to estimate the least-cost control options to achieve set national emission targets. However, the costs of mercury emission control were not considered in their study.

This article evaluates mercury removal options for the coal-fired power sector in China and the mercury removal effectiveness and costs of APCDs. It provides policy makers and the private sector with updated information on cost-effective approaches to reduce mercury emissions, and their impact on the environment and human health. This study is the first to apportion the costs of co-benefit mercury control technologies using a pollutant-equivalent method that follows China's national regulations on pollution charges. The economic analysis also includes dedicated technologies to control mercury emissions from Chinese fleet of electricity generating units.

1. Methods

1.1. General description

A cost-effectiveness analysis was performed at two levels (Fig. 1): (1) from the perspective of a single private enterprise in China and (2) from the governmental perspective for the entire coal-fired power sector in China.

The post-combustion APCDs for this analysis include co-benefit APCDs (for particulate matter (PM), SO_2 and nitrogen oxides (NO_x) control) and dedicated APCDs (*i.e.* ACI and HI). Capital and O&M costs of the APCDs were taken primarily from Chinese literature and direct communications with vendors and plant managers regarding specific experiences in China; costs for APCD combinations are the sum of the individual capital and O&M costs of each technology. At the enterprise level, the cost-effectiveness of mercury control technologies was analyzed for a typical pulverized coal (PC) electric power boiler with a capacity of 600 MW burning bituminous coal. At the national level, the analysis involved the development of a database representing the national fleet of electricity generation units, and included estimates of the costs of the baseline case (2010) and two different scenarios for 2020 and 2030.

1.2. Effectiveness of APCDs for mercury control

APCDs designed to control other pollutants (*e.g.*, PM, SO_2, and NO_x) can provide co-benefit mercury removal. Gaseous mercury can be adsorbed onto fly ash and collected in downstream PM control devices, including the electrostatic precipitator (ESP) and fabric filter (FF). Both devices effectively capture Hg_p in flue gas (Zhang et al., 2012; Li et al., 2010). The intimate contact between the gas and collected particles on the filter cake of FF significantly enhances the gas-phase mercury collection efficiency relative to what is possible with an ESP (for both bituminous and sub-bituminous coals). Recent studies by

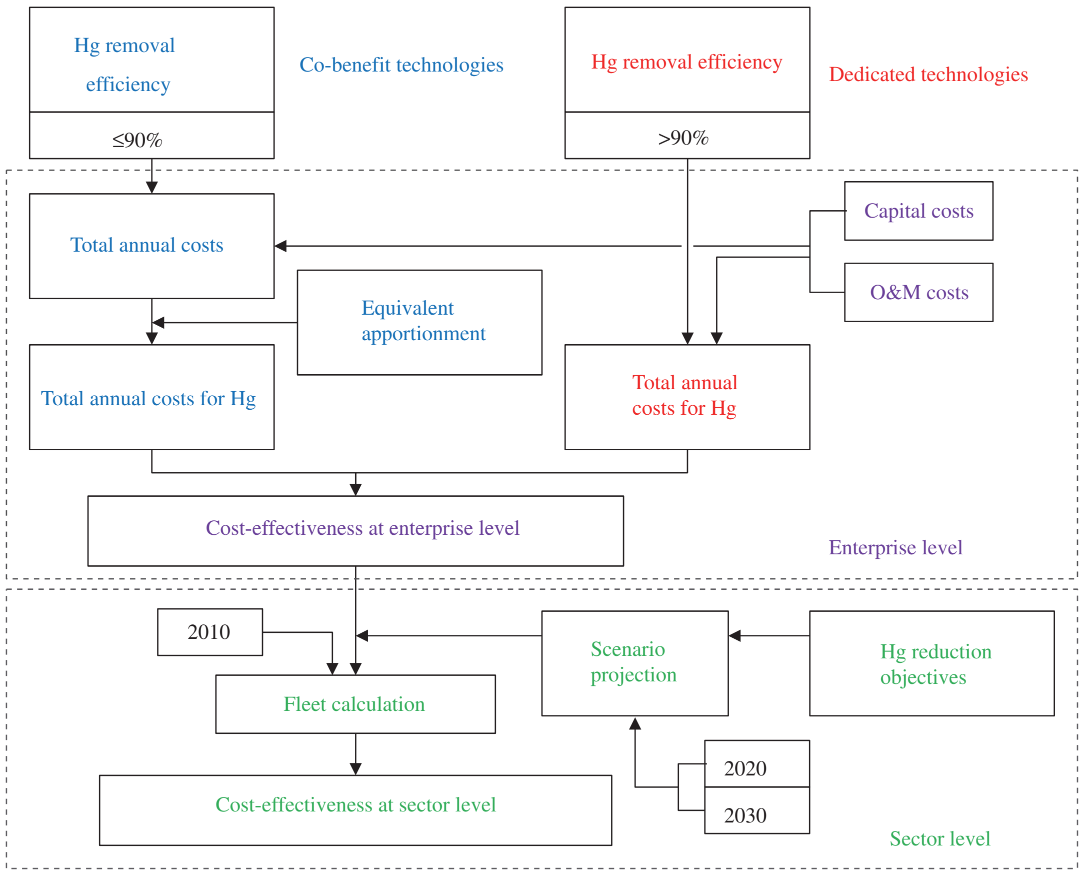

Fig. 1 – Methodology for cost-effectiveness analysis at two levels.

Zhang et al. (2008) and Wang et al. (2009) about the effects of PM control technology on the capture of mercury in Chinese power plants confirm that the mercury removal efficiency is influenced by the speciation profiles, which in turn are influenced in particular by the chlorine and bromine contents of the coal. Hg^{2+} is generally water-soluble and can be absorbed in the aqueous slurry of a WFGD system. The dissolved species react with dissolved sulfides from the flue gas, such as H_2S, to form mercuric sulfide (HgS), which precipitates from the liquid solution as sludge. The capture of mercury in power plants equipped with WFGD is dependent on the relative amount of Hg^{2+} in the inlet flue gas and, for overall mercury capture, on the PM control technology used (Zhang et al., 2008; Zhang, 2012). There are a number of different NO_x control technologies, including low NO_x burners (LNBs), over-fire air (OFA), reburning, selective non-catalytic reduction (SNCR), and selective catalytic reduction (SCR). However, only SCR has an impact on the speciation of mercury in flue gas, because the catalyst used in SCR can promote the oxidization of a significant portion of Hg^0, enhancing subsequent capture in WFGD (CCICED, 2011).

Activated carbon injection (ACI) and halogen injection (HI) are the most commercially mature mercury-specific control technologies. The effectiveness of ACI at reducing mercury emissions has been demonstrated on a number of full-scale applications since 2005. ACI technology controls mercury in the flue gas through injection of activated carbon. Activated carbon is the most common sorbent due to its high degree of micro-porosity, which increases the surface area available for adsorption or chemical reactions. Mercury and other pollutants are adsorbed onto the surface of the activated carbon and subsequently removed by PM control technologies. The application of ACI and PM control technologies alone is able to achieve high mercury removal rates, up to 90% for power plants burning bituminous coal using ESP or FF and no other APCDs (Sloss, 2012). A typical configuration involving this control technology would include the injection of powdered sorbent upstream of an existing PM control device (ESP or FF). Alternatively, sorbent can be injected downstream of an existing ESP and captured in a secondary PM control device (FF). As most of the PM in flue gas is removed by the primary PM control device, the lower PM loading allows for a smaller secondary FF and allows flue gases to pass through the filter with much less pressure drop. In addition, since the sorbent is collected in the downstream FF, it effectively segregates the fly ash, preserving its quality. HI, as analyzed in this paper, consists of spraying bromine additives (*e.g.* a $CaBr_2$ solution) directly on the coal before it is fed into the boiler. Added bromine ions bind to the elemental mercury in the flue gas, enhancing the mercury removal performance of the WFGD system. The effects of these additives on the quality of fly ash (for use in cement production and building materials) or on the quality of the WFGD gypsum have not been sufficiently investigated. Therefore their application is still in the pilot stage, although this technology has been commercially used to reduce mercury emissions from incineration plants in Germany since 2001.

The mercury removal efficiencies achieved by APCD combinations reflect their effectiveness in mercury control. Table 1 summarizes results from previous studies on the average mercury removal efficiencies by APCD combinations for coal-fired power plants in China. Six of the most popular co-benefit APCD combinations and three mercury-specific APCD combinations are included.

Previous studies (Zhang et al., 2008; Wang et al., 2009, 2012) on the impacts of PM control technologies on the capture of mercury in Chinese coal-fired power plants confirm that removal efficiency is influenced by the mercury speciation profile, which in turn is influenced by coal characteristics, including the chlorine and bromine contents of the coal. ESP and FF can remove over 99% of Hg_p in flue gas, and FF can reduce about 60% of Hg^{2+}. The mercury removal efficiencies observed in the tests performed in Chinese plants ranged from 7% to 56% for ESP and 53% to 91% for FF, respectively (Zhang, 2012). These values are comparable with values measured in US plants consuming bituminous coal (UNEP, 2005). The average mercury removal efficiencies of ESP and FF used in this study are 28% and 67% respectively.

WFGD can remove over 80% of Hg^{2+}. A WFGD downstream of an ESP can collectively capture 39% to 84% of mercury (Zhang, 2012). The combination of ESP + WFGD has an average mercury removal efficiency of 62% (Wang et al., 2013). A WFGD downstream of an FF increases the mercury removal efficiency to 86%, as found in the study by Wang et al. (2013). With the operation of SCR, the mercury removal efficiency of WFGD can be further improved. A study by the China Council for International Cooperation on Environment and Development (CCICED, 2011) reported the overall removal efficiency of SCR + ESP + WFGD to be 66%, slightly higher than that of ESP + WFGD. The values used in this study for the combinations of SCR + ESP + WFGD and SCR + FF + WFGD are 69% and 90%, respectively, based on studies of mercury capture in Chinese power plants (Wang et al., 2013).

Co-benefit technologies can achieve no more than 90% mercury removal. To further improve the mercury removal efficiency, dedicated control technologies are necessary. A typical configuration involving ACI technology would involve sorbent injection upstream of an existing PM control device (ESP or FF). Alternatively, sorbent can be injected downstream of an existing ESP and captured in a secondary PM control device (FF). The US Electric Power Research Institute (EPRI) licenses two designs (Feeley et al., 2008) — the toxic emission control process (TOXECON) and the compact hybrid particulate collector (COHPAC). COHPAC, with lower sorbent requirements, could achieve 90% mercury removal with a secondary FF. Combined with existing APCDs, the combinations of SCR + ACI + FF + WFGD and SCR + ESP + ACI-FF + WFGD can achieve 97% and 99% reduction of total mercury, respectively.

HI technologies are still in the demonstration stage. Full-scale tests were conducted using a $CaBr_2$ additive at a 25 ppm in coal equivalent level: a total mercury removal efficiency of 92%–97% was consistently observed on a 600 MW power unit burning subbituminous coal and equipped with an SCR (Rini and Vosteen, 2009). Bromides can promote the oxidation of mercury even if only small amounts are added. This was confirmed in an extensive testing program by EPRI. Mercury oxidation of 80% could be achieved by adding less than 200 ppm of bromine-based additive. The average mercury removal efficiency of HI + SCR + ESP + WFGD is estimated to be 95% in this study.

1.3. Costs of co-benefit mercury control technologies

Research from Wang (2014) is the primary source for Chinese-specific capital costs (in CNY/kW) and O&M costs (in CNY/kW/year) for commercially-available co-benefit mercury control technologies. These costs are provided for three size ranges of power plants (*i.e.*, nameplate capacity lower than 100 MW, between 100 and 300 MW, and over 300 MW), allowing a more refined analysis of costs at the sector level. Table 2 summarizes the cost values. Costs of the combinations of control technologies are the arithmetic sums of capital costs and O&M costs of each of the technologies.

Total annual costs are computed as the sum of capital costs, multiplied by a capital recovery factor, which takes into account the economic life of the equipment (15 years for WFGD and SCR systems and 20 years for ESPs and FFs) and an interest rate of 7% charged to the total capital investment, and the O&M costs.

Table 1 – Average mercury removal efficiencies by air pollution control device (APCD) combinations (%).

APCD combination	Wang et al. (2010)	Wang et al. (2012)	Wang et al. (2013)	Other studies	This study
ESP	24	28	29		28
FF		76	67		67
ESP + WFGD	73	64	62		64
FF + WFGD		90	86		86
SCR + ESP + WFGD			69	66[a]	69
SCR + FF + WFGD		90	93		90
SCR + ACI + FF + WFGD				97[b]	97
SCR + ESP + ACI-FF + WFGD				99[b]	99
HI + SCR + ESP + WFGD				95[c]	95

ACI: activated carbon injection; HI: halogen injection; FF: fabric filter; SCR: selective catalytic reduction; WFGD: wet flue gas desulfurization; ESP: electrostatic precipitator.

[a] Data from CCICED report (2011).

[b] Integrated mercury removal efficiencies based on EPRI data (Feeley et al., 2008).

[c] Integrated mercury removal efficiency based on results from Rini and Vosteen (2009).

Table 2 – Costs of conventional air pollution control devices in power plants.

APCD	Capacity (MW)	Capital cost (CNY/kW)	O&M cost (CNY/kW/year)
ESP	<100	108 ± 8	7 ± 2
ESP	<300	100 ± 7	6 ± 2
ESP	>300	94 ± 7	5 ± 2
FF	<100	91 ± 8	10 ± 4
FF	<300	80 ± 7	9 ± 3
FF	>300	71 ± 6	9 ± 3
WFGD	<100	736 ± 178	74 ± 29
WFGD	<300	410 ± 99	56 ± 22
WFGD	>300	151 ± 37	36 ± 14
SCR	<100	123 ± 29	43 ± 18
SCR	<300	99 ± 23	31 ± 13
SCR	>300	75 ± 18	20 ± 8

O&M: operation and maintenance.

However, the conventional APCDs are not dedicated to mercury emission control, and therefore the total costs of the co-benefit mercury control technologies have to be apportioned to different air pollutants. To do so, we used a pollutant equivalent apportionment (PEA) method, based on the official pollution factors given by the China's State Council's Administrative Regulation on Levying Pollution Emission Fees (NDRC, 2003).

The pollution equivalent factors for SO_2, NO_x, PM, and Hg in China, which are 0.95, 0.95, 2.18, and 0.0001 respectively, are intended to reflect each pollutant's impacts on human health and the environment. The emissions of the pollutant are divided by the pollutant equivalent factor to normalize different emissions into a total equivalent amount of pollution, on which the government applies an emission fee (0.6 CNY per kg of pollution equivalent).

First, for any given capacity of power plant, we calculated each pollutant's emissions reduced by each combination of APCDs. We then divided these removals by the corresponding equivalent factor to obtain the equivalent pollution as per this equation:

$$E_i = \frac{A_i}{f_i} \tag{1}$$

where, E_i is the equivalent pollution for pollutant i (i = Hg, PM, SO_2, NO_x); A_i is the total amount of the removal of pollutant i; and f_i is the pollutant equivalent factor for pollutant i.

The total equivalent pollution for each combination of APCDs was calculated as the sum of individual pollutant equivalents. This value was used as an equivalent ratio for each APCD combination.

Total annualized costs – as described above – for each combination of APCDs are multiplied by the equivalent ratio to obtain each pollutant's apportioned costs, using the following equation:

$$C_{Hg} = C_T \cdot \frac{E_{Hg}}{\sum_i E_i} \tag{2}$$

where, C_{Hg} is the cost apportioned to mercury emission control; C_T is the total cost of the APCD combination; and E_{Hg} is the pollutant equivalent for mercury.

1.4. Costs of dedicated mercury control technologies

Costs of the ACI technology in China have been adapted from values used in the US EPA Coal Utility Environmental COST (CUE COST) Model (US EPA, 2009) with the following assumptions: (1) capital costs for the installation of ACI at power plants with existing FF are projected to be 20% lower because of the commercial maturity of the technology; (2) capital costs of ACI-FF installed at power plants with an existing ESP have been calculated as the sum of the costs of ACI (see previous note) and the costs of a standard FF in China; and (3) variable O&M costs are 40% lower than in the US due to the lower sorbent prices and disposal costs in China. It should be noted that O&M costs in this study do not include the loss of sales due to fly ash contamination. Costs for an ACI retrofitted on a 600 MW power plant are summarized in Table 3 and are expressed in CNY with a currency conversion factor (USD/CNY) of 6.3.

For the HI technology, the cost data were derived from personal communications with vendors. The capital costs of the HI technology are negligible relative to the O&M costs. The cost of pure $CaBr_2$ ranges from $2250 to $3750 per ton, and the injection ratio (Br to coal) varies widely from 5 to 200 ppm, depending on the type of coal and the presence of additional NO_x APCDs. In this study, we assumed that $CaBr_2$ injection is likely to be installed on power plants already equipped with SCR + ESP + WFGD, and an average cost of $3000 was used with an injection ratio of 25 ppm to accomplish a total mercury removal efficiency of 95% based on the study of Rini and Vosteen (2009). The capital costs and total O&M costs are shown in Table 3.

1.5. Future emission control scenarios

For the sector-level analysis, we developed a database of coal-fired power plants in China for the year 2010 based on results from Zhao et al. (2013) – the baseline scenario – and projections for 2020 and 2030. The projections are based on the assumptions that coal, which represents 69% of the total energy capacity of the baseline year, will be used to produce 62% and 59% of the total energy production in 2020 and 2030 respectively. The total nameplate capacity is aggregated by boiler technology (grate, sub-critical, supercritical, ultra supercritical and fluidized bed combustion) and distributed into boiler types by capacity range (CEC, 2011; Minchener, 2012), as shown in Fig. 2. Consistent with the on-going policies launched within the 11th and 12th Five-Year Plans for national social and economic development, it is assumed that the smaller inefficient sub-critical boilers will be replaced by bigger, super-critical and ultra-supercritical units.

Two scenarios for mercury emission control for coal-fired power plants in China were developed. The business as usual (BAU) scenario is based on the assumption that mercury would be controlled not with specific standards or technologies but with a variety of actions including mandatory installations of high-efficiency APCDs for new sources and flexible mercury control options for existing sources. The second scenario, the emission control (EC) scenario, assumes the implementation of an emission standard for atmospheric mercury emissions much more stringent than the one currently in place, which will require wider use of dedicated mercury technology. Fig. 3

Table 3 – Costs of dedicated mercury control technologies in China.

Dedicated mercury control technologies and practices	Capital costs (CNY/kW)	Total O&M costs (CNY/kW/year)
ACI (for SCR + FF + WFGD)	10 ± 7	11 ± 6
ACI-FF (for SCR + ESP + WFGD)	81 ± 29	20 ± 4
HI (for SCR + ESP + WFGD)	–	1.7 ± 0.5

illustrates the current and projected future deployment of APCDs by 2020 and 2030 under the two different scenarios. The main assumption in projecting the APCD deployment in the future up to 2030 is the "retirement" of ESPs and their substitution with FFs, and gradual introduction of dedicated devices to control mercury.

2. Results

The cost-effectiveness of co-benefit and dedicated mercury control technologies were assessed at the enterprise and sector levels. The analysis presented here is based on total annualized costs, which allow us to compare costs of mercury control technologies with different lifespans.

2.1. *Costs of co-benefit technologies attributed to mercury emission control*

For the enterprise-level assessment, we calculated the total annualized costs of APCD combinations for a 600 MW power plant to abate mercury emissions. The costs of co-benefit APCDs were apportioned to each pollutant to isolate the relative costs for mercury control. The apportionment was done with the application of official government pollutant equivalent factors issued by China's National Development and Reform Commission. For a plant equipped with SCR + ESP + WFGD, the resulting costs apportioned to SO_2 removal were almost double that of PM removal, about 5 times that of NO_x removal and about 15 times that of mercury removal, as shown in Fig. 4. The use of the official pollutant equivalent factors provides a reasonable approximation to establish the share of costs of co-benefit technologies attributable to mercury control.

For a 600 MW power plant, less than 15% of costs of co-benefit control technologies are attributed to mercury abatement. The highest share of costs attributable to mercury removal is borne by the FF, which, among control devices, has the highest mercury removal efficiency. The lowest apportioned mercury control costs are for SCR + FF + WFGD due to the highly cost-effective co-benefit mercury control relative to the other APCD combinations. The costs of co-benefit mercury control technologies increase with the capacity of the power plant in slightly different ways, as shown in Fig. 5. The increase for an ESP is less steep than that for FF, which, for plants with capacity over 600 MW, can be as high as an ESP with WFGD. This is the reason why, in spite of ESP's lower effectiveness in reducing fine particulates, it will still be the preferred choice by many utilities, at least until tighter standards are put in place and enforced.

Compared with the mercury-apportioned costs of co-benefit APCDs, dedicated technologies with higher mercury removal efficiencies have higher costs, as shown in Table 4. Only HI is at the same level as the co-benefit technologies. The additional cost of control through the enhancement of mercury oxidation with injection of a $CaBr_2$ solution of 25 ppm is only 3657 CNY/kg

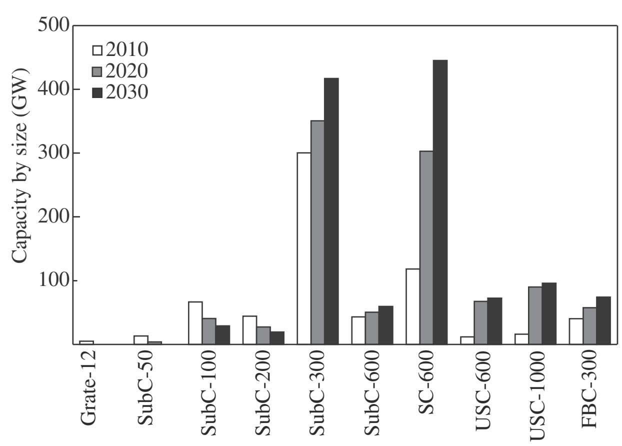

Fig. 2 – Installed capacity of coal-fired power units by boiler type and size. Grate-12: grate boilers, 12 MW; FBC-300: fluidized bed combustors, 300 MW; SubC-300: sub-critical pulverized coal boilers, 300 MW; SubC-600: sub-critical PC boilers, 600 MW; SC-600: supercritical pulverized coal boilers, 600 MW; USC-1000: ultra-supercritical pulverized coal boilers, 1000 MW.

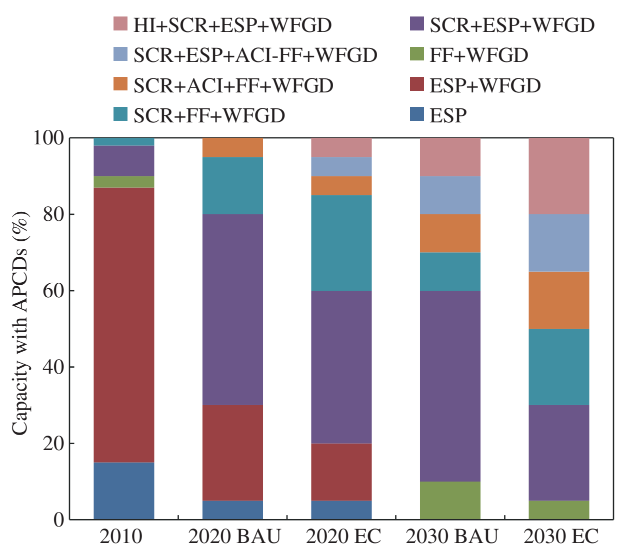

Fig. 3 – Projections of air pollution control devices' deployment for 2020 and 2030 under two scenarios. ACI: activated carbon injection; HI: halogen injection; FF: fabric filter; SCR: selective catalytic reduction; WFGD: wet flue gas desulfurization; ESP: electrostatic precipitator; BAU: business as usual; EC: emission control.

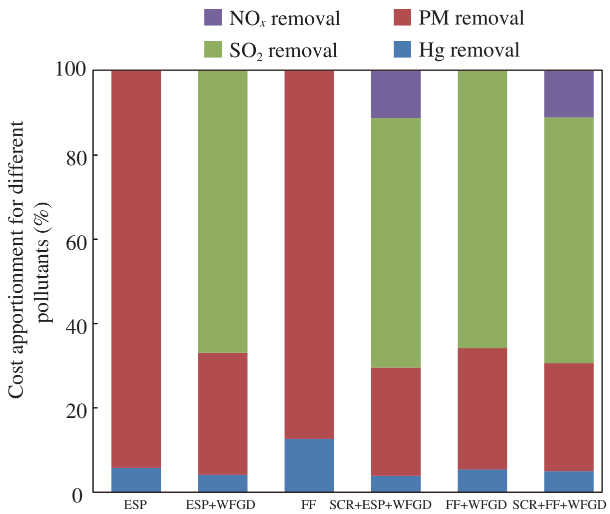

Fig. 4 – Cost apportionment of total annualized costs of air pollution control devices combinations for different pollutants.

of Hg removed, which is enough to achieve an extra 5% mercury removal from the highest co-benefit approach. It should be noted that the use of HI is still at the pilot stage, which might affect the potential for nationwide adoption. ACI technology, on the other hand, is much more expensive than co-benefit technologies.

The costs of the two types of ACI applications are as high as 26,134 and 57,619 CNY/kg of Hg removed. However, ACI technology is more commercially mature, and could be adopted with a high degree of confidence in its ability to control mercury emissions.

Table 5 compares the results from this study and previous studies (Brown et al., 2000; Pacyna et al., 2010; Wu et al., 2011) on the cost-effectiveness of mercury control options. Apparently in the US or EU the costs of ACI are much higher than in China. The ACI cost estimated by Wu et al. (2011) is lower because only the O&M costs for ACI technology were considered. Both Pacyna et al. (2010) and Wu et al. (2011) regard the total cost of other air pollutant control technologies (such as SCR and WFGD) with co-benefit on mercury removal as the cost for mercury control. This study, for the first time,

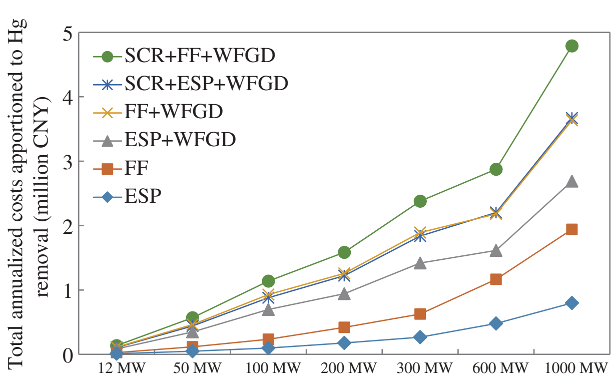

Fig. 5 – Total annualized costs apportioned to mercury removal for air pollution control devices by capacity of the power plant.

apportions the costs to mercury, which is one of the main advantages and novelties compared with previous studies.

2.2. Cost-effectiveness analysis at the enterprise level

Fig. 6 summarizes the annualized costs of different mercury control technologies, including their mercury removal efficiencies. The graph shows an inflection point where three control technologies, FF + WFGD, SCR + FF + WFGD and HI + SCR + ESP + WFGD, are plotted. This indicates that these technologies are cost-effective approaches for mercury emission control for the power sector in China.

The most cost-effective co-benefit technology combination for mercury emission control is FF + WFGD, with a total mercury removal efficiency of 86%. With the addition of SCR, this co-benefit combination can remove up to 90% of the total mercury in flue gas. With more ambitious mercury emission reduction requirements in the future, dedicated mercury APCDs may be necessary. A typical 600 MW power plant featuring an SCR + ESP + WFGD combination can choose to substitute ESP with FF to increase the mercury removal efficiency by about 20%.

Generally, FF is a better option than ESP for a new power plant in terms of its ability to cost-effectively maximize the removal of mercury. Additional benefits of the FF relative to ESP include more effective control of PM_{10} and $PM_{2.5}$. This makes FF a better choice not only for its co-benefit mercury removal but also in view of tighter $PM_{2.5}$ pollution standards established by the Chinese government. ESPs, with an average life of 20 years, have been widely installed in Chinese coal-fired power plants for more than 10 years. Considering more stringent mercury emission limits in the future, it might be cost effective to convert ESPs into FFs as the ESPs approach "retirement age" rather than undergo a major overhaul to renew them. Conversion of an ESP to a pulse jet fabric filter (PJFF), whereby the bag-house is installed in the existing ESP footprint, is an option that has been pursued in the US, UK, Australia, and EU in the past decade, and might prove sensible in China as well. Among its advantages are lower capital costs than constructing a FF in new space. Other advantages include minimal ductwork modifications and reuse of existing hoppers and ash-conveying systems. The system would be ready for efficient mercury abatement with sorbent injection.

Given the potential of co-benefit APCDs for mercury removal, it makes economic sense to install ACI only on power plants already equipped either with SCR + ESP + WFGD or SCR + FF + WFGD to comply with more stringent mercury control regulations. This could be the case after ratification of the Minamata Convention, the international treaty on global mercury emission reduction, and its entry into force, when tighter emission standards requiring at least 90% mercury removal are likely to be put in place.

2.3. Cost-effectiveness analysis at the sector level

The total annualized costs and total mercury removal of the national coal-fired power fleet are shown in Fig. 7. Total annualized costs in 2010 for a total estimated mercury removal of 193 tons are 2.7 billion CNY. The 12th Five-Year Plan – the social and economic master plan designed by the National Development and Reform Commission of China –

Table 4 – Annualized costs apportioned to mercury removal by different technologies for a 600 MW power plant.

APCD combination	Annualized costs apportioned to Hg removal (CNY)	Amount of Hg removed (kg)	Annualized costs per kg Hg removed (CNY/kg)	Dedicated annualized costs per kg Hg removed (CNY/kg)
ESP	478514	82	5861	–
ESP + WFGD	1613110	187	8644	–
FF	1166579	195	5971	–
SCR + ESP + WFGD	2199963	201	10934	–
FF + WFGD	2180705	251	8696	–
SCR + FF + WFGD	2874405	262	10953	–
HI + SCR + ESP + WFGD	3213028	277	11599	3657
SCR + ACI + FF + WFGD	10266356	283	36297	26134
SCR + ESP + ACI-FF + WFGD	18833053	289	65240	57619

mandates significant reductions of PM, SO_2, and NO_x. The current and projected deployment of APCDs to meet these targets will result in a total mercury removal of 338 tons by 2020 under the BAU scenario, with a total annual investment of 5.7 billion CNY apportioned to mercury. An additional 26 tons of mercury could be removed by 2020 with an additional investment of 2.2 billion CNY.

By 2030, both a replacement of ESPs with FFs and the expected increase in SCR use will contribute to a total mercury removal of 479 tons, while more stringent standards for mercury emissions and subsequent diffusion of HI would remove an additional 39 tons, for a corresponding increase in costs of 3.8 billion CNY.

The increase in costs from 2010 to 2020 is high, over 3 billion CNY. The corresponding mercury removal is 145 tons. A similar jump in mercury removal (141 tons) is projected from 2020 to 2030 in the BAU scenario, when total annualized costs at the national level will double. This indicates that higher marginal costs for total mercury removal are expected for the decade of 2020–2030 relative to the decade of 2010–2020. Under the EC Scenario by 2030, the combinations of SCR + ESP + WFGD, SCR + FF + WFGD and HI + SCR + ESP + WFGD will each contribute over 100 tons of mercury removal with costs of about 1.5 billion CNY each, while the ACI technologies will cost 12 billion CNY in total and remove another 173 tons of mercury.

The cost estimates described above do not take into account the government subsidies for the operation of SO_2 and NO_x control devices (0.015 and 0.010 CNY/kWh, respectively). These subsidies are designed to reflect the O&M costs of the APCDs. If these subsidies were taken into account, different costs and emission reductions might result. If the government used a similar methodology to establish and apply subsidies for dedicated mercury control technologies, the subsidies for ACI with existing FF and ACI with ESP and therefore needing an additional FF would be approximately 0.003 and 0.006 CNY/kWh, respectively, much lower than existing subsidies for SO_2 and NO_x. However, the costs of ACI systems described above do not include any losses from fly ash sales due to the deterioration of fly ash quality for reutilization.

3. Discussion

A new national standard (MEP, 2011) sets a mercury emission limit of 0.03 mg/m^3 beginning 1 January 2015 for all newly built and existing coal-fired power plants in China. Our analysis shows that this standard can be achieved with the existing (2010) installations of APCDs, which do not feature dedicated mercury APCDs. The 12th Five-Year Plan demands that by 2015, the total emissions of mercury (as well as As, Cd, Cr and Pb) in key areas decline by 15% compared to 2007 and do not exceed the 2007 level in other areas. According to our sector-level analysis, the coal-fired power sector alone could achieve this target if dedicated mercury APCDs were gradually installed as per our assumptions in the EC scenario. However, international pressure leveraging on the transboundary nature of atmospheric mercury pollution and the entry into force of the Minamata Convention might compel China to require more stringent standards.

In fact, the current Chinese emission standard for mercury is far lower than the one put in place in the US by the Mercury

Table 5 – Annualized costs (CNY) per kg Hg removed: comparison with other studies.

APCD combination	USA Brown et al., (2000)	EU Pacyna et al., (2010)	China Wu et al., (2011)	China (This study)
ESP		456339	22466	5861
ESP + WFGD			891069	8644
FF		165151	28507	5971
SCR + ESP + WFGD				10934
FF + WFGD			1129506	8696
SCR + FF + WFGD				10953
HI + SCR + ESP + WFGD				11599
SCR + ACI + FF + WFGD	437803 [a]	455008 [a]	15480 [a b]	36297
SCR + ESP + ACI-FF + WFGD	941420 [a]			65240

[a] The cost does not include that for co-benefit control technologies (SCR, ESP, FF or WFGD).
[b] Only the operation and maintenance costs for ACI technology were considered in Wu et al. (2011).

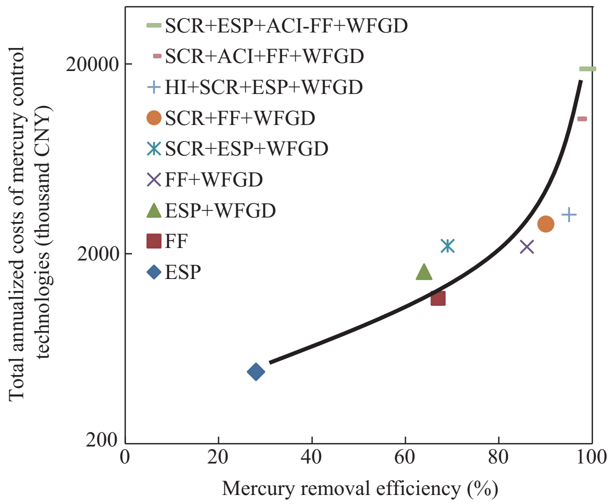

Fig. 6 – Relationship between mercury removal efficiency of air pollution control devices' combinations and the total annualized costs apportioned to mercury removal.

and Air Toxics Standards (MATS) rule (US EPA, 2011a). The MATS demands ultimately that all the US coal-fired power plants reduce mercury emissions by about 90% (US EPA, 2011b). This requirement translates into national compliance costs of $9.6 billion annually (*i.e.*, 60 billion CNY), much higher than the total costs of the EC scenario in 2030 (17 billion CNY). The demand for SO_2 control in the US is not as prominent as in China due to lower sulfur content in US raw coals and wide application of coal cleaning processes. Hence, WFGD application in the US – 60% of all coal-fired electricity generating capacity in 2010 – is lower than in China, and therefore the co-benefit capture of mercury has not been fully exploited. According to our estimates, if China had to enforce emission limits similar to those of the MATS rule by 2020, only 550 plants would be able to comply; over 2200 power plants would have to be retrofitted in the BAU scenario, compared to about 1600 utilities to be retrofitted under the EC scenario.

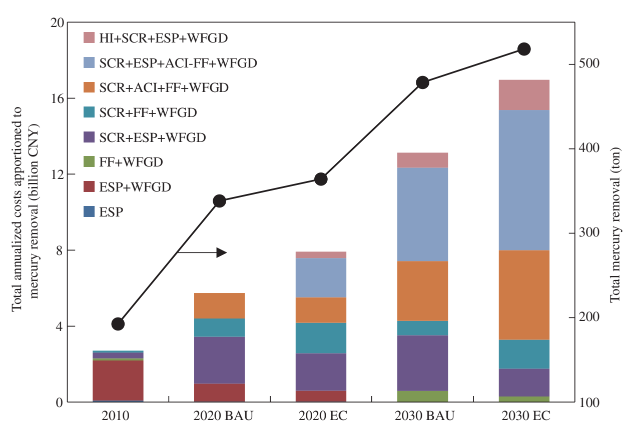

Fig. 7 – Total annualized costs and total mercury removal of China's power fleet.

The European Union (EU) has achieved significant atmospheric mercury emission reduction (67% in 20 years) exclusively by the use of co-benefit technologies and the switching of fuel from coal to natural gas. Additional co-benefits are expected to be achieved by increased coverage of APCDs to remove NO_x, SO_2 and PM as required by the Industrial Emissions Directive (2010/75/EU) and the upcoming revision of the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Weem, 2011). However, there had been a proposal to revise the Heavy Metal Protocol to tighten the mercury emission standard to 3 $\mu g/m^3$ (UNECE, 2011). If this proposal had been pursued, the installations that are not equipped with SCR would have had to apply dedicated mercury control technologies. The cost-effectiveness of these technologies is estimated to be €10,000 per kg mercury removed (Visschedijk et al., 2010). At the regional level, the highest-cost scenario is that half of all EU installations will have to apply these measures, with costs of more than €1 billion (8.3 billion CNY). Under such a scenario, in 2020 the EU would have had to bear similar mercury control costs as those for China under the EC scenario presented in this paper.

In Canada, coal-fired utilities are the largest source of mercury emissions in the country, and are subject to the Canada-Wide Standard (CWS) (CCME, 2012), which consists of both provincial caps on mercury emissions from existing coal-fired power plants and emission limits for new plants. The CWS demanded that in 2010 annual mercury emissions be reduced by 58% compared to the total estimated emissions that would occur without control. Although as of 2012 the caps had not been met in several jurisdictions, the Canadian experience on the joint use of emission caps and emission standards could prove a useful reference for China. Lessons can be drawn also about setting overly ambitious goals, which entail unaffordable costs and cannot be achieved.

4. Conclusions

This paper provides the first economic analysis of six co-benefit and three dedicated mercury control options to abate mercury pollution from coal-fired power plants in China using the most recent and China-specific mercury removal efficiencies. Co-benefit APCDs' annualized costs were attributed to mercury control using a pollutant equivalent apportionment method. The most cost-effective co-benefit control combination for a typical 600 MW power plant is FF + WFGD. This can remove up to 86% of the mercury emissions with costs of 8696 CNY/kg of Hg removed. A power plant equipped with SCR + ESP + WFGD can substitute ESP with FF to cost-effectively achieve an extra 21% mercury removal efficiency. HI application allows an extra 26% mercury removal from SCR + ESP + WFGD with costs of 3657 CNY/kg of Hg removed. ACI technology, although commercially more mature, is currently substantially more expensive than HI or co-benefit technologies. Regarding the national-level analysis, the coal-fired power sector alone could achieve the 12th Five-Year Plan's mercury emission goals if dedicated technologies were gradually applied as per the assumptions in our EC scenario. Higher national costs for total mercury removal are expected for the decade of 2020–2030 relative to 2010–2020, reflecting the higher costs for additional emission reductions by dedicated controls. The use of conventional APCDs in China has higher co-benefit mercury removal than in the US due to the wider WFGD coverage in China.

Acknowledgments

This work was sponsored by the Major State Basic Research Development Program of China (973 Program) (No. 2013CB430001), the National Natural Science Foundation of China (No. 21307070), the MEP's Special Funds for Research on Public Welfares (201209015) and the Sino-Norwegian cooperation project (SINOMER III).

REFERENCES

Brown, T.D., Smith, D.N., O'Dowd, W.J., Hargis Jr., R.A., 2000. Control of mercury emissions from coal-fired power plants: a preliminary cost assessment and the next steps for accurately assessing control costs. Fuel Process. Technol. 65–66, 311–341.

Canadian Council of Ministers of the Environment (CCME), 2012. Canada-wide Standard for Mercury Emissions from Coal-fired Electric Power Generation Plants.

China Council for International Cooperation on Environment and Development (CCICED), 2011. Special Policy Study on Mercury Management in China, Beijing.

China Electricity Council (CEC), 2011. Annual Development Report of China's Power Industry 2011. China Market Press, Beijing.

Development, National, Reform Commission (NDRC), 2003. Administrative Regulations on Levy and use of Pollutant Discharge Fee. Beijing: NDRC, 2003., Beijing, China.

Feeley, T.J., Brickett, L.A., O'Palko, B.A., Jones, A.P., 2008. DOE/NETL's mercury control technology R&D program—taking technology from concept to commercial reality. MEGA Symposium. Baltimore, MD, USA.

Li, G.H., Feng, X.B., Li, Z.G., Qiu, G.L., Shang, L.H., Liang, P., et al., 2010. Mercury emission to atmosphere from primary Zn production in China. Sci. Total Environ. 408 (20), 4607–4612.

Minchener, A., 2012. Non-greenhouse Gas Emissions from Coal-fired Power Plants in China. CCC/196. IEA Clean Coal Centre, London 978-92-9029-516-7.

Ministry of Environmental Protection of China (MEP), 2011. Emission standard of air pollutants for thermal power plants (GB 13223–2011). MEP, Beijing.

Pacyna, J.M., Sundseth, K., Pacyna, E.G., Jozewicz, W., Munthe, J., Belhaj, M., et al., 2010. An assessment of costs and benefits associated with mercury emission reductions from major anthropogenic sources. J. Air Waste Manage. Assoc. 60 (3), 302–315.

Rini, M.J., Vosteen, B.W., 2009. Full-scale test results from a 600 MW PRB-fired unit using Alstom's KNX™ technology for mercury control. MEC6 Conference. Ljubljana, Slovenia.

Sloss, L., 2012. Legislation, Standards and Methods for Mercury Emission Control. CCC/195. IEA Clean Coal Centre, London 978-92-9029-515-0.

Sun, J., Schreifels, J., Wang, J., Fu, J.S., Wang, S.X., 2014. Cost estimate of multi-pollutant abatement from the power sector in the Yangtze River Delta region of China. Energ. Policy 69, 478–488.

Tian, H.Z., Wang, Y., Cheng, K., Qu, Y.P., Hao, J.M., Xue, Z.G., et al., 2012. Control strategies of atmospheric mercury emissions from coal-fired power plants in China. J. Air Waste Manage. Assoc. 62 (5), 576–586.

United Nations Economic Commission for Europe (UNECE), 2011. Options for Revising the Protocol on Heavy Metals. ECE/EB.AIR/WG.5/2011/19.

United Nations Environment Programme (UNEP), 2005. Toolkit for Identification and Quantification of Mercury Releases (Geneva, Switzerland).

United Nations Environment Programme (UNEP), 2013. Global Mercury Assessment 2013: Sources, Emissions, Releases and Environmental Transport (Geneva, Switzerland).

United States Environmental Protection Agency (US EPA), 2009. CUECost Workbook Development Documentation (Version 5.0). EPA/600/R-09/131.

United States Environmental Protection Agency (US EPA), 2011a. Mercury and Air Toxics Standards (MATS) for Power Plants. United States Environmental Protection Agency, Washington, DC, USA.

United States Environmental Protection Agency (US EPA), 2011b. Regulatory Impact Analysis for the Final Mercury and Air Toxics Standards. Research Triangle Park, NC, USA.

Visschedijk, A., van der Gon, H.D., Kuenen, J., van der Brugh, H., 2010. Heavy metal emissions and reduction costs. In: Slootweg, J., Posch, M., Hettelingh, J.-P. (Eds.), Progress in the Modelling of Critical Thresholds, Impacts to Plant Species Diversity and Ecosystem Services in Europe: CCE Status Report 2010. Netherlands, pp. 69–81.

Wang, J., 2014. Synergetic Control Strategy for multiple air Pollutants from Multiple Sectors in the Yangtze River Delta Region. M.S. thesis. Tsinghua University, Beijing, China.

Wang, Y.J., Duan, Y.F., Yang, L.G., Zhao, C.S., Shen, X.L., Zhang, M.Y., et al., 2009. Experimental study on mercury transformation and removal in coal-fired boiler flue gases. Fuel Process. Technol. 90 (5), 643–651.

Wang, S., Zhang, L., Li, G., Wu, Y., Hao, J., Pirrone, N., et al., 2010. Mercury emission and speciation of coal-fired power plants in China. Atmos. Chem. Phys. 10 (3), 1183–1192.

Wang, S.X., Zhang, L., Zhao, B., Meng, Y., Hao, J.M., 2012. Mitigation potential of mercury emissions from coal-fired power plants in China. Energy Fuels 26 (8), 4635–4642.

Wang, S.X., Zhang, L., Wang, L., Wu, Q.R., Wang, F.Y., Hao, J.M., 2013. A new inventory on atmospheric mercury emissions from anthropogenic sources in China, 2000–2010. The 11th International Conference on Mercury as a Global Pollutant. ICMGP, Edinburgh, Scotland, UK.

Weem, A.P., 2011. Reduction of mercury emissions from coal fired power plants. Working Group of Strategies and Review, 48th Session. United Nations Economic Commission for Europe, Geneva, Switzerland.

Wu, D., Zhang, S.Q., Zhu, T., 2011. Controlling mercury emission for China's coal fired electricity plants: an economic analysis. Energy Proc. 5, 1439–1454.

Zhang, L., 2012. Emission Characteristics and Synergistic Control Strategies of Atmospheric Mercury from Coal Combustion in China. Ph.D. thesis. Tsinghua University, Beijing.

Zhang, L., Zhuo, Y.Q., Chen, L., Xu, X.C., Chen, C.H., 2008. Mercury emissions from six coal-fired power plants in China. Fuel Process. Technol. 89 (11), 1033–1040.

Zhang, L., Wang, S.X., Meng, Y., Hao, J.M., 2012. Influence of mercury and chlorine content of coal on mercury emissions from coal-fired power plants in China. Environ. Sci. Technol. 46 (11), 6385–6392.

Zhao, B., Wang, S., Liu, H., Xu, J., Fu, K., Klimont, Z., et al., 2013. NO_x emissions in China: historical trends and future perspectives. Atmos. Chem. Phys. 13, 9869–9897.