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

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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.

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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