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Meeting Minamata: Cost-effective compliance options for atmospheric mercury control in Chinese coal-fired power plants

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HIGHLIGHTS

- First Minamata Convention compliance toolset for coal-fired power plants in China.
- BAT decision tree regarding the most comprehensive set of Hg control technologies.
- Co-benefit Hg control technology and its enhancement could be early measures.
- ACI and HI application needed for China to reproduce the goal of MATS in the US.
- Policy options on Hg emission reduction targets achievable at reasonable costs.

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ABSTRACT

A new international treaty, Minamata Convention, identifies mercury (Hg) as a global threat to human health and seeks to control its releases and emissions. Coal-fired power plants are a major source of mercury pollution worldwide and are expected to be the first key sector to be addressed in China under Minamata Convention. A best available technique (BAT) adoption model was developed in the form of a decision tree and cost-effectiveness for each technological option. Co-benefit control technologies and their enhancement with coal blending/switching and halogen injection (HI) can provide early measures to help China meet the Minamata Convention obligations. We project future energy and policy scenarios to simulate potential national mercury reduction goals for China and estimate costs of the control measures for each scenario. The “Minamata Medium” scenario, equivalent to the goal of the US Mercury and Air Toxics Standards (MATS) rule, requires the application of activated carbon injection (ACI) and HI on 30% and 20% of power plants, respectively. The corresponding total costs would be \$2.5 billion, approximately one-fourth the costs in the US. An emission limit of 3 $\mu g/m^3$ in 2030 was identified as a feasible policy option for China to comply with Minamata Convention.

1. Introduction

Mercury (Hg) is of global concern because of its long-range atmospheric transport, persistence in the environment and bioaccumulation in ecosystems, and significant impacts on human health (UNEP, 2009). In October 2013, a legally-binding treaty, the Minamata Convention on Mercury, was adopted internationally to jointly control mercury emissions and releases. With its ratification the Minamata Convention will bind Parties, of which China is expected to be one, to adopt a series of measures aimed at mercury control and possible reductions from key point sources, including national quantified mercury emission reduction goals and application of nation-specific best available techniques (BATs) for mercury emission control. In accordance with Article 8 of the Minamata Convention, these measures have to be described within a National Implementation Plan (NIP) that China is expected to develop.

The Global Mercury Assessment 2013 identifies coal combustion as a major source of mercury emissions, accounting for 474 t globally in 2010, 66% of which are attributed to coal-fired electricity generating units (Arctic Monitoring and Assessment Programme (AMAP)/United Nations Environment Programme (UNEP), 2013). In China, coal-fired electricity generating units emitted 134 t in 2007 (Tian et al., 2012), and 99 t in 2010 (Zhang, 2012). In the last decade, policies aimed at reducing emissions of conventional

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pollutants have had significant co-beneficial mercury control. In particular, coal-fired electricity generating units in China significantly reduced sulfur dioxide (SO_2) with demonstrated co-benefit mercury emission control (Wang et al., 2010; Tian et al., 2012; Wang et al., 2014). Recent policies, such as fine particulate matter ($PM_{2.5}$) reduction goals in the 2013–2017 Action Plan on Air Pollution Prevention and Control (China State Council, 2013), are also likely to provide co-beneficial mercury emissions control. China has also started to take actions directly addressing mercury emissions. The Emission Standard of Air Pollutants for Thermal Power Plants (MEP, 2011a), requires existing and new power plants to control atmospheric mercury emissions to 30 $\mu g/Nm^3$ beginning January 2015. In addition, the government introduced a mercury reduction target for the first time in the 12th Five-Year Plan for National Environmental Protection (2011–2015) (MEP, 2011b). The Plan, however, does not specify the sources responsible for achieving the reduction target of 15% below 2007 levels, or the regions in which it applies. Ministry of Environment Protection (MEP) of China has also 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, covering key coal-producing provinces (e.g., Shanxi, Inner Mongolia). Both on-line and off-line mercury monitoring methods are adopted for comparison. Coal-fired electricity generating units are expected to be the first key source category that MEP and the Chinese government will address under the Minamata Convention.

Other countries and regions have relied largely on co-benefit mercury control from conventional air pollutant control programs. In the European Union (EU) conventional pollutant regulations have resulted in steady reductions of mercury emissions from coal combustion (European Union, 2011). Despite coal-fired power plants being responsible for half of total anthropogenic atmospheric mercury emissions in Europe (United Nations, UNEP, 2013), only Germany has an applicable emission standard. Germany recently tightened its mercury Emission Limit Value (ELV) from 30 $\mu g/Nm^3$ to 10 μg /Nm^3 for all coal-fired power plants beginning in 2019 (German Federal Government, 2013). In Japan, stringent emission standards for major air pollutants under the Air Pollution Control Law and for dioxins under the Act on Special Measures against Dioxins have contributed to a decline of mercury emissions from coal-fired power plants which in 2010 totaled 1 t (Japan Ministry of Environment, 2013). The US has the most stringent mercury emission standards for coal-fired electricity generating units. The MATS rule, promulgated in December 2011, requires that US coal-fired electricity generating units limit mercury emissions to approximately 2 $\mu g/Nm^3$, approximately 90% mercury control, beginning in 2015 (US EPA, 2011a). In Canada, coal-fired electricity generation units are the largest source of mercury emissions and are subject to the Canada-Wide Standard (CWS) for Mercury Emissions From Coal-Fired Electric Power Generation Plants (CCME, 2006). The CWS establishes provincial caps on mercury emissions from existing coal-fired power plants and emission limits for new plants. The 2006 CWS required annual mercury emissions reductions of 60% in 2010 compared to uncontrolled levels with provisions to tighten that requirement to 80% in 2018.

As policymakers in China explore policy options for achieving the objectives of the Minamata Convention, it will be important to understand their cost-effectiveness. A number of researchers have explored the various mercury emission control options and there effectiveness in developed countries and China. Krishnakumar et al. (2012) introduced tools to identify a broad range of mercury control options for coal-fired electricity generating units, including energy efficiency improvements, fuel switching, co-benefit effects (i.e., maximizing mercury capture in existing pollution control systems), and dedicated mercury control technologies. The user-friendly software they developed estimates the emissions and removal rates of these technological choices for a wide range of coal properties and boiler types. Trovant (2013) presented a generalized asset-based approach to identify basic upgrade requirements for US coal-fired electricity generating units to comply with the MATS rule. The road map they identified for US electricity generating units began with several choices based on coal properties and included dedicated mercury control technologies. For China, Wang et al. (2010) estimated the total mercury emission reductions achievable under different control scenarios in China's power sector, looking only at synergistic, or co-benefit, control options. Wu et al. (2011) reviewed the costs and potential emission reductions from installation of co-benefit control technologies, and estimated the mercury emission abatement attributable to on-going SO_2 control policies. The China Council for International Cooperation on Environment and Development conducted a study that looked at national policy strategies for mercury control from the power sector in China (CCICED, 2011). It suggested that an emission limit for Chinese power plants of 5 $\mu g/m^3$ by 2015 and 3 $\mu g/m^3$ (or lower) by 2020, approximately 90% lower than the current emission standard, would provide a 40% national, economy-wide emission reduction relative to 2007. Tian et al. (2012) also proposed control strategies for mercury reduction in China based on an assessment of mercury emission trends and characteristics. However, their proposals are related only to technological control choices based on qualitative observations.

To date, technological or policy options recommended in the existing China-specific studies have not been linked to international best practices or the Minamata Convention requirements. This study provides a BAT adoption model to identify mercury control compliance paths that results in a decision tree for Chinese coal-fired electricity generating units. The marginal costs of each compliance path are estimated to illustrate the cost-effectiveness of different technological choices for individual power plants. The study also includes analyses of future scenarios at the sector level to estimate the cost-effectiveness of different mercury control measures and identify viable policy options that could inform China’s NIP for the Minamata Convention.

2. Methodology

2.1. APCDs and their impact on mercury emissions

Several available emission control technologies and practices have the potential to reduce mercury emissions from coal-fired electricity generating units. We classify them in this study using the following categories: (1) pre-combustion technologies and techniques, used to clean the coal before it is burned (e.g., washing and chemical cleaning of coal to remove sulfur, ash, and pyrite); (2) post-combustion co-benefit air pollution control devices (APCD), used after the coal is combusted, meant to control criteria pollutants such as particulate matter (PM), SO_2, and nitrogen dioxides (NO_X) but with a co-beneficial impact on mercury capture; (3) co-benefit APCD mercury capture enhancement techniques; and (4) dedicated post-combustion mercury APCD designed specifically to reduce mercury emissions from flue gas. The removal efficiencies and costs of these technologies used in this study are summarized in Table 1. It should be noted that the costs of co-benefit technologies are apportioned to mercury emission control with a Pollutant Equivalent Apportionment (PEA) method described in detail in our previous paper (Ancora et al., 2015).

2.1.1. Pre-combustion mercury control technologies

Coal cleaning is an option for removing mercury from the fuel

Table 1
Mercury removal efficiencies and costs by technique for a 600 MW power plant.

APCD combination	Removal efficiency (%)	Costs in CNY/g Hg removed	References
Pre-combustion			
Coal washing	30	117	UNEP (2010), Wu et al. (2011)
Co-benefit			
ESP	28	5861	Wang et al. (2012), Ancora et al. (2015)
FF	67	5971	Zhang et al. (2015), Ancora et al. (2015)
ESP+WFGD	64	8644	Wang et al. (2012), Ancora et al. (2015)
FF+WFGD	86	8696	Zhang et al. (2015), Ancora et al. (2015)
SCR+ESP+WFGD	69	10,934	Zhang et al. (2015), Ancora et al. (2015)
SCR+FF+WFGD	90	10,953	Wang et al. (2012), Ancora et al. (2015)
Co-benefit enhancement			
CBS+ESP+WFGD	68	12,515[a]	Bustard et al. (2005), Wang et al. (2012), 5E Energy Weekly (2015)
CBS+SCR+ESP+WFGD	74	14,348[a]	Bustard et al. (2005), Wang et al. (2012), 5E Energy Weekly (2015)
HI+SCR+ESP+WFGD (25 ppm $CaBr_2$ solution)	95	11,599	Rini and Vosteen (2009)
Dedicated technologies			
SCR+ACI+FF+WFGD	97	26,134	Feeley et al. (2008), Ancora et al. (2015)
SCR+ESP+ACI-FF+WFGD	99	57,619	Feeley et al. (2008), Ancora et al. (2015)

[a] Co-benefits on PM and SO_2 control from coal blending/switching are not considered.

prior to combustion. The amount of mercury reduction from coal preparation is highly variable, ranging from about 10% to as high as 70% (Pavlish et al., 2003; Yudovich and Ketris, 2005). The efficiency of coal preparation in removing mercury depends on: (1) the amount, type, and size of pyrite in the coal; (2) mercury concentration in the pyrite; (3) the ratio of mercury in the pyrite to organic mercury; and (4) the effectiveness of the coal preparation process at removing the type and size of pyrite in the coal (Kolker et al., 2006). China's estimates of mercury removal efficiencies from coal washing are very limited and within this research we assumed 30% mercury removal, the average of the range provided in the UNEP Process Optimization Guidance for Reducing Mercury Emissions from Coal Combustion in Power Plants (UNEP, 2010). The cost to washed coal for a typical coal-fired power plant in China is estimated to be 17 CNY/kW/year (Wu et al., 2011).

2.1.2. *Co-benefit emission control technologies*

Gaseous mercury can be adsorbed on fly ash and collected in downstream PM control devices such as electrostatic precipitators (ESPs) and fabric filters (FFs). However, FFs show higher mercury removal efficiencies than ESPs because the PM collected on the filter cake of the FFs act as a sorbent for gas-phase mercury for both bituminous and sub-bituminous coals. The mercury removal efficiencies observed in the tests performed in Chinese plants ranged from 7% to 56% for ESPs and 53% to 91% for FFs, respectively (Zhang, 2012). In this study we used Hg removal efficiencies of ESPs and FFs of 28% and 67% respectively, after Ancora et al. (2015). Gaseous oxidized mercury (Hg^{2+}) is generally water-soluble and absorbs in the aqueous slurry – typically water and limestone or hydrated lime – of wet flue gas desulfurization (WFGD) systems. Therefore, mercury capture by wet FGD scrubbers is dependent on the relative amount of Hg^{2+} in the WFGD inlet flue gas. WFGD downstream of ESPs can collectively capture 39–84% of mercury (Zhang, 2012). In our study, the combination of ESP+WFGD is assigned an average mercury removal efficiency of 64% (Wang et al., 2012). A WFGD downstream of FFs increases the mercury removal efficiency to 86%, as found in the study by Zhang et al. (2015). Selective catalytic reduction (SCR) for NO_X control can have an impact on mercury removal if it is combined with downstream WFGD systems. The catalyst of the SCR, which promotes the reduction of NO_X into molecular nitrogen and water vapor, also promotes the oxidization of a significant portion of elemental mercury (Hg°), enhancing subsequent capture in WFGD systems (Pavlish et al., 2003). In this study we assumed that SCR is installed on power plants which are already equipped with a PM removal device and a WFGD, with removal efficiencies typically monitored in Chinese power plants of 69% for the SCR+ESP+WFGD and 90% for the SCR+FF+WFGD combinations. By converting the total emissions of different air pollutants to equivalent emissions, the co-benefits on different pollutants are evaluated in our previous paper (Ancora et al., 2015). Taking the combination of SCR+ESP+WFGD as an example, the shares of co-benefits on mercury, PM, SO_2 and NO_X are 3.9%, 25.7%, 59.2% and 11.2%, respectively.

2.1.3. *Enhancement of co-benefit emission control technologies*

Fuel choices and treatment practices can enhance co-benefit mercury capture in APCDs. For example, optimizing coal qualities or treating coal to enhance the conversion from Hg° to Hg^{2+} during combustion can lead to greater mercury emission control. Coal blending/switching (CBS) and halogen injection (HI) are included in these practices. Coal rank does not provide exact information on physical or chemical properties of coal. However, because some of these properties are closely related to rank and may impact mercury emissions from coal combustion, coal rank may be used for regulatory purposes (Kolker et al., 2006), as is the case for the US MATS emission limits (US EPA, 2011a). Studies in the US have demonstrated that burning bituminous coal results in a higher fraction of Hg^{2+} in flue gas relative to burning sub-bituminous coal (Bustard et al., 2005). While more studies are recommended to draw conclusions in China, the few literature references suggest this is also the case in China (Chen et al., 2007; Tian et al., 2012). Because the Hg^{2+} form is easier to capture in co-benefit APCDs, blending of lower rank coals (e.g., sub-bituminous and lignite) with bituminous coal has the potential to increase mercury capture in post-combustion APCDs. In addition, blending lower rank coals with bituminous coal can reduce the overall environmental impact of coal use because, on average, bituminous coal burned in China has a higher energy content and is lower in sulfur and ash than sub-bituminous and lignite coals (Zhang, 2012). In this study we assume that coal blending/switching, from sub-bituminous or lignite to bituminous coal, can increase the removal efficiencies of post-combustion technologies combinations such as ESP+WFGD and SRC+ESP+WFGD, as illustrated in Table 1. It is worth noting that boilers are generally designed for specific coal ranks and qualities. Deviations from those characteristics, such as switching coal rank without making modifications to the boiler and coal handling equipment, can affect the

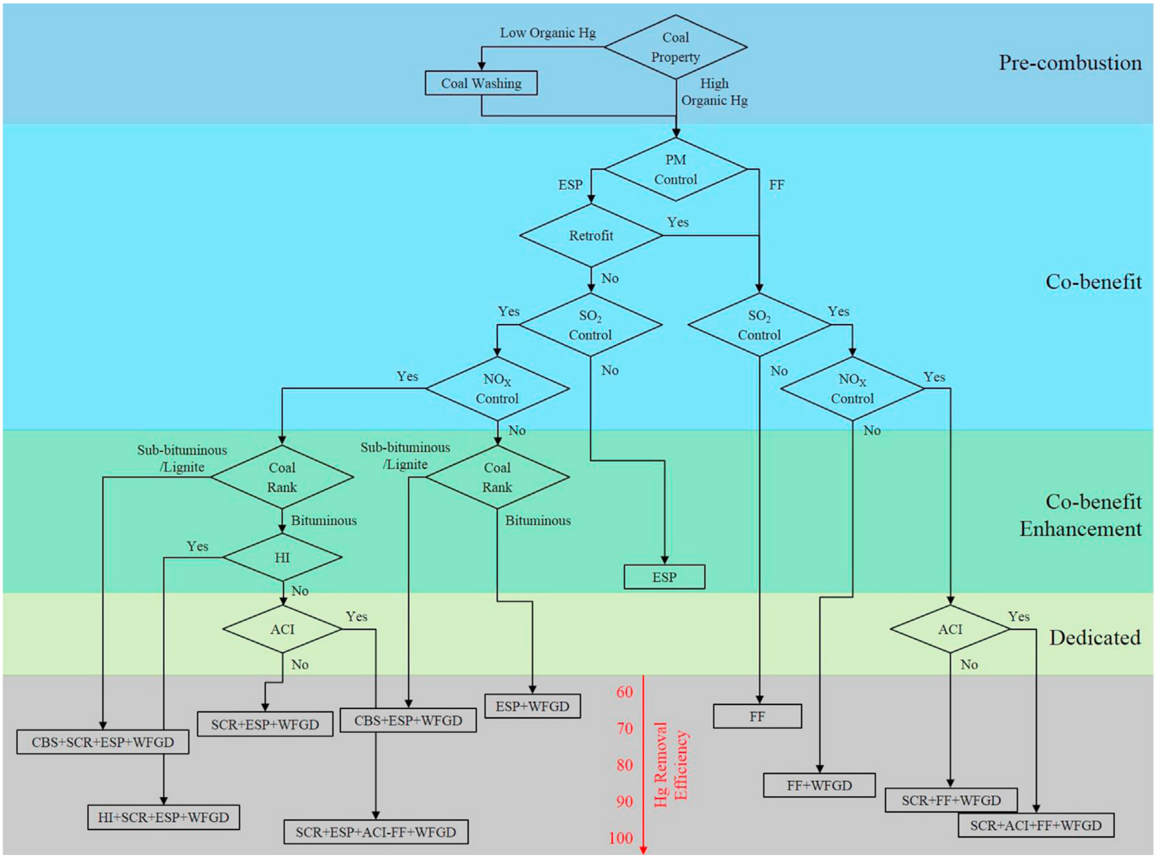

Fig. 1. Best available technique adoption model for atmospheric mercury control technologies.

performance of the boiler and potentially result in damage to the boiler (e.g., slagging) or other equipment (e.g., damage to coal mills). However, power plant operators have demonstrated the ability to successfully blend coals at a certain range. The introduction of stricter SO_2 emission limits in the US created incentives for engineers to innovate and led to techniques for blending coals to reduce emissions and limit impacts and boilers and equipment (Napolitano et al., 2007). A further consideration for fuel blending/switching is fuel cost. The higher cost of bituminous coal relative to sub-bituminous coal could be a deterrent for blending/switching fuel, but would have to be balanced with the higher energy content of bituminous coal that might bring efficiency gains as well as improved mercury control.

Using HI, a solution of calcium salt of hydro bromic acid ($CaBr_2$) is sprayed directly on the coal before it is fed into the boiler. Added bromine ions bind to the Hg° in the flue gas and transform it into Hg^{2+} for subsequent enhanced removal in the downstream WFGD system (Rini and Vosteen, 2009). Mitsubishi Heavy Industries Corporation developed another experimental technique specifically meant for mercury capture – integrated with SCR and FGD technologies, this technique consists of injecting ammonium chloride (NH_4Cl) in the ductwork upstream of the SCR catalyst to promote greater oxidation of elemental mercury. This technique has been successfully tested at Alabama Power's James H. Miller Electric Generating Plant in the US. The technique offers several advantages, including reduced risk of boiler corrosion and reduced generation of salt which may cause deposition on ductworks (Honjo et al., 2012). However costs for injecting this solution are comparable with those of $CaBr_2$ solution and they require a more sophisticated installation on the injection system. Therefore, this approach is not included in this analysis.

2.1.4. Dedicated mercury control technologies

Activated Carbon Injection (ACI) is one of the primary mercury-specific control options. In ACI, mercury and other pollutants adsorb to the surface of the activated carbon which is then removed downstream by PM control technologies (e.g., FFs, ESPs) (NESCAUM, 2010). In this study we included two versions of a typical ACI configuration: (1) injection of powdered sorbent upstream of existing FFs for PM control; and (2) sorbent injection downstream of existing ESPs and subsequent capture in a secondary PM control device (ACI-FF).

By definition, BAT are a dynamic set of practices aimed at limiting pollutant discharges because advances in scientific knowledge, technologies, and societal values change continuously as to what is “reasonably achievable”, “best practicable”, and “best available”. While its strict definition would imply the acquisition of the best state of the art technology available, no matter the costs, in practice BAT take costs into consideration. As a result, co-benefit mercury control technologies, which might not be the most advanced techniques for the highest abatement level, are typically considered BAT. In Europe, where the principle of BAT was first applied, co-benefit technologies are the only BAT currently adopted for mercury control. Japan has taken a similar approach for mercury control from coal-fired electricity generating units. Both Europe and Japan are exploring or beginning to adopt enhanced co-benefit control technologies for better mercury control. In the US, apart from coal washing, other BAT for mercury control include dedicated technologies, specifically ACI.

2.2. BAT adoption model

Using mercury removal efficiencies and costs provided in Table 1 we ranked the most popular co-benefit APCDs installed in coal-fired electricity generating units in China and the most promising dedicated mercury APCDs and practices. In each APCD category described in Section 2.1, we identified six primary decision factors that influence the BAT adoption paths: (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 Fig. 1) on this BAT adoption model is provided to offer guidance for individual power plant owners and operators about the BAT options to reduce mercury emissions and comply with potential mercury emission targets necessary to meet China's obligations under the Minamata Convention.

Occurrence form of mercury in coal determines the mercury removal efficiency of coal washing. Pyrite-bond mercury can be 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). A power plant may have already installed ESPs to control PM emission. The installation of a WFGD, which is required to abate SO_2 emission, can significantly enhance the total mercury removal efficiency. The additional SCR system, needed to comply with the stringent requirements on NO_X control, can further increase the efficiency of mercury removal by averagely 5%. The retrofit from ESPs to FFs for the control of fine particles 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 since ACI is the most effective but also the most expensive approach.

2.3. Key assumptions for future scenario analysis

2.3.1. Energy scenarios

The total electricity generation in 2010, the baseline year, is 42,053 GWh, 75.2% of which is fueled by coal (China Electricity Council (CEC), 2011). We distributed the coal-fired electricity generation units by boiler technology and size combining data from Zhao et al. (2013), Organization for Economic Co-operation and Development (OECD)/International Energy Agency (IEA) (2006), and Minchener (2012). The resulting inventory, shown in Table 2, is then projected into the future following two different assumptions about the share of coal in China's national energy mix in 2020 and 2030 developed by Zhao et al. (2013). The "Energy Scenario 1" (ES1) projects that coal-fired electricity generation will decline slightly to 74.4% in 2020 and 73.3% in 2030. The corresponding coal-based electricity generation capacities (MW) in 2020 and 2030 represent 70.6% and 70.2% respectively of the total installed capacity. The "Energy Scenario 2" (ES2) projects coal-fired electricity generation will decline more substantially, to 64.2% in 2020 and 56.8% in 2030. In the ES2 the use of coal for electricity generation declines more rapidly due to increased natural gas and renewable energy deployments, consistent with planning goals and guidelines issued by the State Council and government ministries. It is worth noting that in ES1 the coal-fired electricity generating capacity surges from 2010 to 2020 and declines from 2020 to 2030, but the 2030 level is still higher than 2010.

Table 2
Number of coal-fired electricity generation plants by technology type and size (under the Energy Scenario 1), including grate boilers (Grate); sub-critical PC boilers (SubC); supercritical PC boilers (SC); ultra-supercritical PC boilers (USC); and fluidized bed combustors (FBC).

Boiler technology-capacity (MW)	2010	2020	2030
Grate-12	426	0	0
SubC-50	266	80	0
SubC-100	665	420	300
SubC-200	222	140	100
SubC-300	1001	1205	1433
SubC-600	72	86	102
SC-600	197	520	765
USC-660	18	105	113
USC-1000	16	93	99
FBC-300	134	198	255
Total	**3017**	**2847**	**3167**

2.3.2. Control scenarios

We developed four scenarios to simulate realistic mercury reduction targets that could be included in China's NIP. Under the BAU scenario, based on current policies in China, overall mercury removal efficiency reaches 70% in 2020. The "Minamata Low" scenario assumes that Chinese coal-fired electricity generating units are encouraged to apply mercury control measures to achieve an overall mercury removal efficiency of 75% in 2020. This target is comparable with the 2006 "Canada-Wide Standard (CWS) for Mercury Emissions From Coal-Fired Electric Power Generation Plants", which demanded 70% and 80% overall mercury removal efficiency in 2018. Under the "Minamata Medium" scenario coal-fired electricity generating units apply mercury control measures to remove over 80% mercury in 2020 and 90% of mercury in 2030. This last goal is comparable to the requirements of the US MATS. The MATS rule is expected to lead to significant additions of ACI, requiring about one third of coal-fired electricity generating units to install ACI in order to comply with emission limits (US EPA, 2011b). This is similar to this study's "Minamata Medium" scenario, where the use of ACI is predicted on 30% of coal-fired power plants in 2030. In the "Minamata High" scenario, coal-fired power plants would have to achieve an overall mercury removal efficiency of 85% in 2020 and 94% in 2030. The latter goal, corresponding to an increase in overall mercury removal efficiency of 70% in 20 years, is comparable to the one originally proposed by the US EPA with the US Clean Air Mercury Rule (CAMR) (United States Environmental Protection Agency, US EPA, 2005). This was the first ever attempt to cap and reduce mercury emissions from coal-fired power plants and it required a mercury emission reduction of 70% in 2018 compared to 1999. However, the courts vacated CAMR, ruling the EPA was using the wrong section of the US Clean Air Act to control mercury emissions from coal-fired electricity generating units.

APCD coverage assumptions associated to each of the above control scenarios are illustrated in Fig. 2. The rate of replacement of PM control devices is estimated on the assumption that at the end of their life-time (i.e., 20 years) ESPs will be replaced with FFs because FFs allow easier compliance with recent $PM_{2.5}$ control policies. As of 2010, ESPs were installed on about 95% of the coal-fired power plants in China, the reminder being equipped with FFs. This is consistent with statistics produced in Tsinghua University (2011). In our scenarios the percentage of ESPs and FFs changes to 60% and 40%, respectively, in the 2030 BAU scenario and 40% and 60%, respectively, in the "Minamata Medium" scenario. The rate of penetration of WFGD increases from 85% in 2010 (Schreifels et al., 2012) to complete coverage (i.e., 100%) in 2030 in all scenarios, on the assumption that Chinese power plants will have to install demonstrated and commercially-available SO2 APCDs to comply with the tightened SO_2 emission standards issued in 2011 (MEP, 2011a). The assumed rate of penetration of SCR

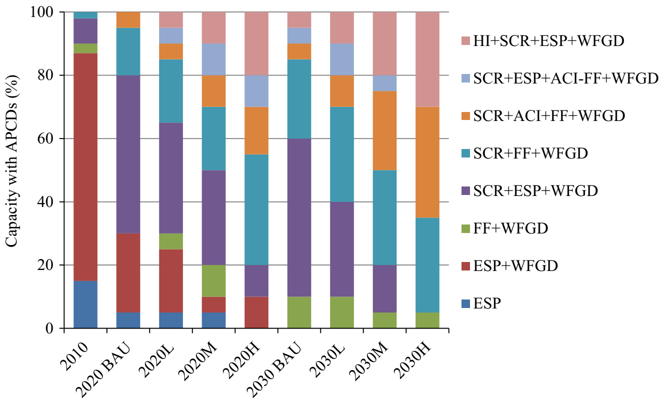

Fig. 2. Projections of APCD deployment under the BAU and Minamata scenarios.

follows the NO_X control requirements of the 12th (and likely 13th) Five-year Plan. The 2010 SCR penetration rate of 10% for the Chinese fleet of coal-fired power plants (MEP, 2011b) is assumed to increase to 70% and 90% of coal-fired power plants in 2020 and 2030, respectively, in the BAU scenario to comply with on-going NO_X control policies. For the "Minamata Medium" and "Minamata High" scenarios, where SCR would be preferred to low NO_X burners because of its ability to enhance conversion of Hg° to Hg^{2+}, the 2030 SCR penetration rate is assumed to be 95%. In our control scenario assumptions, ACI, currently only at the stage of pilot application in China (Trovant, 2013), will reach a national penetration rate of 20% in 2020 and 30% in 2030 for the "Minamata Medium" scenario, and slightly higher coverage in the "Minamata High". The other dedicated mercury control technology considered in this study, HI, is assumed to be applied on power plants equipped with SCR+ESP+WFGD on 5%, 10%, and 20% of Chinese coal-fired power plants in 2020 respectively in the "Minamata Low", "Minamata Medium" and "Minamata High" scenarios. In 2030 these coverage rates increase to 10%, 20%, and 30% over the three scenarios respectively. Despite its lower cost, HI application is foreseen to be chosen less frequently than ACI-FF to compensate for the ESPs' lower mercury removal efficiency, acknowledging that HI has yet to reach the commercial maturity of ACI.

2.4. Calculation method for mercury emission reduction

Atmospheric mercury emission reductions for each of the four scenarios – BAU, Minamata Low, Minamata Medium, and Minamata High – are estimated as a function of uncontrolled emissions of mercury per MWh of electricity generated and mercury removal efficiencies (see Eq. (1)). Uncontrolled emissions are calculated as the product of mercury content in coal and the coal consumed per MWh of electricity produced. These emissions per MWh are multiplied by the removal efficiency factors of each APCD combination described in Table 1 to obtain the potential mercury emission reductions, expressed in grams per MWh, and ultimately the reductions for each policy scenario.

$$R = \sum_{i} \sum_{j} (M_i \cdot C_i \cdot P_{ij} \cdot \eta_j) \tag{1}$$

where R is the total mercury reduction; M is the mercury content in coal, assumed to be 0.17 mg/kg (Zhang, 2012); C is coal combusted; P is the percentage of total sector capacity with different APCD combinations; η is the mercury removal efficiency of the APCD combination; I is unit size; j is APCD combination.

3. Results and discussion

3.1. BAT decision tree and technological paths

While other atmospheric pollutants such as SO_2 and NO_X are captured in a relatively linear way with dedicated APCDs, capture of mercury is highly variable and dependent on coal type and APCD installations. Therefore, the choice of mercury control is site-specific. Having presented in the previous sections how coal type and APCDs affect mercury removal efficiencies, we present here a road map, or decision tree, outlining a range of techniques and APCD combinations, or BAT, that can satisfy different mercury reduction requirements. The decision tree in Fig. 1 is relatively straightforward. First, electricity generating unit owners or operators should assess the properties of coal consumed at the unit because the effectiveness of coal washing for mercury removal is highly variable and dependent on chemical and physical characteristics of the coal and the form in which the mercury is embedded in the coal (e.g., pyritic, metallic, or chemically bound to organic matter) (Swaine, 1990). Literature shows that coal washing is not effective in reducing mercury if it is associated with organic matter in the coal (Kolker et al., 2006; López-Antón et al., 2006). Thus the decision tree starts with the choice of coal washing dependent on the level of organically-bound mercury. In China estimates indicate that coal washing is applied on fuel supplying about 2% of electricity generating units (CEC, 2011). An increase in coal washing would provide a variety of co-benefits, including control of mercury and other pollutants. However, the government should also create incentives and policies to ensure that mercury is not released to the soil or water bodies in by-products.

After considering options for pre-combustion mercury mitigation the owner or operator should consider existing and future APCD installations that can cost-effectively reduce mercury emissions. For example, a coal-fired electricity generating unit with ESPs can increase mercury removal from 28% to 64% with the addition of a WFGD – a necessary APCD to meet national government SO_2 emissions goals. With the addition of SCR, the electricity generating unit can achieve up to 69% mercury removal efficiency. In order to achieve mercury removal efficiencies in excess of 90%, a coal-fired electricity generating unit equipped with SCR+ESP+WFGD might have to enhance the co-benefit mercury capture by adopting HI practices or installing ACI. Our study finds that the HI option is cost-effective for small power plants (e.g., less than 300 MW), and it achieves a 95% mercury removal efficiency. Another opportunity to enhance the mercury capture performance of co-benefit technologies is provided by blending or switching fuel. This measure can improve the mercury removal efficiency of downstream ESP+WFGD and/or SCR+ESP+WFGD by about 5%.

Compared with the toolsets developed by Trovant (2013) for the US case and by Wu et al. (2011) for China, the BAT adoption model developed within this study provides a set of choices which are specifically designed for Chinese coal-fired power plants. The options available to a power plant equipped with existing WFGD technology are fairly important to China, while not as important in the US case. Pollutant Equivalent Apportionment (PEA) method was used for co-benefit technologies to better evaluate their contribution to mercury emission control. Co-benefit enhancement technologies and dedicated mercury control technologies were for the first time introduced into a BAT adoption model for Chinese coal-fired power plants.

3.2. Marginal costs of different technological paths

Fig. 3 complements the information of the BAT decision tree with information on the marginal costs of mercury removal

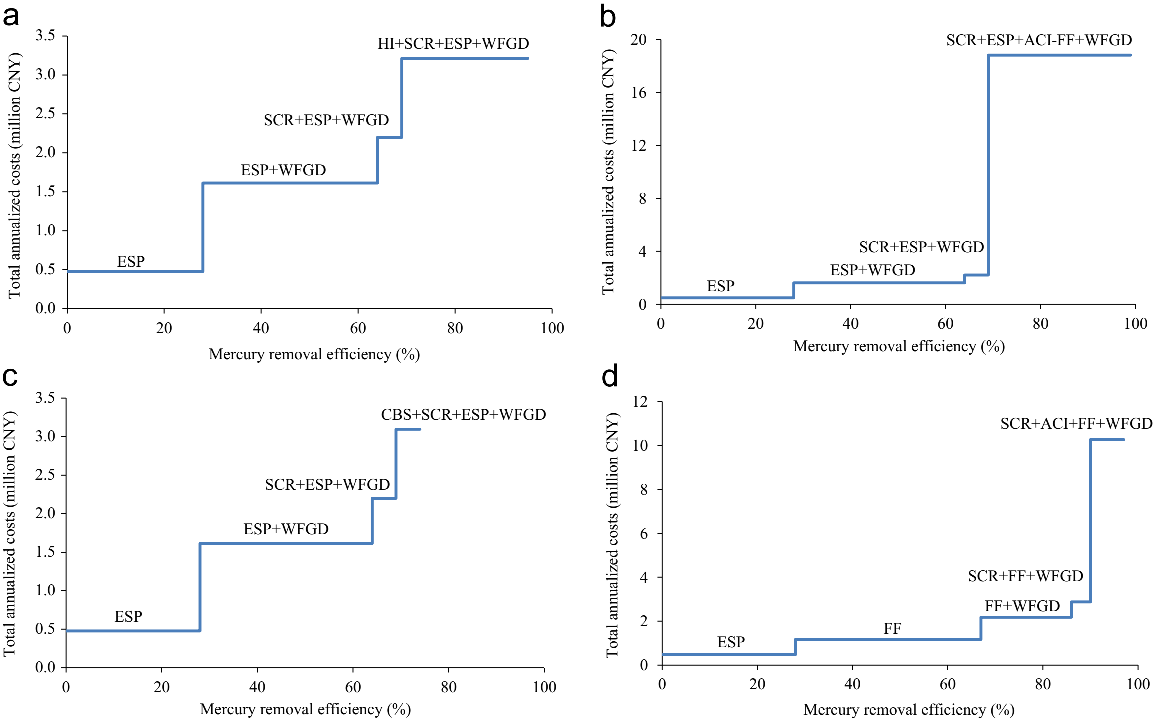

Fig. 3. Alternative best available technique adoption paths (a: Path 1; b: Path 2; c: Path 3; d: Path 4).

related to each alternative choice of post-combustion APCD for a 600 MW power plant. The additional total annualized cost apportioned to mercury removal of ESP+WFGD relative to ESP only is 1.89 CNY/kW and provides a gain in mercury removal efficiency of 36%. Installing SCR enhances the mercury removal efficiency from 64% to 69% and would require incremental costs of 0.98 CNY/kW and provide other environmental benefits associated with NO_X control. A similar increase in removal efficiency, from 64% to 68%, can be achieved by a coal-fired power plant equipped with ESP+WFGD through switching from sub-bituminous (or lignite) coal to bituminous coal. Path 1 and 2 in Fig. 3 culminate with different choices of dedicated mercury APCD leading to removal efficiencies in excess of 90%, but different costs. In fact, a power plant can choose to use HI to increase the mercury removal efficiency by 26% (from 69% to 95%) with corresponding additional total cost of 1.69 CNY/kW (Path 1). Alternatively, the power plant can increase the mercury removal efficiency to 99% by injecting sorbent downstream of existing ESPs and capturing the mercury-laden sorbent in a secondary PM control device (ACI-FF), with total additional costs of 27.72 CNY/kW (Path 2). Path 3 illustrates that coal blending/switching ahead of SCR+ESP+WFGD can improve mercury capture efficiency from 69% to 74% with incremental costs of 1.49 CNY/kW. It should be noted that co-benefits on SO_2 and PM control from coal blending/switching are not considered in this study.

The Alternative Path starts with the same ESP as the only initial APCD, but includes the conversion of the ESP to FF, providing an increase in mercury removal efficiency of 39%. The additional costs of this mercury capture are 1.15 CNY/kW. Adding WFGD to FFs would increase the total mercury removal to 86% with additional costs of 1.69 CNY/kW. Adding SCR to the FF+WFGD combination would bring the mercury removal efficiency to 90% with additional costs of 1.16 CNY/kW. This could be increased further, to 97%, with the injection of powdered sorbent through an ACI installed upstream of the FFs. However this addition of ACI would cost 12.32 CNY/kW, an amount that would likely not be cost effective for smaller electricity generating units (e.g., below 300 MW capacity).

3.3. *Potential of mercury emission reduction under Minamata control scenarios*

In this section we review the emissions impacts of mercury pollution control strategies under the BAU and Minamata scenarios. These are summarized in Fig. 4 as total mercury reductions (tons) and clearly show the significant impact of the energy patterns. The 12th Five-Year Plan – the social and economic master plan designed by the National Development and Reform Commission of China – mandates significant reductions of PM, SO_2, and NO_X. The current and projected deployment of APCDs to meet these targets under the BAU scenario in 2020 will result in total mercury removals of 349 and 225 t under Energy Scenario 1 (ES1) and Energy Scenario 2 (ES2) respectively. Thanks to the decline of coal-based electricity generation in Chinese energy mix, the

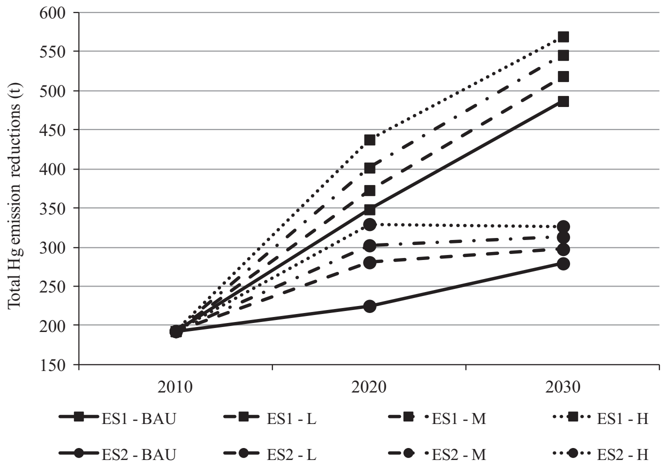

Fig. 4. Total mercury emission reductions achieved by China's power sector under the Business As Usual and Minamata scenarios.

benefit from energy policies can be even more significant in 2030. Mercury removals in ES1-BAU and ES2-BAU in 2030 are 487 and 279 t respectively.

By 2020, the Minamata Low scenario would achieve about 373 t and 281 t of total mercury removal under ES1 and ES2, respectively. The overall mercury removal efficiency under the ES1 in Minamata Low is 75%. It is a 5% increase in overall removal efficiency compared to the BAU scenario which is achieved with additional costs of about 2 billion CNY. These additional reductions and corresponding costs can be attributed to the assumed rate of application of ACI in the Minamata Low scenario. Assuming an average 10,000 m^3 of flue gas is emitted per ton of coal burned and an average of 0.17 mg of Hg/kg of coal, our analysis shows that a limit of 5 μg/m^3 is achievable in 2020 under the “Minamata Low” scenario. To achieve this mercury compliance rate, the coal-fired power sector would have to spend a total of 8 billion CNY which is very limited compared to the expected investment in WFGD technology for the coal-fired power sector in China by 2020, estimated at 620 billion CNY (McIlvaine, 2009).

Under the “Minamata Medium” scenario total mercury emission reductions in 2020 are estimated to be 402 and 302 t under ES1 and ES2 respectively. With the same percentage of additional costs (91%) in comparison to the 2020 BAU scenario, the incremental mercury removals of ES1 and ES2 are 15% and 34% respectively, indicating the mercury control measures will be more cost-effective under low energy scenario. The total mercury removal efficiency achieved under this scenario in 2030–90% – is similar to the requirements of the US MATS rule and corresponds to total mercury reductions of 546 t. In 2030 China could require an emission limit similar to the United States, about 3 μg/m^3. The costs associated with BAT installation rates foreseen in this scenario 15.5 billion CNY (or $2.5 billion using an exchange rate of 6.2 CNY:USD) are about one fourth those of the US MATS compliance costs, estimated at $9.6 billion (US EPA, 2011b).

The total reductions achieved under the “Minamata High” scenario in 2020 and 2030 are 438 t and 570 t under ES1, respectively, and 330 and 327, respectively, in the ES2. The “Minamata High” scenario under ES1 provides 245 and 377 t of mercury emission reduction in 2020 and 2030 respectively, relative to the 2010 levels. Still in 2020, the additional reductions gained with the control assumptions of the “Minamata High” scenario, compared to the BAU in the same year are quite different in the ES1 (26%) and ES2 (46%) scenarios. In ES2 in 2020 coal-fired power plants are responsible for 60% of electricity generation (versus 70% in ES1), meaning that the aggressive penetration rates of SCR, ACI and HI foreseen under the “Minamata High” are effective in achieving high-levels of overall mercury removal. The emission reductions are achieved with almost double the costs of the 2020 BAU scenario, about 13 billion CNY. These costs are also about 1.6 billion CNY more than the 2020 “Minamata Medium” that relies less on HI (and ACI). In the period 2010-2020 achieving the overall removal efficiencies under all control scenarios would cost about 25% less in ES2 than ES1; in the 2020–2030 period a sharper decline in the use of coal would allow China to achieve the same mercury removal performances with on average 45% less cost. This provides further support for energy efficiency improvement and other clean coal policies.

3.4. *Cost-effectiveness of the Minamata control scenarios*

The cost-effectiveness of mercury control strategies at China's coal-fired electricity generating units is presented in Fig. 5. The cost-effectiveness of the control strategies significantly increases in the 2010–2020 period, pointing to a significant opportunity for co-beneficial mercury control from other APCD that are expected to dominate during this period in all control scenarios. The “Minamata Low” scenario shows remarkable differences in cost-effectiveness under both energy scenarios compared to the other scenarios in 2020. While the “Minamata Low” scenario under ES1 exhibits a cost-effectiveness of 21.5 CNY/g of mercury reduced in 2020, the “Minamata Medium” and “Minamata High” scenarios yield costs of 28.1 and 29.6 CNY/g of mercury removed respectively. As explained above, this is due to the dominant use of co-benefit control options in the “Minamata Low” relative to other scenarios. In the 2010–2020 period, cost effectiveness under the three Minamata scenarios remains rather similar under both energy scenarios. However, in the 2020–2030 period, the cost-effectiveness remains relatively steady under ES1– except for the BAU scenario because mercury input is lower – while it declines under ES2. In the “Minamata Medium” scenario, for example, in 2030 it would cost CNY 29 to remove a gram of mercury under ES1, while it would cost 27.3 CNY/g of mercury removed under ES2. The “Minamata High” scenario's cost-effectiveness increases in 2030 compared to 2020, from 29.6 CNY to 28.9 CNY per gram of mercury removed under ES1 and from 29.7 CNY to 27.1 CNY per gram of mercury removed under ES2. This is attributed to more aggressive use of ACI on SCR+FF+WFGD and HI on SCR+ESP+WFGD, with respective application rates of 133% and 50% more in 2030 than in 2020. These results provide evidence that switching to a less coal-dependent energy structure (as well as improving energy efficiency) can have significant co-benefits for atmospheric mercury pollution. In the Chinese case, the cost-effectiveness of these options is higher than in the US, with total annual costs to achieve a 90% reduction in 2030 estimated as one fourth the costs in the US.

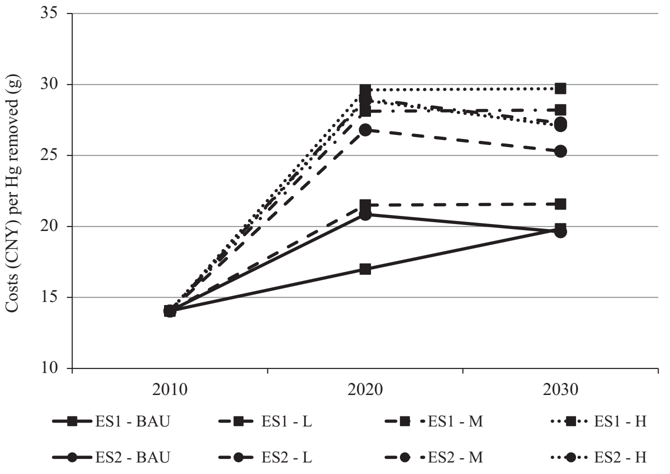

Fig. 5. Cost-effectiveness of the mercury emission control scenarios (ES1= Energy Scenario 1; ES2= Energy Scenario 2; BAU= Business As Usual; L= Minamata Low; M= Minamata Medium; H= Minamata High).

3.5. *Uncertainty and sensitivity analysis*

Uncertainties on the future costs of control technologies directly affect the cost-effectiveness results in this analysis. To explore the potential uncertainty of the overall costs for mercury control, assessments of uncertainty levels for capital costs and O&M costs of APCD technologies were conducted based on the dataset of costs. More detailed information can be found in our previous paper (Ancora et al., 2015). The overall uncertainty levels of capital costs and O&M costs 16% and 38%, respectively. Here we only considered the current cost uncertainties, but it is also possible that costs could decrease due to economies of scale, commercial maturity, or technical innovation. If costs decreased, they would enhance the cost-effectiveness of mercury removal. The analysis shows that O&M variables have a greater impact than capital costs. If the capital costs and O&M costs increase by 16% and 38% respectively, the total annualized mercury control costs for the power sector can be raised by 30% in 2010 (from CNY 2.7 billion to 3.5 billion). We also conducted a sensitivity analysis to assess the impact of the two different energy scenarios on the costs in the BAU scenario in 2020 and 2030. This shows that a 22% reduction of coal-based power capacity in 2030 in the ES2 compared to the ES1 is responsible for an average increase in cost-effectiveness of 6% throughout all scenarios.

4. Conclusions and policy implications

4.1. Conclusions

Mercury is a toxic compound of global concern and it is important to control its anthropogenic emissions and releases in the environment. One of the major sources of atmospheric mercury emissions in China is coal combustion in electricity generating units. These units will therefore be an important target, likely one of the first, in government efforts to control mercury emissions under the Minamata Convention. Controlling significant amounts of atmospheric mercury emissions from coal-fired electricity generating units is possible through an optimized choice of pre-combustion coal washing techniques, co-benefit APCDs, enhanced capture techniques, and dedicated mercury control technologies. Our study tailors the first BAT model for mercury control for individual Chinese power plants. The BAT model presented in this paper is China specific because it looks at technology options which are already well-established at Chinese power plants or are likely to be adopted in light of their practicality, such as ACI-FF and HI. It provides an easy-to-follow decision tree that facilitates selection of mercury control technology options. The decision tree is complemented by cost curves substantiating the cost-effectiveness of compliance paths with costs of co-benefit technologies apportioned to mercury. Our BAT decision tree includes the application of coal washing, coal blending/switching and HI practices, to enhance mercury emission control in co-benefit technology combinations popular in China, and culminates with dedicated mercury control technologies for removal efficiencies in excess of 95%. Our study suggests several different realistic policy options for China's power sector that might contribute to China's NIP to be submitted by 2021 to the Conference of Parties of the Minamata Convention. We provide information about costs and effectiveness, measured as overall mercury removed, of BAU and the three “Minamata” scenarios that simulate quantified reduction targets enforced in other countries.

4.2. Policy implications

The Minamata Convention requires that Parties to the agreement commit to national strategies to control and where possible reduce mercury emissions from the key sources listed in Annex D, which includes coal-fired electricity generating units. The measures suggested in Article 8 of the Minamata Convention for this key category include mandating the use of BAT and/or committing to a quantified national reduction goal and/or emission limit values. Our study shows that co-benefit BAT are highly cost-effective in China and suggests that policymakers and the power sector should therefore leverage the on-going initiatives to reduce conventional pollutants, such as the 2013–2017 Action Plan on Air Pollution Prevention and Control, and improve energy efficiency to take advantage of complementary interactions with mercury control. Coal washing is a practice that could be made mandatory for selected coal types, such as coals with low organically-bound Hg, since it also has clear co-benefits for other pollutants. The BAU scenario simulates an optimized use of co-control technology, whereby FFs replace lower performing ESPs, and shows that significant reductions can be achieved with great cost-effectiveness. WFGD, installed downstream of FFs or ESPs, can increase the overall mercury removal efficiency in a cost-effective way. The addition of SCR can further improve mercury capture. Blending bituminous coal with sub-bituminous and lignite coals may be a cost-effective option for plants equipped with ESP+WFGD and SCR+ESP+WFGD to increase their mercury removal efficiencies. Even more cost-effective is the adoption of HI practices in conjunction with SCR+ESP+WFGD, with significant gains in mercury removal efficiency and modest additional costs. Although ACI is not as cost-effective as the previous options, if mercury control targets are tightened ACI may be necessary to achieve removal efficiencies in excess of 95%. Its costs in China would still be lower than in the US.

The results of our study offer useful information about costs and effectiveness of several national emission reduction targets which can be achieved in China in the next 15 years. These goals could be included in the 13th FYP for Environmental Protection. In spite of being one of the largest emitters worldwide, China's power sector is subject to lenient standards – 30 $\mu g/m^3$ – compared to the most stringent emission limit applied at US coal-fired electricity generating units. The current Chinese standard is equivalent to Germany's current standard, the only European mercury emission limit for electricity generating units. However, in 2013, Germany promulgated a new standard to enter into force in January 2019 that is three times more stringent than the current one. China could exceed this and achieve a limit value of 5 $\mu g/m^3$ in 2020, aiming to achieve a 3 $\mu g/m^3$ limit in 2030.

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