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Cost estimate of multi-pollutant abatement from the power sector in the Yangtze River Delta region of China

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HIGHLIGHTS

- Multi-pollutant emission data with various control measure information are provided.
- We use LP algorithm to optimize the cost estimate of multi-pollutant abatements.
- High reduction percent will raise the cost exponentially for different regions.
- For different regions, the cost for the same removal percentage can vary dramatically.

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ABSTRACT

Coal-fired power plants in China have emitted multiple pollutants including sulfur dioxide, nitrogen oxides and fine particulates, contributing to serious environmental impairments and human health issues. To meet ambient air quality standards, the installation of effective pollution control technologies are required and consequently, the cost of installing or retrofitting control technologies is an important economic and political concern. A multi-pollutant control cost model, CoST CE, is developed to calculate the cost of multi-pollutant control strategies in the Yangtze River Delta region (YRD) of China, adopting an LP algorithm to optimize the sorting of control technology costs and quickly obtain a solution. The output shows that total costs will increase along with emission abatement. Meanwhile, the slope becomes steeper as greater emission reductions are pursued, due to the need to install highly effective, but expensive, technologies like SCR and FF. Moreover, it is evident that the cost curve shapes, maximum abatement potential and total cost for the three provinces in the YRD region are quite different due to differences in power plant type and technologies, current emission levels and existing pollution controls. The results from this study can aid policy makers to develop cost-effective control strategies for the power sector.

1. Introduction

Due to rapid urbanization and economic development, China's Gross Domestic Product (GDP) has grown at a high annual rate of greater than 9% between 1978 and 2009 (Zhang and Yang, 2013). Concomitantly, China's energy consumption increased exponentially during this period of time. Among the various forms of energy, coal is the dominant resource for generating electricity and heat in China. According to the China Statistical Yearbook 2012 (National Bureau of Statistics, 2013), total primary energy consumption reached 3.48 billion tons of standard coal equivalent in 2012, representing 68.4% of the total primary energy consumption. Compared to the statistics in 2000, total energy consumption had increased by 185.3% and total coal consumption had risen by 190.8% (National Bureau of Statistics, 2001; 2013). Of total coal consumption, 48.4% was consumed in coal-fired power plants in 2011 to generate electricity (National Bureau of Statistics, 2013). Due to the usage of low quality coal with relatively high sulfur, nitrogen and ash content, coal combustion releases large amounts of gaseous pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_X),

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and particulate matter, including fine particulate matter with diameters less than or equal to 2.5 μm ($PM_{2.5}$). In the ambient atmosphere, SO_2 and NO_X, together with their secondary pollutants, can have serious impacts on the environment and human health (Lu et al., 2010; Du et al., 2012; Chen et al., 2012). $PM_{2.5}$ is a major contributor to the regional haze (i.e., visibility reduction) and has considerable effects on respiratory diseases and global climate change (Yang et al., 2013). Human mortality caused by particle pollution could reach 1.4 million people each year in China (Florig, 1997). In 2011, the World Health Organization (WHO) investigated air pollution in 1100 cities around the world. In the Yangtze River Delta (YRD) region of China, Nanjing, Hangzhou, and Shanghai are unfortunately among the 110 most polluted cities in the world (2011, available from http://www.who.int/phe/health_topics/outdoorair/databases/en/). Meanwhile, the serious regional haze in Shanghai in January 2013 and over more than 25 provinces, including YRD region, in December 2013 raised the public's awareness of the importance of reducing emissions that lead to primary and secondary particulate patter.

To mitigate the severe impact of anthropogenic emissions from power plants on human health and the environment, it is necessary for the Chinese government to implement control strategies to reduce SO_2, NO_X and $PM_{2.5}$ emissions. Governments at the national, provincial, and municipal level in China have already implemented several control strategies over past few years. Since 2006, installation of Flue-Gas Desulfurization (FGD) devices at coal-fired power plants were mandated through China's 11th Five-Year Plan (2006–2010) policies and the China Ministry of Environmental Protection's (MEP's) efforts to reduce SO_2 emissions by 10% relative to 2005 levels (Lu et al., 2011). During the 11th Five-Year Plan period, SO_2 emission reductions exceeded the target, falling 14% from 2005 levels and this success was due in large part to improved policy design that established accountability, focused on performance, and prioritized incentives, and political support to implement and enforce the policies (Schreifels et al., 2012). In the 12th Five-Year Plan (2011–2015), the government has established new goals to further reduce SO_2 emissions by 8% and NO_X emissions by 10% relative to the 2010 emission levels (available at: http://english.sepa.gov.cn/News_service/infocus/201202/t20120207_223194.htm). While significant progress has been made to reduce SO_2 emissions from the power sector, achieving the NO_X reduction goal will require effective pollution control devices such as Selective Catalytic Reduction (SCR), Selective Non-Catalytic Reduction (SNCR), and Low-NO_X Burners (LNB) at coal-fired power plants. For reducing particulate matter, efforts have been underway for many years. China's first ambient air quality standards, published in 1982, prescribed limits for daily average total suspended particulates (TSP) and PM_{10} levels (Florig et al., 2002). According to current inventories, all coal-fired power plants built before 2010 in the YRD region are installed with PM abatement technologies like cyclones (CYC), wet scrubbers (WET) or electrostatic precipitators (ESP). Although there is not currently an absolute target for direct $PM_{2.5}$ emissions, which are finer and have a greater impact on human health, China's State Council promulgated a new ambient air quality standard for $PM_{2.5}$ in 2012 (GB 3095–2012) and the action plan for air pollution prevention and control in September 2013 (available from: http://english.mep.gov.cn/News_service/infocus/201309/t20130924_260707.htm?COLLCC=1069211751&). To meet the new standards, coal-fired power plants may have to install additional or replace existing particulate controls with high-efficiency pollution controls, such as Fabric Filters (FF).

If coal-fired power plants will have to install and operate a number of control technologies to meet these standards, it raises a crucial question: how much money will the government or industry need to invest in the installation and operation of pollution control devices to reduce SO_2, NO_X and $PM_{2.5}$ emissions? Gipson et al. (1975) developed a least-cost evaluation of regional strategies for control of SO_2 and TSP in 1973 for the United States. They formulated an integer programming problem by considering availability of fuel and control devices. Different methods of solving this problem were evaluated and a Linear Programming (LP) round-off plus heuristic technique was recommended as the most promising approach to find the regional least-cost solution. In 1981, Cass and McRae (1981) summarized past work to develop least-cost solutions and pointed out future areas of research and potential barriers for practical application of models, such as data resources (spatially and temporally resolved data on pollutant concentrations, wind speed, wind direction, inversion base height, terrain height and solar radiation), technology transfer and time limits (waiting for administrative review and approval, and training inexperienced personnel). Harley et al. (1989) conducted a least-cost study based on a receptor-oriented model. In their work each air monitoring site was treated as a receptor. They adopted a simplex algorithm for LP coupled with subroutines that implemented a branch and bound algorithm for integer programming. Recently, Fu et al. (2006) conducted research to identify cost-effective control strategies for ozone based on Emission Least Cost (ELC) and Ambient Least Cost (ALC) approaches. They adopted a heuristic method using only a small number of simple air quality model simulations and then refined with a complex air quality model, which might reduce the number of complex model runs. Elliston et al. (2013) used a generic algorithm to identify the least cost for a 100% renewable electricity scenario in the Australian national electricity market. The scenario proved to be cheaper on an annual basis than the replacement scenario for addressing climate change. Vijay et al. (2010) applied a bottom-up method to develop NO_X Marginal Abatement Cost Curves (MACCs) for coal-fired utility boilers in the United States. This method was based on the technical details associated with specific boiler configurations and retrofit technologies, which should have a high resolution. Nevertheless, a shortcoming of their work was that it did not take the pre-existing control technologies into account and could not be interpreted as a policy prescription. It also failed to provide detailed information for each power plant under a specified emissions reduction standard, which was of significant value to the assessment by modelers and policy analysts.

Hence, to bridge the methodological gap above and consider the fact that few studies have been done to investigate the cost issue in China, a multi-pollutant cost model for the YRD region in China was developed to calculate the cost of achieving emission reductions. This model calculates not only the installation cost of new control measures at power plants, but also retrofit cost from existed devices to new and more effective technologies. In addition, it can specify the detailed control strategy for each power plant and show them directly in the cost model. Section 2 describes the cost model methodology in more detail. Section 3 presents the results from the cost model and related discussion. Section 4 highlights our conclusion, policy implications and future work.

2. Material and methods

2.1. Governing equations

Assuming there are N power plants and M types of control technologies for pollutant j, the mathematical formulation for emission control can be written as:

$$R_{j,k} = E_{j,k}\left(1 - \sum_{i=1}^{M}(EFF_{i,j}x_{i,k})\right) \tag{1}$$

Table 1
Summary of data sources.

Data element	Data sources
Electric-generating technology, stock, coal consumption, etc. for power plants in YRD	1. China electricity council statistics 2. National inventory of desulphurization facilities for coal-fired generating units (2011, available from http://www.mep.gov.cn/gkml/hbb/bgg/201104/W020110420407642353906.pdf) 3. National inventory of denitrification facilities for coal-fired generating units (2011, available from http://www.mep.gov.cn/gkml/hbb/bgg/201104/W020110420407642383272.pdf) 4. Dissertation of Zhao (2008)
Emission factors	Dissertation of Zhao (2008)
Coal sulfur content	1. Dissertation of Xing (2011) 2. Study and assessment on the ambient air quality during 2010 Shanghai World Expo (in Chinese). Shanghai Environmental Protection Bureau, 2011 (Lu et al., 2011, available from http://www.doc88.com/p-898572222805.html)
Coal ash content	Dissertation of Zhao (2008)
Sulfur content in ash	Dissertation of Xing (2011)
Removal efficiency of control technologies for different pollutants	1. Dissertation of Yu (2009) 2. Dissertation of Zhao (2008)
Capital cost, FOM cost and fuel cost	1. Data supplied by power plants in the YRD region 2. Policy of NO_X control technology at thermal power plants (2013, available from http://www.chinacses.org/d/2013-01/04/201301041420055.pdf) 3. The 11th Five-year Plan for sulfur dioxide control at coal-fired power plants (2007, available from http://www.zhb.gov.cn/gkml/hbb/gwy/200910/t20091030_180722.htm) 4. Technical and economic comparison of ESP and bag filters for flue gas of thermal power plants (Chen et al., 2007) 5. Coal price survey for the YRD region

$$\sum_{i=1}^{M} x_{i,k} = 1, \quad k = 1, 2, \ldots N \tag{2}$$

$$x_{i,k} \in \{0, 1\}, \quad k = 1, 2, \ldots N; \quad i = 1, 2, \ldots N \tag{3}$$

where $R_{j,k}$ is the remaining emissions of pollutant j after installing control technology i at power plant k, which can be calculated by Eq. (1); $E_{j,k}$ is the original emission of pollutant j at power plant k, (unit: ton); $EFF_{i,j}$ is the removal rate of control technology i for pollutant j, (unit: %); $x_{i,k}$ implies the extent to which the control technology i is applied to reduce the emission from power plant k. $x_{i,k}$ belongs to the set of integers 0 and 1, as shown in Eq. (3). If the control measure is used, $x_{i,k}=1$; if not, $x_{i,k}=0$. Eq. (2) also applies a constraint that only one control technology or pre-defined combination of control technologies can be installed at power plant k for each pollutant j. For SO_2, FGD is the only option; for NO_X, control measures include SCR+LNB – a pre-defined combination of two technologies. We combine them into one technology to reduce the clauses in the model's code, resulting in the assumption that only one control technology or pre-defined combination of control technologies can be used for each power plant. This will help avoid the duplicate installation of like technologies, such as LNB and SCR+LNB at one power plant at the same time. For $PM_{2.5}$, this assumption will prevent the simultaneous application of two or more PM abatement devices, with the exception of a pre-defined combination of ESP and FF – ESP+FF. It is unlikely that power plants in the YRD region would install other combinations of control technologies for particulate matter. The cost of installing control technology i for pollutant j at power plant k is expressed in the following equation:

$$C_{i,j,k} = (CC_{i,j,k} + FOM_{i,j,k} + FUEL_{i,j,k})P_k \tag{4}$$

where $C_{i,j,k}$ is the total cost of control technology i for pollutant j at power plant k, (unit: 2010 US Dollars); $CC_{i,j,k}$ is the capital cost of control technology i for pollutant j at power plant k, (unit: 2010 US Dollars/MW); $FOM_{i,j,k}$ is the fixed operating and maintenance costs of control technology i for pollutant j at power plant k over the lifetime of control technology i (30 years), (unit: 2010 US Dollars/MW); $FUEL_{i,j,k}$ is the fuel cost of control technology i for pollutant j at power plant k over the lifetime of control technology i (30 years), (unit: 2010 US Dollars/MW); P_k is the electric generating capacity of power plant k, (unit: MW). Therefore, our objective function for the cost problem of certain pollutant j is:

$$TC_j = \sum_{k=1}^{N} \sum_{i=1}^{M} (C_{i,j,k} x_{i,k}) \tag{5}$$

where TC_j is the total cost of installing control technologies for pollutant j at N power plants, (unit: 2010 US Dollars).

2.2. Emission data

In this paper, the detailed point source information, including electric-generating technology, stock and coal consumption for the YRD region, comes primarily from China's power industry statistics compiled by China Electricity Council. The information about existing pollution control technologies installed on power plants in the YRD region comes from an MEP announcement from 2011 (available at: http://www.mep.gov.cn/gkml/hbb/bgg/201104/t20110420_209449.htm). The emission factor approach used by Fu et al. (2013) is used to estimate pollutant (SO_2, NO_X and $PM_{2.5}$) emissions. For example, the approach to calculate the uncontrolled SO_2 emission factor is described as:

$$EF_{SO_2} = 2C_s(1 - r_s) \tag{6}$$

where EF_{SO_2} is the uncontrolled emission factor for SO_2; C_s is the sulfur content; r_s is the rate of sulfur retention in ash; the factor of 2 is used to convert the mass of sulfur into sulfur dioxide. The uncontrolled emission factor is multiplied by activity data (i.e. coal consumption) to obtain pre-control SO_2 emissions. The emission factors NO_X and $PM_{2.5}$ are based on studies by Zhao et al. (2008 and 2010). The parameters such as sulfur and ash content in each fuel type are provided at the provincial level and taken from Zhao et al. (2008). Cost data such as capital cost, FOM cost, and fuel cost for pollution control technologies are case-dependent and usually refer to engineering practices of vendors supplying pollution control technologies. Table 1 summarizes the general data sources for the emission and cost values.

2.3. Calculation procedure

The China Multi-Pollutant Control Cost Model, CoST CE, is a Linear Programming (LP) model designed to quickly find a possible solution to achieve an emission target (expressed as a percent reduction from baseline emission data). Based on emission targets supplied by the model operator, the model uses data about the power plant inventory, current mass emissions of each pollutant (i.e., SO_2, NO_X and $PM_{2.5}$), capital and operating costs and emission control efficiency of different control technologies (FGD for SO_2; LNB, SCR, SNCR, SNCR+LNB, SCR+LNB for NO_X; CYC, WET, ESP, FF, ESP+FF for $PM_{2.5}$), and electricity demand to calculate total costs. The model can be explained mathematically as:

$$\text{Solve} \quad TC_j = \sum_{k=1}^{N}\sum_{i=1}^{M}\left[(CC_{i,j,k} + FOM_{i,j,k} + FUEL_{i,j,k})P_k\right] \tag{7}$$

Subject to:

$$CC_{i,j,k} \geq 0 \tag{8}$$

$$FOM_{i,j,k} \geq 0 \tag{9}$$

$$FUEL_{i,j,k} \geq 0 \tag{10}$$

$$\overline{\mathbf{E_j}} \geq \sum_{k=1}^{N}\sum_{i=1}^{M} e_{i,j,k} \tag{11}$$

$$Q \leq \sum_{k=1}^{N} u_k \tag{12}$$

$$0 \leq u_k \leq (P_k a_k) \tag{13}$$

where $\overline{\mathbf{E_j}}$ is the aggregate annual emission target (i.e., constraint) for pollutant j at the N power plants, (unit: ton); $e_{i,j,k}$ is annual emissions after installation of pollution control technology i for pollutant j at power plant k, (unit: ton); Q is aggregate annual electricity demand, (unit: MWh); u_k is annual electric output (MWh) at power plant unit k; a_k is the capacity factor for power plant k.

The initial Eq. (7) is simply a restatement of Eqs. (4) and (5) that says total costs are equal to the total annualized capital costs of newly installed pollution controls and retrofits plus the annual costs of operating and maintaining those controls. The constraints are designed to enforce specific assumptions within the multiple pollutant control cost model. The first three constraints (Eqs. (8)–(10)) state capital costs, operating and maintenance costs and fuel cost must be greater than or equal to zero (zero costs represent a scenario in which the power plant does not install any additional controls.) The fourth (Eq. (11)) states the emission limit for the policy case minus predicted emissions must be greater than or equal to zero, which is another way of stating the emission reduction target must be met. In the model, to develop the scatter plots, the emission reduction target for each pollutant was initialized at a 1% reduction. To obtain the values for Eq. (11), the original emission amount was multiplied by the emission reduction target (100–1%, initially). It should be noted that the predicted emissions are typically lower than the emissions target (i.e., the power plants reduce emissions more than required) because the model does not allow partial emission controls. Each subsequent model run decreases the emission target by two percent from the previous predicted emissions level (i.e., if the predicted emission level is 1.5%, the next model run seeks a 3.5% emission reduction.). This strategy is used to ensure that each scenario produces a unique result because of the partial control constraint. The fifth (Eq. (12)) states that total electricity output must be greater than or equal to total electricity demand. The sixth (Eq. (13)) states that electricity generation for each power plant must be greater than or equal to zero and less than or equal to the boiler's nameplate capacity multiplied by a capacity factor.

The key algorithm adopted for this model is an optimization LP algorithm. It sorts the costs of different control technologies to obtain a solution quickly. The cheapest strategy is applied for each power plant and the resulting reduction percentage is checked against the target emission control. If the desired target reduction is not achieved, the model conducts another iteration using the next lowest-cost technology until the emission reduction goal is achieved. After completing the iterations, the model outputs the results including emissions reductions, including cost per ton removed, capital cost and operating and maintenance costs for incremental pollution controls at each power plant. Note that for a given reduction percentage, the answer to how many power plants have to be installed and operate control measures may not be unique as we only provide one possible solution. The model does not account for power plant location, allowing flexibility to reduce emissions at any location.

Some retrofit rules are proposed in this model to implement the LP algorithm. We prescribe that the current abatement devices can only be retrofitted by technology that has higher control efficiency. For example, if the power plant does not have any control technology for SO_2, FGD will be installed; If FGD has already been installed, no further measure will be taken since this is the only alternative strategy. For NO_X, if an LNB is already installed on a unit, SCR or SNCR can be added to form SCR+LNB or SNCR+LNB, respectively; if SCR+LNB has already been installed, no further controls can be added because no control or combination of controls has a higher NO_X control efficiency. For $PM_{2.5}$, traditionally, coal-fired power plants have installed and operated WET, ESP or FF. However, as tighter emission limits will be adopted in the future, coal-fired power plants around the globe have to again invest heavily to layer PM controls, making it more common to see ESP+FF. For example, in the US, more than 65 coal-fired boilers have ESP+FF with approximately 30 more installations planned to achieve new emission limits for PM and/or mercury. This represents approximately 10% of all currently operating coal-fired units in the US. While China's emission limits for mercury may not be as stringent as the new limits in the US, the new $PM_{2.5}$ emission limits will require additional actions beyond an ESP for many power plants. Hence, if CYC or WET or no device is built, FF is the only option for retrofit; If ESP is applied, ESP+FF may be

Table 2
Emissions of SO_2, NO_X and $PM_{2.5}$ for three provinces in the YRD region.

Province	Original emission of SO_2 (t)	Current emission of SO_2 (t)	Original emission of NO_X (t)	Current emission of NO_X (t)	Original emission of $PM_{2.5}$ (t)	Current emission of $PM_{2.5}$ (t)
Shanghai	599,716	104,830	573,884	211,787	279,198	10,080
Jiangsu	2,945,527	469,517	1,629,329	937,366	1,183,860	38,741
Zhejiang	2,491,750	350,340	1,736,677	468,699	635,263	20,549

Table 3
Parameters of emission control technologies.

Control technology	Removal percent (%)	Capital cost (Dollars/MW)	FOM cost (Dollars/MW)	FUEL cost (Dollars/MW)
SO_2 control				
FGD	92.00	29,556.07	17,251.26	50,371.42
NO_X control				
LNB	32	4285.63	0	0
SNCR	40	6443.22	37,391.14	0
SCR	80	18,176.98	75,242.01	0
SNCR+LNB	59.2	10,728.85	37,391.14	0
SCR+LNB	86.4	22,462.61	75,242.01	0
$PM_{2.5}$ control				
CYC	10.00	5911.21	3064.85	4235.67
WET	70.00	8866.82	4597.27	4235.67
ESP	93.62	14,778.03	7662.119	10,886.47
FF	99.00	11,822.43	14,251.54	8471.35
ESP+FF	99.90	20,837.03	6436.18	9678.91

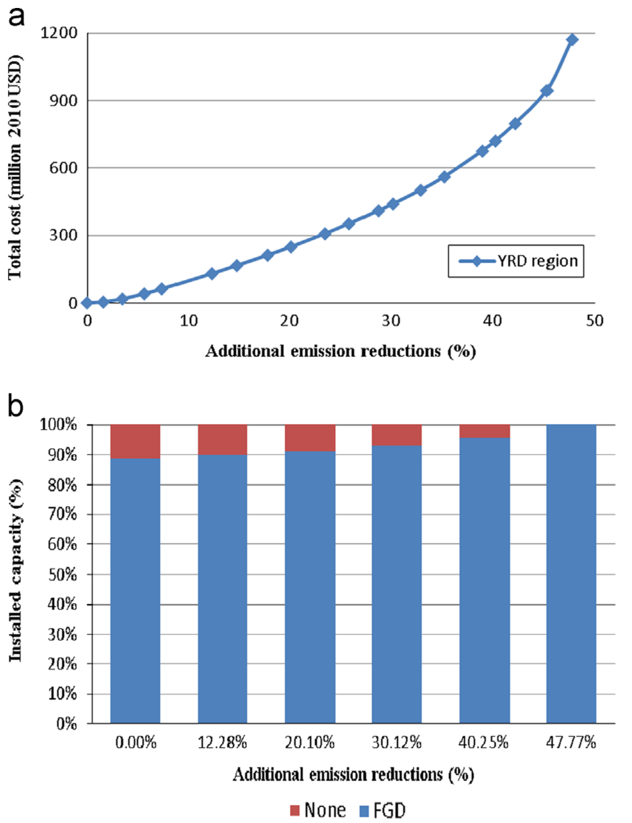

Fig. 1. (a) SO_2 emission reductions (%) relative to current emissions vs. total abatement cost (million 2010 US Dollars) for the YRD region and (b) SO_2 emission reductions (%) relative to current emissions vs. FGD application (%) for the YRD region.

applied to improve removal efficiency; If FF is installed, there is no need for a retrofit since FF alone can achieve the emission standard. Note that FGD will also reduce some $PM_{2.5}$ at coal-fired power plants. This PM co-benefit is factored into each plant's $PM_{2.5}$ emission factors. Nevertheless, FGD is not treated as a potential choice of $PM_{2.5}$ control technology in the algorithm as its removal efficiency is only 59.4% based on the emission input. The new national standard may require 99% reduction of $PM_{2.5}$ at power plants, which cannot be met with ESP+FGD or WET+FGD. Therefore, we set the constraints in the algorithm that only ESP+FF and FF are available for installation because of its high control efficiency of $PM_{2.5}$.

3. Results and discussion

3.1. Overview of emission and control technology in YRD

After running several cases, we obtained data for each pollutant (SO_2, NO_X and $PM_{2.5}$) in the YRD region (Shanghai, Jiangsu Province and Zhejiang Province). The SO_2, NO_X, and $PM_{2.5}$ emissions for these three provinces are listed in Table 2 and the electricity generating capacity is 16,972 MW, 56,291 MW and 34,650 MW for Shanghai, Jiangsu Province and Zhejiang Province, respectively. In Table 2, the emission figures represent the pre-control and post-control emission levels. In other words, original emissions are the combustion-related emissions based on fuel consumption and current emissions are the post-pollution control emissions discharged into the atmosphere. According to Table 2, the current emission levels of SO_2 for Shanghai, Jiangsu and Zhejiang Province are 104,830 t, 469,517 t and 350,340 t, respectively. The current emission levels of NO_X for Shanghai, Jiangsu and Zhejiang Province are 211,787 t, 937,366 t and 468,699 t, respectively. The current emission levels of $PM_{2.5}$ for Shanghai, Jiangsu and Zhejiang Province are 10,080 t, 38,741 t and 20,549 t, respectively. Hence, the percent of SO_2, NO_X, and $PM_{2.5}$ emissions controlled from existing pollution controls at power plants in the YRD region reached 84.7%, 58.94% and 96.7%, respectively. Table 3 shows the parameters for different control technologies, including removal percentage, capital cost, FOM cost and fuel cost for each control technology. Note that these costs should be related to the capacity of a power plant and its actual operation (capacity factor). Unfortunately, due to lack of data, it is difficult to develop a comprehensive dataset to specify the operating parameters and capacity factors for each power plant. Therefore, we provided a general capacity factor based on our research and we applied this general capacity factor to all units. We believe this is a suitable approximation for most power plants in the region. Also, it is worth noting there are other SO_2 control measure alternatives (e.g., dry FGD). However, the SO_2 abatement options for the YRD region were limited to wet FGD because it is the most widely adopted control technology there. The emission control removal efficiency and cost data in Table 3 are applied to a database of existing power plants in 2010. The total costs to control emissions represent the costs during the expected useful life of the control equipment (projected out from 2010 to 2040 (in 2010 US Dollars), representing the 30 year expected equipment life). It is true that power capacity over the next three decades will change significantly. However, the purpose of this study is to develop a cost model and estimate the cost of retrofitting existing power plants with pollution control technologies to achieve the existing emission control requirements and is not intended to estimate the costs of new capacity or the controls required on those new units. It is also worth noting that most of the new capacity that will be added must install advanced emission controls as part of their approval conditions. Hence, the FOM cost and Fuel cost shown in the text reflect the life-of-equipment estimates to achieve the current emission constraints at existing power plants in 2010. All present value calculations assume a 10% discount rate. The cost of emission controls for new electric generating capacity added after 2010 are not included in the assessment because these are outside the scope of the study and not necessary to explain the aggregate costs to achieve the current emission constraints.

3.2. Cost estimate of SO_2 emission control

Fig. 1(a) shows the total abatement cost of different reduction goals for SO_2 emissions in the YRD region. The blue markers indicate the results from the model. It is worth noting the *X* axis is the additional SO_2 removal percentage based on current emission levels, not the

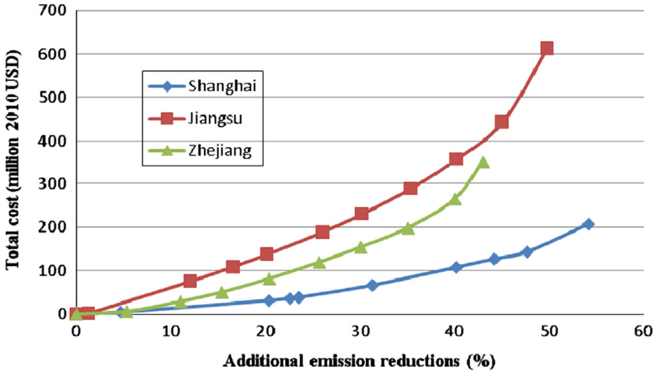

Fig. 2. SO_2 emission reductions (%) relative to current emissions vs. total abatement cost (million 2010 US Dollars) for provinces in the YRD region (Blue: Shanghai; Red: Jiangsu Province; Green: Zhejiang Province). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Current sector-wide emission reductions percentages for each pollutant in each province in the YRD region.

Region	SO_2 (%)	NO_X (%)	$PM_{2.5}$ (%)
Shanghai	82.52	63.1	96.39
Jiangsu	84.06	42.47	96.73
Zhejiang	85.94	73.01	96.77
YRD	84.68	58.94	96.69

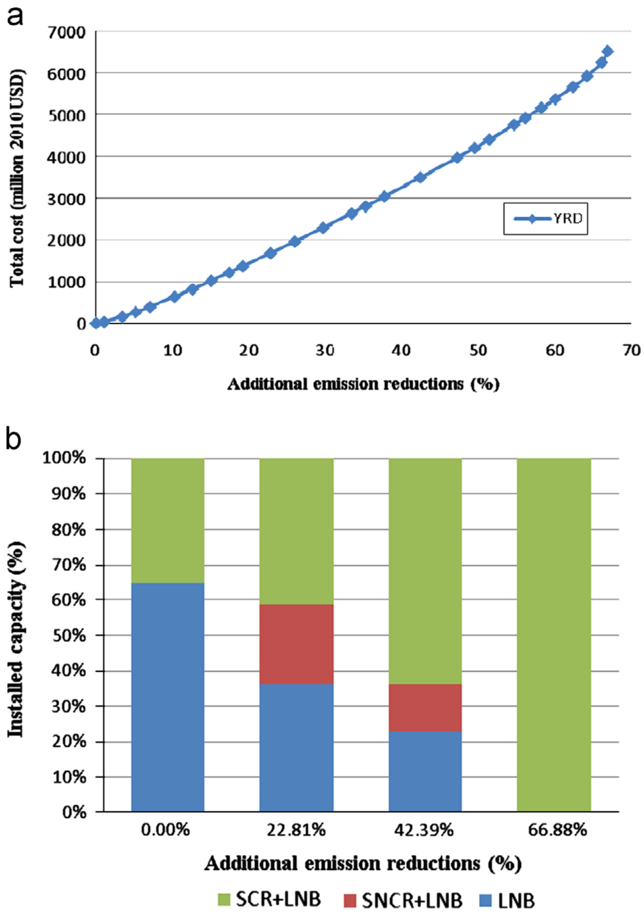

Fig. 3. (a) NO_X emission reductions (%) relative to current emissions vs. total abatement cost (million 2010 US Dollars) for the YRD region and (b) NO_X emission reductions (%) relative to current emissions vs. abatement technology application (%) for the YRD region.

original, pre-control emission levels. (Note: All *X* axes in the figures of this paper have the same meaning). Fig. 1(b) presents the percentage of power plants with FGD installed at different emission reduction goals. Close to 90% of coal-fired electricity generating capacity in the YRD region has already installed FGD. The total abatement cost would increase with incremental installation of FGD to achieve the higher emission reduction goals. The highest total cost – a nearly 47.8% emission reduction goal – could cost up to 1172 million (2010 US dollars).

Fig. 2 shows the total abatement cost of different SO_2 emission reduction goals for the three YRD region provinces – Shanghai, Jiangsu Province and Zhejiang Province. The blue, red and green markers represent the data of Shanghai, Jiangsu Province and Zhejiang Province, respectively. The dashed line, dotted line, and solid line are the corresponding fitting curves. Considering the current status of FGD installations in coal-fired power, Shanghai, Jiangsu Province and Zhejiang Province have already achieved 82.5%, 84.1% and 85.9% reduction of SO_2 emissions, which is consistent with the previous work (Zhao et al., 2013). Therefore, it is not surprising the results indicate Shanghai has larger potential emission reductions while Zhejiang Province has the least potential because of its high initial level of FGD installations. The shape for these three curves is similar – as the emission reduction grows as a percentage of current emissions, the derivative of the cost curve displays an increasing trend, similar to the line in Fig. 1 (a). This non-linear increase of marginal abatement costs for FGD is attributed to the electric generating capacity and the LP algorithm itself. According to Eq. (4), the cost for power plants with larger generating capacity to install FGD is much higher than those with smaller capacity. In addition, the LP algorithm provides one possible solution for the target reduction goal and it guarantees that the power plant with low cost/ton (expressed as total control cost ($)/removed pollutant amount (ton)) will install the FGD first. Therefore, the marginal abatement costs increase exponentially as larger emission reductions are required in Figs. 1 (a) and 2. Meanwhile, for the same emission reduction goal, Jiangsu Province has the highest total retrofit cost while Shanghai has the lowest. Referring to Eq. (4), the cost for each power plant is proportional to its electric generating capacity. In our model, FGD control efficiency is the same for all power plants and we assume power plants with larger generating capacity have higher original, pre-control emissions. Therefore, the total cost of achieving the same removal percentages for these three provinces are then only determined by their uncontrolled or insufficiently controlled, electric generating capacity. According to Table 4, Jiangsu Province has the largest uncontrolled generating capacity and Shanghai has the smallest, therefore, it is understandable that total retrofit costs for Jiangsu Province are higher than the other provinces for a given emission reduction target.

3.3. *Cost estimate of NO_X emission control*

The plot of total abatement cost for NO_X control versus NO_X emission reductions in the YRD region is shown in Fig. 3(a). The general feature for this curve is similar to that of SO_2, but the range of the X axis here is much wider. This is due to the fact that although power plants in the YRD region have installed basic NO_X control devices (e.g., LNB), a smaller proportion of NO_X emissions (58.94%) is reduced because of the low removal efficiency of LNB (see Tables 2 and 3). Thus, there is a large potential to install control technologies for NO_X emission reduction with higher removal rates. Moreover, the highest total abatement cost, corresponding with 66.88% reduction percent, is 6522 million (2010 US

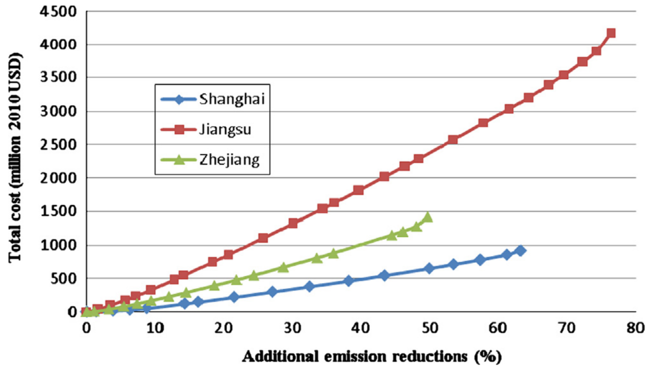

Fig. 4. NO_X emission reductions (%) relative to current emissions vs. total abatement cost (million 2010 US Dollars) for provinces in the YRD region (Blue: Shanghai; Red: Jiangsu Province; Green: Zhejiang Province). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Dollars), much higher than the cost of SO_2 reductions. Referring to the Table 3, the capital cost, FOM cost and FUEL cost for FGD is 29,556.07 (2010 US Dollars)/MW, 17,251.26 (2010 US Dollars)/MW and 50,371.42 (2010 US Dollars)/MW, respectively. Note that all power plants in the YRD region have installed LNB to reduce NO_X. Therefore, the addition of SNCR or SCR will convert to SNCR+LNB or SCR+LNB. Thus, the capital cost for SNCR or SCR, and the FOM cost and FUEL cost of SNCR+LNB or SCR+LNB are used to calculate the total abatement cost. The costs for capital, FOM, and FUEL for SNCR are 6443.22 (2010 US Dollars)/MW, 37,391.14 (2010 US Dollars)/MW and 0.00 (2010 US Dollars)/MW, respectively, and for SCR are 18,176.98 (2010 US Dollars)/MW, 75,242.01 (2010 US Dollars)/MW and 0.00 (2010 US Dollars)/MW, respectively. It is evident that the FOM cost for SCR+LNB is much higher than for FGD. Furthermore, as shown in Fig. 3(b), around 64.7% of the current NO_X emission reduction is achieved by the installation of LNB on all power plants in the YRD region as SCR+LNB is only installed on 35.3% of capacity. By contrast, FGD is installed on almost 90% of capacity. Hence, there is more potential to install SCR to further reduce NO_X emissions. As a result, more power plants are subject to installing additional control technologies for NO_X than SO_2 (i.e., a higher capacity P resulting in greater total capital costs for new installations). In addition, Fig. 3(b) indicates that LNB and SNCR+LNB are capable of providing NO_X emission reductions of 22.81%. However, for higher NO_X emission reduction goals, like 42.39%, the percentage of power plants with LNB alone and SNCR+LNB decrease rapidly and more effective technology, SCR+LNB, increases to more than 60%. For the 66.88% NO_X emission reduction target, all power plants in the YRD region must install SCR+LNB.

Fig. 4 depicts the total abatement cost versus emission reduction for NO_X in Shanghai, Jiangsu Province, and Zhejiang Province. Based on the current status of the installation of LNB and SCR+LNB devices in YRD, the NO_X reductions in Shanghai, Jiangsu Province, and Zhejiang Province have already reached 63.1%, 42.47% and 73.01%, respectively. Thus, the maximum additional removal percentages for these three regions are substantially different. Each curve grows rapidly when larger emission reductions are required. This is due to the installation of more effective and more expensive technologies. The total abatement costs for the same reduction percentage vary among Shanghai, Jiangsu Province, and Zhejiang Province for the same reasons discussed in the SO_2 control section. Compared to Fig. 2, it is evident that Fig. 4 has more data scatter and wider control range, and thus the fitting curve is less non-linear. The primary reason is that more control technologies and power plants are available to control NO_X; as a result, the model can provide solutions for small emission reduction increments and it, therefore, yields more output data based on the control technology options.

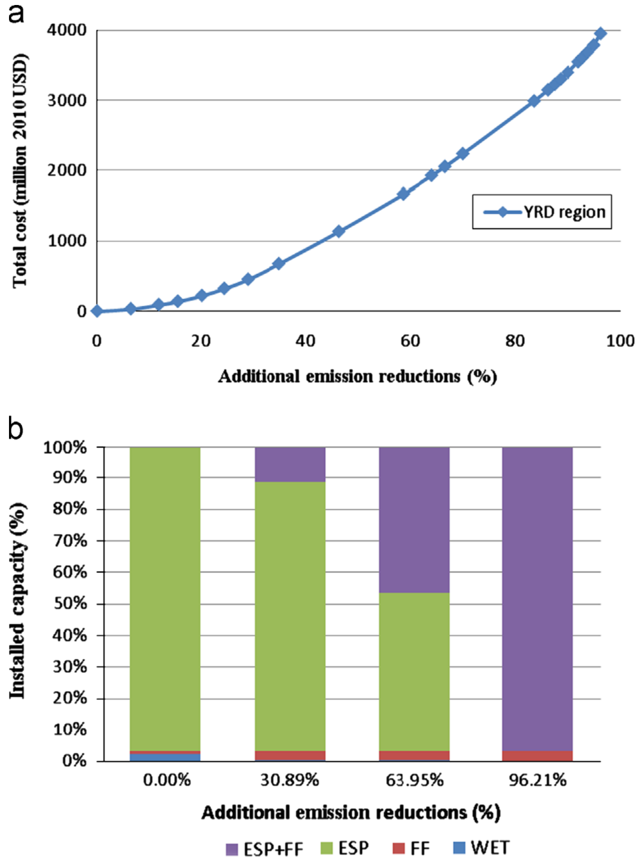

Fig. 5. (a) $PM_{2.5}$ emission reductions (%) relative to current emissions vs. total abatement cost (million 2010 US Dollars) for the YRD region and (b) $PM_{2.5}$ emission reductions (%) relative to current emissions vs. abatement technology application (%) for the YRD region.

3.4. Cost estimate of $PM_{2.5}$ emission control

Fig. 5(a) plots the total abatement cost of $PM_{2.5}$ control versus the $PM_{2.5}$ emission reduction goals for the YRD region. Nearly 97% of power plants have installed ESP devices to control particulate matter. Close to 2% have installed WET devices and less than 1% have installed FF. Thus a very high rate of $PM_{2.5}$ emission control (96.7%) has already been achieved in the YRD region. Although the curve is more linear than the SO_2 and NO_X curves, the derivative still increases as $PM_{2.5}$ emission reductions grow. However, compared with Figs. 1 and 3(a), the X axis has a larger range. Considering the fact that more than 96% of direct $PM_{2.5}$ emissions has been reduced, a wider range of X can be attributed to the high efficiency of retrofit control technologies like FF (99% control percent) and ESP+FF (99.9% control percent). In addition, the plot of Fig. 5(b) shows the percentage of power plants with ESP+FF will grow dramatically with increasing $PM_{2.5}$ reduction levels. For an additional 96.21% reduction, all power plants in the YRD region with ESP will be retrofitted to ESP+FF and plants with WET will be updated to FF. Therefore, around 97% of capacity in the YRD must install and operate ESP+FF to attain the highest emission reduction levels.

The plot of total abatement cost versus emission reduction for $PM_{2.5}$ in the three provinces is shown in Fig. 6. Due to the wide installation of PM control measures at power plants, Shanghai, Jiangsu Province and Zhejiang Province have accomplished 96.4%, 96.7% and 96.8% reduction of $PM_{2.5}$, respectively. The curves grow

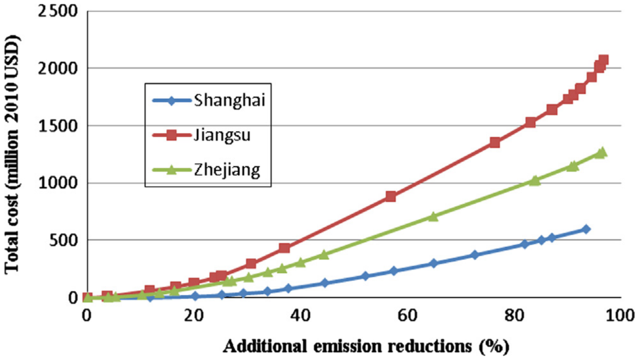

Fig. 6. $PM_{2.5}$ emission reductions (%) relative to current emissions vs. total abatement cost (million 2010 US Dollars) for provinces in the YRD region (Blue: Shanghai; Red: Jiangsu Province; Green: Zhejiang Province). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

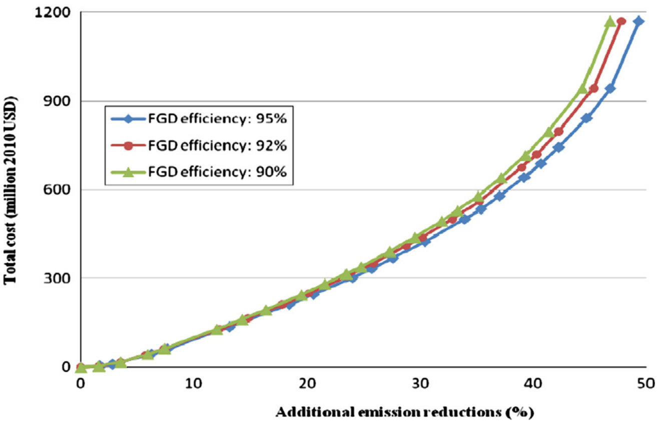

Fig. 7. Sensitivity analysis for SO_2 emission reduction (%) vs. total abatement cost (million 2010 US Dollars) for the YRD region with different FGD removal efficiencies (Blue: 95%; Red: 92%; Green: 90%). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

slowly at first and rise rapidly at higher control levels because effective but expensive pollution control devices like FF and ESP+FF must be installed to achieve the higher emission control levels. Contrary to the observation above, Shanghai has the lowest current direct $PM_{2.5}$ emission reductions but does not have the largest potential. The reason for this is that 5% of the capacity in Shanghai has already installed FF equipment while none of the power plants in Zhejiang and Jiangsu Provinces have installed FF. Since FF achieves MEP's $PM_{2.5}$ emission standard, there is no need to install ESP+FF. That is the key reason Shanghai does not attain the largest emission reduction levels. In addition, for both NO_X and $PM_{2.5}$, there are more power plants subject to retrofit and more efficient but expensive control technologies available. Thus the marginal abatement costs for these two pollutants increase in a non-linear fashion but the steeper trend under higher emission reduction requirements is not as distinct as the costs for SO_2.

3.5. *Sensitivity analysis of removal efficiency*

The sensitivity analysis for this study is quite complex as it is not just an issue of potential removal efficiency, but also power plant operations and control technology removal efficiency. Control technologies may not operate at all times or at full efficiency. Thus the removal efficiencies of FGD, SCR and PM controls may vary among different power plants and it is difficult to get plant-by-plant metrics. The efficiency data used in this study are the average values measured from Chinese power plants. Using field studies and measurement data, we performed a sensitivity study on the removal efficiency of FGD for the YRD region for illustration purposes. In previous work, Zhao et al. (2010) found that wet-FGDs had removal efficiencies above 90%. Xu (2011) conducted studies in 7 Chinese power plants and found that SO_2 removal efficiencies of wet-FGD were about 95%. The SO_2 removal percentage of wet-FGD used in this study is 92%, which is consistent with the FGD removal efficiency derived from the Continuous Emission Monitoring system (CEMs) (unpublished data). For the purpose of the sensitivity analysis, we assume that wet FGD removal efficiencies vary in the range of 90–95% (92% removal efficiency was used for the results discussed above.) Fig. 7 includes three curves with different maximum additional emission reduction percentages for the YRD region. The curves are relatively close at the beginning, but start to diverge as the emission reduction target increases. Moreover, when the actual removal rates are higher than the rates used in this study (i.e. 95%), coal-fired power plants in the YRD region are observed to reduce emissions more than the scenario of 92% removal efficiency used in this study, with the same total abatement cost. Conversely, if actual removal rates are only 90%, emissions may exceed the aggregate annual emission targets for the same total abatement cost. This means more investment may be required to achieve the emission abatement targets and the costs per ton of pollutant removed will be higher than our estimates.

3.6. *Effect of subsidy from central government*

While these control costs are significant, they represent private costs to industry. Government policies may partly offset these private costs. For example, to encourage the installation and operation of post-combustion pollution controls, the central government provides a subsidy for coal-fired electric power plants with controls. These plants can receive a price premium on electricity sales to offset the FOM and fuel costs of new pollution controls. The power plants receive up to 0.0022 (2010 US Dollars) and 0.0015 (2010 US Dollars) for each kWh of electricity generated and sold if the SO_2 and NO_X controls, respectively, are operating and achieving minimum removal rates. These subsidies are a transfer from the grid system operator and central government to the power companies and, therefore, do not affect the total social cost of the pollution control efforts. They do, however, serve to reduce the private costs of compliance.

To assess the impact of the price premium for units that install pollution controls, we used aggregate statistics for the YRD region. For each province, the fractions of capacity that install additional FGD and/or SCR controls in this analysis can be calculated as:

$$\text{Fraction} = \frac{P_k^*}{P_k} \tag{14}$$

where P_k^* is the unit capacities at province k that have not already installed control measures for pollutant i and are projected to install pollution controls in the policy case, (unit: MW) and P_k is the unit capacities at province k that are currently uncontrolled, (unit: MW). Referring to the input data, the percentages of electricity generating capacity that install additional FGD devices are 87.4%, 88.8% and 89.56% for Shanghai, Jiangsu Province and Zhejiang Province, respectively. Fig. 2 shows that the total estimated costs of installing FGD for the power plants that do not currently have controls are about 208 million (2010 US Dollars), 613 million (2010 US Dollars) and 351 million (2010 US Dollars) for Shanghai, Jiangsu Province and Zhejiang Province, respectively. The price premium for installing FGD at these power plants can be calculated by the following equation:

$$S_{i,j} = G^{*}_{i,j} r_i f \tag{15}$$

where $S_{i,j}$ is the subsidy amount for pollutant i at province j, (unit: Million Dollars); $G^{*}_{i,j}$ is the electricity generation of all power plants in province j that have no or lower-efficiency control measures installed for pollutant i and are projected to install pollution controls in the policy case, (unit: GWh); r_i is the subsidy rate of installing reduction devices for pollutant i, (unit: Dollars/kWh). The factor f is multiplied to account for the whole subsidy during the lifetime of a power plant (30 years in this study), as we have converted the total control cost into a one year value. Being consistent to the discount rate of 0.1 in the methodology section, the factor of f can be estimated as:

$$f = \frac{1-(1/1.1)^{30}}{1-(1/1.1)} \tag{16}$$

Therefore, considering the current SO_2 subsidy rate of 0.0022 (2010 US Dollars) per kWh of electricity generated and sold, the total subsidies are up to 232 million (2010 US Dollars), 803 million (2010 US Dollars) and 367 million (2010 US Dollars), which could offset about 112%, 131.06% and 104.46% of total SO_2 abatement costs for Shanghai, Jiangsu province and Zhejiang province, respectively. Similarly, the fractions of stock that have installed SCR are 41.95%, 20.63% and 55.89% for Shanghai, Jiangsu province and Zhejiang province, respectively. In Fig. 4, the total estimated costs of installing SCR+LNB for all power plants are around 920 million (2010 US Dollars), 4174 million (2010 US Dollars) and 1428 million (2010 US Dollars). Using the NO_X price premium of 0.0015 (2010 US Dollars) per kWh of electricity generated and sold for Eq. (15), yields total subsidies of up to 712 million (2010 US Dollars), 3793 million (2010 US Dollars) and 1035 million (2010 US Dollars), corresponding to nearly 77.39%, 90.87% and 72.48% of total NO_X abatement costs for Shanghai, Jiangsu province and Zhejiang province, respectively. The main purpose of mentioning the subsidy here is to illustrate that the central government may play an important role in the actions taken by power plants to reduce pollution. Shown in the results above, the current subsidy can offset more than the total investment for SO_2 emission control and up to 91% for NO_X emission control. These numbers indicate that the subsidy can be a strong incentive to promote the installation of pollution controls at power plants in the YRD region, as all or most of the private investment in pollution controls has been offset.

Table 5
Maximum additional sector-wide emission reduction percentages for each pollutant in each province in the YRD region.

Region	SO_2 (%)	NO_X (%)	$PM_{2.5}$ (%)
Shanghai	54.24	63.15	93.41
Jiangsu	49.82	76.36	96.74
Zhejiang	43.09	49.61	96.60
YRD	47.77	66.88	96.21

4. Conclusions and policy implications

4.1. Conclusion

In this article, we adopt an LP algorithm to develop a cost model and apply it to the YRD region. Considering that power plants have already installed some pollution control devices to control SO_2, NO_X and $PM_{2.5}$, the cost curves for these three pollutants in each part of the YRD region are different. According to Tables 4 and 5, Shanghai, Jiangsu Province and Zhejiang Province have already achieved 82.5%, 84.1% and 85.9% SO_2 emissions reduction, respectively. Hence the maximum additional SO_2 emission removal potentials are 54.2%, 49.8% and 43.1%, respectively, at a total cost of 208 million (2010 US Dollars), 613 million (2010 US Dollars) and 351 million (2010 US Dollars), respectively. For NO_X, the current removal rates for Shanghai, Jiangsu Province and Zhejiang Province are 63.1%, 42.47% and 73.01%, respectively. The maximum potential for additional emissions reductions are 63.15%, 76.36% and 49.61%, respectively, corresponding to a total cost of 920 million (2010 US Dollars), 4174 million (2010 US Dollars) and 1428 million (2010 US Dollars), respectively. For $PM_{2.5}$, Shanghai, Jiangsu Province and Zhejiang Province have currently installed pollution controls to reduce emissions 96.4%, 96.7% and 96.8%, respectively. The corresponding maximum additional removal potentials are 93.4%, 96.7% and 96.6%, respectively, with a total cost of 596 million (2010 US Dollars), 2077 million (2010 US Dollars) and 1278 million (2010 US Dollars), respectively. Table 6 summarizes the application of control technologies of SO_2, NO_X and $PM_{2.5}$ for the YRD region in the base year (2010) and in the future. It clearly shows the current installments of emission control technologies and the penetration of the technologies under different abatement targets. In addition, the cost curves for these three pollutants all grow nonlinearly as the additional emission abatement of a pollutant grows. Meanwhile, the marginal abatement cost increases as well since more effective but more expensive pollution control devices must be applied to achieve the larger emission reductions. However, different provinces have different maximum removal potentials for each pollutant because the percentage of electricity generating capacity with existing pollution controls varies among the provinces. Also, the shapes of curves for different pollutants differ. This could be caused by the iteration steps in the model, electricity generating capacity of power plants, capital cost, FOM cost, and

Table 6
Application of control technologies for SO_2, NO_X and $PM_{2.5}$ for the YRD region in base year (2010) and policy case (%).

Pollutant	**Control technologies**	**2010**	**Control target 1 (20.1%)**	**Control target 2 (40.25%)**
SO_2	FGD	88.8%	91.2	95.7
Pollutant	**Control technologies**	**2010**	**Control target 1 (22.81%)**	**Control target 2 (42.39%)**
NO_X	LNB	64.7%	36.17	23.07
	SNCR+LNB	0%	22.37	13.11
	SCR+LNB	35.3%	41.46	63.82
Pollutant	**Control technologies**	**2010**	**Control target 1 (30.89%)**	**Control target 2 (63.95%)**
$PM_{2.5}$	WET	2.34%	0.44	0.28
	FF	0.79%	2.69	2.85
	ESP	96.87%	85.52	50.52
	ESP+FF	0%	11.35	46.35

fuel cost. The shape will also be influenced if we change the retrofit rules and assumptions.

Central government policies can partly offset the private costs to industry through a subsidy for coal-fired electric power plants with advanced emission controls. Up to 0.0022 (2010 US Dollars) and 0.0015 (2010 US Dollars) for each kWh of electricity generated and sold are offered by the central government to encourage the implementation of advanced SO_2 and NO_X controls, respectively. According to the calculations in this study, the total subsidies for additional FGD installations in the YRD region could be up to 232 million (2010 US Dollars), 803 million (2010 US Dollars) and 367 million (2010 US Dollars), which could offset about 112%, 131.06% and 104.46% to total SO_2 abatement cost for Shanghai, Jiangsu province and Zhejiang province, respectively. The subsidies for advanced NO_X controls – SCR+LNB – are up to 712 million (2010 US Dollars), 3793 million (2010 US Dollars) and 1035 million (2010 US Dollars), corresponding to nearly 77.39%, 90.87% and 72.48% of total NO_X abatement costs for Shanghai, Jiangsu province and Zhejiang province, respectively. These numbers indicate that by offsetting most of the private investment in pollution controls, the installation of advanced controls can be strongly promoted through central government subsidies.

4.2. Policy implications

In this study, we are able to provide an estimate of the total abatement costs to achieve specific emission reduction targets at the provincial level. Information about total abatement cost, the installation of control measures and the corresponding emission reductions are estimated for each power plant in each province. These costs and impacts can inform policy makers at the national and provincial levels as they evaluate options to develop and implement cost-effective control strategies for the power sector in order to improve air quality. Specifically, since the dataset it now available, it can be used as a reference for policy makers in the YRD region and at MEP. High levels of emission reductions can be achieved with the installation of advanced technologies like FGD for SO_2, SCR for NO_X and FF for $PM_{2.5}$. However, the total abatement cost will also rise exponentially as presented in the results and discussion section. So if a lower emission reduction target is set, it will have less effect on improving air quality, requiring other actions, possibly in other sectors, to achieve air quality goals. However, if governmental and societal preferences are to pursue an extremely high abatement goal, most power plants in the YRD region will have to install high-efficiency emission controls and the corresponding costs may not be acceptable. Hence, policy makers should consider the emission reductions against the total abatement costs to develop feasible, cost-effective control strategies to reduce SO_2, NO_X and $PM_{2.5}$ from coal-fired power plants and further improve air quality. Another alternative is that the central government subsidy for advanced emission controls could provide a strong incentive for power plants to install advanced control technologies. The effect of the subsidy has been evaluated above.

The emission reduction results from this study can be imported as an input to a regional air quality assessment model like the Community Multiscale Air Quality (CMAQ) Modeling System as Huang et al. (2014) and Dong, et al. (2013) conducted control strategies in YRD, which could further help us calculate the ambient air quality impacts of additional emission controls associate with the control cost. This would provide policy makers with additional information about the expected outcomes, in terms of air quality, from investments in emission controls. In addition, the model and these findings about total abatement cost and emission reduction potential can aid other social-economic impact analyses in the YRD region and energy policy in China.

4.3. Future work

This is one of the first studies to explore the costs of addressing multiple pollutants in the YRD region using an LP cost model. As such, there are opportunities for further research to enhance the study's conclusions. First, a more accurate dataset for emissions of each pollutant (i.e., SO_2, NO_X and $PM_{2.5}$), improved statistics about emission removal efficiency of in-use control technologies in the YRD region and more information about capital costs and operation & maintenance costs of different types of pollution control. Enhanced data would allow for more plant- and technology-specific operating variables and cost estimates. This would better reflect the fact that actual operating conditions can vary significantly among different power plants. Second, the capacity of renewable energy and non-emitting sources (i.e. solar energy, wind energy and nuclear energy) is growing in the YRD region. Including these non-emitting sources in the power plant inventory will allow for a more comprehensive view of the electric power sector and provide opportunities for shifting generation between different fuel types. In this study we only focus on current power plants and identify control measures for them. Future analyses, however, may be expanded to include projecting new generating capacity and costs for achieving future expected emission constraints. This could also permit shifting generating load to renewable energy as an approach to satisfy electricity demand and pollution abatement requirements (zero emission plants). Third, in addition to cost estimates at the provincial level, it would be helpful for policymakers to know the costs of control in key cities as well. Fourth, the power sector is a major source of emissions in the YRD region, but other sectors (e.g., industry, transportation) are also important contributors to pollution loading. A better understanding of the costs to control emissions from key sectors, including iron and steel, cement and vehicles will be important to inform policymakers about cost-effective solutions to address the air quality challenges in the YRD.

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