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Cost estimate of the multi-pollutant abatement in coal-fired power sector in China

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ABSTRACT

Seriously stringent emission regulations are applied in the coal-fired power sector in China. GB13223-2011 standards and ultra-low emission limits are promulgated to improve the application of pollutant abatement systems and reduce emissions, respectively. However, the accompanying problem of additional economic burden may affect the operation of power units and sectors. This study proposed a cost estimate model of multi-pollutant control and designed several scenarios to evaluate the total cost of different emission standards in China's coal-fired power sector. The operating costs of NO_x, SO_2, and PM control of a typical 300 MW unit were 6.9, 11.7, and 4.3 CNY/MWh, respectively, when meeting the GB13223-2011 emission standard and 8.2, 13.8, and 7.9 CNY/MWh, respectively, when meeting the ultra-low emission limits. Investment, energy consumption, and catalyst greatly influenced the operating cost. The scenarios analysis suggested that the total costs of multi-pollutant control under the GB13223-2011 standards and ultra-low emission limits were approximately 141.79–170.28 and 186.35–221.67 billion CNY per year, respectively. Feasible cost reduction strategies were analyzed on the basis of operation management and sector planning. The economic influence of the application of pollutant abatement systems on coal-fired power units should be evaluated comprehensively.

1. Introduction

Coal-fired power generation is the main form of power generation in China, and the coal-fired power sector accounts for half of the total annual coal consumption of the country [1–3]. Coal power is considered a major source of pollution in China. Pollutants such as SO_2, NO_x, and PM emitted from coal-fired power generation are important precursors of regional haze in Eastern China [4]. In addition, SO_2 and NO_x also lead to acid precipitation, and NOx plays an important role in the formation of ground-level ozone [5–11]. The Chinese government has promulgated relevant environmental protection laws and regulations in recent years to promote the application of pollutant control technologies throughout the power sector, and particularly control pollutant emission from the coal-fired power sector. A new thermal power industry standard (GB13223-2011) was implemented nationwide in 2014 to replace the old standard (GB13223-2003), which is considered to be inapplicable to pollution control [12]. Then, a stringent emission limit, called ultra-low emission limits, was promoted throughout the country (available at http://zfxxgk.nea.gov.cn/auto84/201608/t20160804_2283.htm). Under such limits, the emission concentration of SO2, NO_x, and PM in coal-fired power units must not exceed 35, 50 and 5 mg/Nm^3, respectively. The implementation of these regulations and emission standards has further promoted the application of highly efficient pollutant control technologies in the industry to greatly reduce the emission of the power sector.

The installation and operation of pollutant abatement systems cause an additional economic burden for the coal-fired power sector, and it tends to reduce corporate profits. The investment in the construction and installation of pollutant abatement systems is high, and may thus entail long-term loans from power companies to banks. The operation of pollutant abatement systems consumes electricity and other resources. Therefore, an accurate estimation model and an effective strategy are required by the power industry to quantify the impact of the operating cost of pollutant abatement

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systems on power generation cost and to reduce the pollution control cost are required by the power industry, respectively. The overall cost estimation of pollution control can provide theoretical and data support for the formulation and implementation of environmental protection regulations and emission standards. In addition, the research results on cost estimation can be combined with health and environmental benefits to analyze the cost effectiveness of different environmental protection policies and regulations and the effect of different pollutant control technologies. For example, Hainoun et al. investigated the health damage of heavy fuel oil and NG-fired power plants and estimated the damage costs caused by airborne pollutant emissions on the basis of a simplified impact pathway approach [13]. Buke et al. applied the AirPacts model to estimate the health benefits of a coal-fired power plant installed with a flue gas desulfurization (FGD) system and then compared its health benefits with the system investment cost [14]. Jorli et al. quantified the human health impacts caused by the emission of fossil-based power plants [15].

However, studies on the operating costs of pollutant abatement systems for the coal-fired power sector are rarely conducted. Zhang et al. investigated the reduction cost of SO_2 emission with different removal efficiencies and analyzed the possible scenarios of regional SO_2 emission reduction targets to estimate the total cost [16]. Kanada analyzed the regional disparity of SO_2 reduction potential and cost and investigated two typical technologies, namely, FGD and limestone injection (LINJ), for scenario analysis. The study also presented the control cost of FGD and LINJ technologies in different scenarios [17]. Sun et al. conducted a regional cost study of different emission abatement percentages, which was based on the operation parameters of different typical control technologies in China [18]. Cofala et al. designed an optimization routine for SO_2 emission reduction in Asia on the basis of an extension of the RAINS-Asia integrated assessment model; this work presented the marginal cost of different technologies and abatement percentages, which served as the database of the least cost strategy analysis [19]. Rubin et al. conducted an environmental and economic assessment of amine-based CO_2 capture technology. In this work, a process cost model was developed, and a case study was carried out. The results presented the cost estimation model of CO_2 emission reduction and the influence of the operation of air pollutants control systems on CO_2 capture [20]. In addition, other cost analyses of CO_2 capture were also conducted on the basis of field surveys and technology investigations [21–27]. Other studies concentrated on the regional cost of different control strategies and attempted to find the least costly method that could still achieve the emission reduction target. Fu et al. presented an approach for air quality management that entails minimal cost [28]. The method was based on the air quality simulation results, and the abatement cost of different reduction scenarios was presented. Dong et al. investigated the SO_2 emission and reduction scenarios for the application of FGD and LINJ technologies; the abatement cost of each province of China came from the GAINS-China model. The regional cost of SO_2 abatement included the control of power plant, industrial point, and other sources [29]. Cowell et al. designed different abatement strategies for ammonia emissions from agriculture and successfully attained abatement targets at a relatively low cost [30]. An inflection point was observed in the standard cost curve for ammonia reduction, and the reduction percentage exceeding the inflection point greatly increased the total and marginal costs. In addition, other studies analyzed the wastewater treatment cost of different technologies [31,32].

The literature review suggested that the current studies are not well thought out because of the restrictions to data and methods. Some studies calculated the emission reduction cost of different pollutant abatement systems or technologies used in plants on the basis of the investigation of various case studies. Other studies estimated the regional or industrial costs of pollution control on the basis of case data and considered fixed data as the annual cost of pollution control. At present, the comprehensive cost database of different options and parameters, the detailed operating cost estimation model for pollutant abatement systems in the coal-fired power sector, and the relatively precise cost result of regional and industrial pollution control on the basis of the cost estimation of power units are still insufficient. Therefore, the current work focuses on addressing the aforementioned research gaps. The field survey of different coal-fired power units that meet the GB13223-2011 emission standard or ultra-low emission limits provides raw data to establish the database of pollution control costs. The database contains the operating parameters, resource consumption and investment data of different pollutant abatement systems. Then, a cost estimation model of multi-pollutant control in the coal-fired power sector is developed to estimate the emission control cost when meeting the requirement of different emission limits. This model is based on the most mature commercial technologies applied in the power sector, and it considers the different operating and input conditions of power units. Finally, a bottom-up method was used to estimate the regional cost of different scenarios on the basis of the operating cost database and the capacity distribution situation of power units. The upgrade of the present pollutant abatement system and the construction of new systems are also considered in the estimation of regional cost.

2. Material and methodology

2.1. Data sources and analyses

In the present work, the primary data for cost calculation, including the investment information, the operating parameters of pollutant abatement systems, and the management process, are extracted from the database of the distributed control system, the field survey reports, and the post-evaluation research of different power units that meet the GB13223-2011 emission standard or ultra-low emission limits. The data of the power unit distribution are extracted from a government document containing detailed information about coal-fired power units installed with the pollutant abatement systems in 2013 (available at http://www.zhb.gov.cn/gkml/hbb/bgg/201407/t20140711_278584.htm). This document covered the power unit capacity and number in different regions. However, the power sector has greatly changed, and the present situation of power units is not clear due to the installation of pollutant abatement systems that meet the requirements of the GB13223-2011 standard and ultra-low emission limits. The distribution of all coal-fired power units in China is based on the compilation of statistics on power industry in 2015 [33]. Thus, the following hypothesis is presented to explain and estimate regional cost. The power units listed in the government document are assumed to have installed pollutant abatement systems before 2013 and will thus be upgraded to meet the GB13223-2011 emission standard or ultra-low emission limits. The other power units that are not listed in the document are assumed to have installed pollutant abatement systems after 2013.

The investment information about different power units is extracted and listed in Tables 1 and 2. The investment information includes emission control technologies and the project investment for pollutant abatement systems that meet the GB13223-2011 emission standard and the ultra-low emission limits. Table 1 shows the information about the units installed with pollutant abatement systems. The investment cost includes the investment in the original system and the upgrade cost. Table 2 shows the information about the units installed with new pollutant

Table 1
The information of upgrade projects (unit: 10 thousand CNY).

Unit Capacity (MW)	Upgrade Year	WFGD	SCR	ESP	WESP
215	2016	7500	6593	2584	–
300	2015	6472	3480	4907	2000
300	2015	5044	5060	7458	–
320	2015	15700	8090	4803	3508
330	2014	6200	5893	4830	2738
330	2014	6392	4668	2786	2327
350	2016	5635	4600	1341	–
600	2016	8000	11880	6516	–
600	2016	10206	12780	2240	–
660	2016	9220	11880	7861	–
660	2015	12343	8830	3700	3943
1000	2016	11090	11500	7780	–
1000	2016	13312	11304	5840	–

Table 2
The information of new projects (unit: 10 thousand CNY).

Unit Capacity (MW)	Emission standard/ limits	WFGD	SCR	ESP
350	ultra-low	5543	3650	2500/1300 (WESP)
200	GB13223-2011	4300	2700	1400
300	GB13223-2011	5800	3200–4080	2100
600	GB13223-2011	8300	4600–6000	3000
1000	GB13223-2011	10800	6100–8300	4000

abatement systems. The investment in different units with similar capacities is not consistent because various design requirements are considered and the investment in pollutant abatement systems decreases over time. The power units whose capacities are less than 100 MW are considered to be small capacity units and are gradually eliminated in the future because of their poor energy efficiencies and high emission rates. Finding detailed information on these small capacity units using a pollutant abatement system that can meet the GB13223-2011 emission standard and ultra-low emission limits is difficult. The analysis of current cases demonstrates that the capital cost per unit capacity of each unit decreases with an increase in unit capacity. Thus, so the univariate non-linear regression method is used to estimate the investment for small capacity units. The regression results show that the investment in power units decreases exponentially. However, the investment results exhibit great uncertainty with regard to the method of exponential regression and the simulation results cannot reflect practical situations. Thus, the resultant interval is estimated on the basis of the investment of other capacity units in hopes that it applies to practical situations.

2.2. Applied technology

Limestone-gypsum WFGD technology is widely applied in SO_2 control in China because of its high removal efficiency, technical maturity and low-cost absorbent. The removal efficiency of the limestone-gypsum WFGD system is mostly affected by the number of spray layers. In general, the limestone-gypsum WFGD system with five spray layers can enable the emission concentration to meet the ultra-low emission limits. SCR technology is widely used for NOx control in the power sector. Before the reaction of NOx abatement in the SCR reactor, NOx concentration is directly reduced by the LNB installed in the boiler. The cost of LNB is not considered because it is integrated with the boiler and no resource or energy is consumed during operation. ESP technology can reduce the majority of particulate matters in flue gas. However, the technology has an inferior removal effect on fine particulate matters. A common way to improve removal efficiency is to install an additional electric field. An ESP system with four or five electric fields could reduce the PM concentration to approximately 25 mg/Nm^3 according to case surveys. WESP technology can reduce fine particulate matters and is originally used to remove the liquid drops of slurry and gypsum.

2.3. Cost estimate model

The cost estimate model is designed to calculate the additional generation cost of a certain power unit when pollutant abatement systems are installed to meet emission standards. Operating cost is used as the cost indicator to analyze the cost of pollutant control. Operating cost indicates the cost spent on pollutant control, including the variable and fixed costs. Variable cost represents the resources and energy consumed during the abatement process, such as electricity and absorbent consumption. Fixed cost includes the depreciation cost, maintenance cost, wage and welfare, finance and other costs that are not related to the operation conditions of pollutant abatement systems. Depreciation cost suggests that the value of the pollutant abatement system decreases during its service time, depending on the investment of the project. Maintenance cost covers routine and breakdown maintenance. Finance cost represents the interest exchange for the investment loan from a bank. Other costs include tax, management cost, and insurance cost. Therefore, operating cost is the sum of variable and fixed costs. The most common indicator of economic analysis in coal-fired power units is the generation cost. Thus, in this work, the cost of pollutant control is calculated and compared with the generation cost. The result can serve as a reference for power plant managers as they compare the cost of pollutant control with the environmental subsidy of power price provided by the government. The environmental subsidies of the power price of SO_2, NO_x, and PM control are 15, 10, and 2 CNY/MWh, respectively. For ultra-low emission limits, a subsidy of 10 CNY/MWh is added. The cost estimate model can be explained to achieve a straight comparison of the cost and environmental subsidy:

$$COST = COST_f + COST_v \tag{1}$$

$$COST_f = \sum_i \sum_j COST_{f,i,j} \tag{2}$$

$$COST_v = \sum_i \sum_k COST_{v,i,k} \tag{3}$$

where $COST$ is the operating cost of a pollutant abatement system per power generation in a power unit, which can be obtained by Eq. (1); $COST_f$ is the fixed cost, which can be obtained by Eq. (2); $COST_{f,i,j}$ represents the jth sub-cost in the fixed cost of the ith pollutant abatement system; $COST_v$ is the variable cost, which can be calculated by Eq. (3); and $COST_{v,i,k}$ represents the kth sub-cost of the variable cost in the ith pollutant abatement system.

The sub-cost of fixed cost can be calculated by using the following equations:

$$COST_{f,i,1} = \frac{TCI_i \times y}{n_i} \times \frac{1}{Qh} \tag{4}$$

$$COST_{f,i,2} = \frac{COST_{f,i,break} + COST_{f,i,routine}}{Qh} \tag{5}$$

$$COST_{f,i,3} = \frac{N_i W}{Qh} \tag{6}$$

$$COST_{f,i,4} = \left(\frac{TCI_i \times x_i \times (1+r)^{n_i}}{n_i} + COST_{f,i,other}\right) \times \frac{1}{Qh} \tag{7}$$

where depreciation cost can be obtained by using Eq. (4), in which TCI_i is the total cost of investment, n_i is the service time of the pollutant abatement system, y is the rate of the fixed asset, Q is the unit capacity, and h is the annual service hour; the maintenance cost can be obtained by using Eq. (5), in which $COST_{f,i,break}$ is the breakdown maintenance cost and $COST_{f,i,routine}$ is the routine maintenance cost; the wage and welfare can be obtained by Eq. (6), in which N_i is the number of workers, and W is the annual wage and welfare per worker; finance and other costs can be calculated by using Eq. (7), in which x_i is the loan proportion of the total investment, r is the rate of interest, and $COST_{f,i,other}$ includes other costs, such as the management cost.

Variable cost is considered in accordance with the pollutant abatement system. For SO_2 control, the sub-cost can be calculated by using the following equations:

$$COST_{v,1,CaCO_3} = \frac{\left((c_{1,in} - c_{1,out}) \times V \times \frac{M_{CaCO_3}}{M_{SO_2}} \times \frac{\delta_1}{\lambda}\right) \times P_{Ca}}{q} \tag{8}$$

$$COST_{v,1,Electricity} = \frac{e_1(\eta_1, c_{1,in}, c_{1,out}, V, q) \times q \times 1 \times P_E}{q} \tag{9}$$

$$COST_{v,1,Water} = \left(\left(\left(c_{1,in} - c_{1,out}\right) \times V \times \frac{M_{CaCO_3}}{M_{SO_2}} \times \frac{\delta_1}{\lambda}\right) \times \frac{2M_{H_2O}}{M_{CaCO_3}} \times \alpha + \left(w_{evaporation} + w_{waste} + w_{liquiddrop}\right) \times V\right) \times P_W \times \frac{1}{q} \tag{10}$$

where $COST_{v,1,CaCO3}$ is the absorbent cost, based on the material balance and the calcium-sulfur ratio during the operating process, $COST_{v,1,Electricity}$ is the electricity cost for the operation of pumps, booster fans, and other devices based on the survey of each electric equipment. $COST_{v,1,Water}$ is the water cost for the supplement of water consumption, including crystal and slurry water in the gypsum slurry, evaporated water of the whole system, desulfurization wastewater, and the entrained liquid drops in the flue gas. In addition, $c_{1,in}$ and $c_{1,out}$ are the inlet and outlet concentrations of SO_2, respectively; V is the flue gas flow in standard state; δ_1 is calcium-sulfur ratio; λ is the limestone purity; q is the unit load; P is the price; η is the removal efficiency; andα is the quantity ratio of the slurry water.

For NOx control, the sub-cost can be calculated by the following equations:

$$COST_{v,2,NH_3} = \left(V \times \frac{c_{2,in} - c_{2,out}}{M_{NO}} \times \frac{2}{3} \times M_{NH_3} \times \frac{1}{\delta_2} \times \frac{ae \times M_{NH_3}}{V_m}\right) \times P_{NH_3} \times \frac{1}{q} \tag{11}$$

$$COST_{v,2,Catalyst} = \frac{CV \times P_C}{3Qh} \tag{12}$$

$$COST_{v,2,Steam} = \frac{\beta \times CV \times P_S}{q} \tag{13}$$

$$COST_{v,2,Electricity} = \frac{e_2(c_{2,in}, c_{2,out}, \eta_2, CV, V, q) \times q \times 1 \times P_E}{q} \tag{14}$$

where $COST_{v,2,NH3}$ is the reductant cost, based on the material balance and the NH_3-NO_x ratio during the operating process; $COST_{v,2,Catalyst}$ is the catalyst cost; $COST_{v,2,Steam}$ is the cost of steam used for cleaning the dust on catalyst surface; and $COST_{v,2,Electricity}$ is the electricity cost for the operation of pumps, booster fan, and other devices, based on the survey of each electric equipment. $c_{2,in}$ and $c_{2,out}$ are the inlet and outlet concentrations of NO_x, respectively; V is the flue gas flow in the standard state; δ_2 is NH_3-NO_x ratio; ae is the ammonia escape rate; CV is the amount of catalyst; and β is the amount of steam per unit catalyst.

For PM control, the sub-cost can be calculated by the following equations:

$$COST_{v,3\&4,Electricity} = \frac{\left(e_3(V, q, \eta_3, c_{3,out}) + e_4(V, q, c_{4,out})\right) \times q \times 1 \times P_E}{q} \tag{15}$$

$$COST_{v,3\&4,W} = \frac{w \times P_W}{q} \tag{16}$$

$$COST_{v,3\&4,Na} = \frac{Na \times P_{Na}}{q} \tag{17}$$

where $COST_{v,2,Electricity}$ is the electricity cost for the operation of electric fields, pumps, booster fan, and other devices, based on the survey of each electric equipment; $COST_{v,3\&4,W}$ is the water cost; and $COST_{v,3\&4,Na}$ is the cost of NaOH used for neutralizing the acidic component in the flue gas. $c_{3,out}$ and $c_{4,out}$ are the outlet concentrations of ESP and WESP system, respectively; w is the water consumption; and Na is the amount of NaOH.

3. Cost analysis

3.1. Operating cost of the power unit with different capacity levels from case studies

Operating cost is influenced by many factors, including unit capacity, price level, investment, inlet concentration, emission standard, and annual service hour. Some of these factors cannot be adjusted to reduce the operating cost when meeting certain emission standards. Inlet concentration and annual service hour are the variable parameters that can be adjusted by changing the operation conditions of power units. The inlet concentration of different pollutants can be adjusted by changing the coal used for power generation and controlling the combustion process. In this study, a common situation is considered to analyze the operating cost of different power units when meeting the GB13223-2011 emission standards and ultra-low emission limits, respectively. The reference situation represents the most common operating parameters of power units. The inlet concentrations of NO_x, PM, and SO_2 are 300–400 mg/Nm^3, 15–20 g/Nm^3, and 2000–2200 mg/Nm^3, respectively. Most power units in China are installed with LNB system to reduce NO_x emissions. According to the case studies, the inlet concentration of NO_x, which is also the inlet concentration of the SCR system, can be reduced to approximately 350–400 mg/Nm^3 by using the LNB system [34]; other new systems can also

reduce the inlet concentration to approximately 200 mg/Nm^3. However, other old units which are not installed with LNB systems, and if they do have LNB systems, the effects of such systems fail to meet design requirements; hence, the inlet concentration of NO_x may be approximately 600 mg/Nm^3. Thus, the reference situation of NO_x concentration is selected as approximately 400 mg/Nm^3. According to the investment results of coal quality, the sulfur content of coal for power generation in China is different (insert coal quality research reference), and the average sulfur content is 1.02% [35], which corresponds to the inlet concentration range of SO_2. The reference situation of PM concentration is based on the field test. In addition, the annual service hour in the reference situation is based on the case information, that is 5400 h.

Fig. 1 shows the additional generation cost of different typical units, to meet the GB13223-2011 emission standards and ultra-low emission limits, respectively. For a typical 300 MW unit, the operating costs of NO_x, SO_2, and PM control when meeting the GB13223-2011 emission standard are approximately 6.9, 11.7, and 4.3 CNY/MWh, respectively. The operating costs of NO_x, SO_2, and PM control when meeting the ultra-low emission limits are approximately 8.2, 13.8, and 7.9 CNY/MWh, respectively. Large capacity units are less costly than small units due to the scale effect. For example, the operating cost of NO_x control of a 100 MW unit is approximately 10.4–12.1 CNY/MWh, or twice the operating cost of a 1000 MW unit (5.2–6.3 CNY/MWh). The installation of a SCR system on the small unit may not be a wise choice. Furthermore, a small unit has a poor energy efficiency and large combustion loss compared with a large unit. For PM control, the application of ESP technology is enough to meet the GB13223-2011 emission standard, whereas WESP technology is required to meet the ultra-low emission limits. Thus, the additional generation cost of PM control rises when the ultra-low emission limits are met.

Fig. 2 shows the percentages of different sub-costs of dissimilar typical units that meet various emission standards. Compared with other sub-costs, the maintenance cost, wage and welfare, financial cost, interest cost, and other costs are extremely low. Thus, these sub-costs are represented as one item. Depreciation and other costs are closely related to the investment in the pollutant abatement system. Take the NO_x control as an example, the proportion of the depreciation cost and other cost decreases with an increase in unit capacity. This part of the cost accounts to approximately 52.1% of all the cost when the unit capacity is 100 MW, and decreases to 25.3% when the unit capacity is 1000 MW. The investment of per unit increases sharply with the decrease of unit capacity, as shown in the case study. Small units will cost more than large units when installing the pollutant abatement systems and meeting emission standards. PM control is different from SO_2 and NO_x control. Most particulate matters are removed in the ESP system and more than half of the remaining fine particulate matters are removed in the WESP system. The emission of power units can meet the requirements of the GB13223-2011 emission standard through the installation of ESP systems with high-performance design. By contrast, WESP system is required to meet the ultra-low emission limits. The WESP system consumes less energy but more water and alkali compared with the ESP system, which has great demand for electricity.

The sub-cost of the pollutant abatement system of a 300 MW unit, which meets different emission standards, is depicted in Fig. 3. Each sub-cost increases because the system consumes a considerable amount of resources and energy. Therefore, mature technologies can ensure the application of strict emission standards because technology improvement is based on existing mature technologies. For NO_x control, meeting ultra-low emission limits requires catalysts and reductants other than those required by the GB13223-2011 emission standard. Energy consumption increases

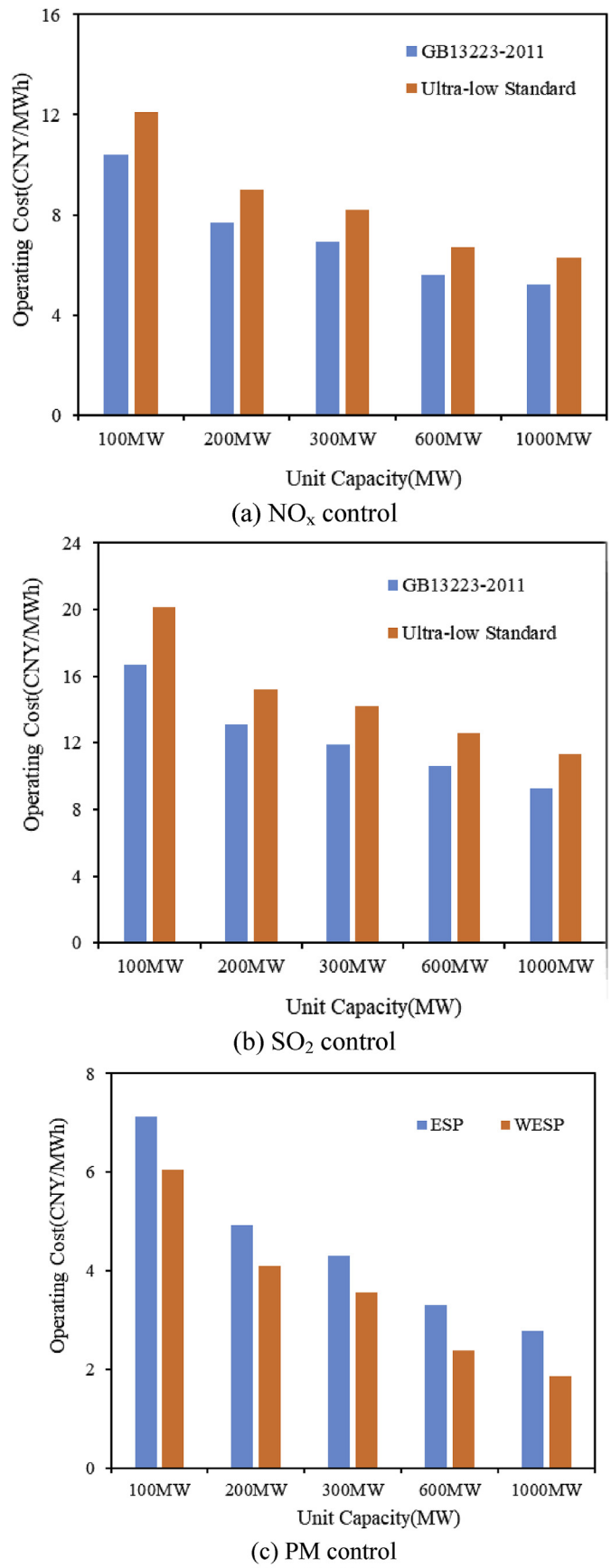
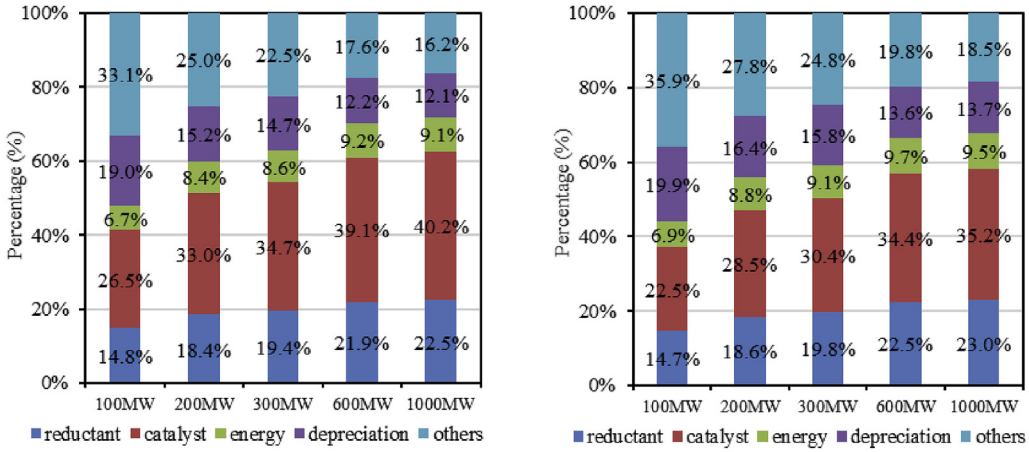
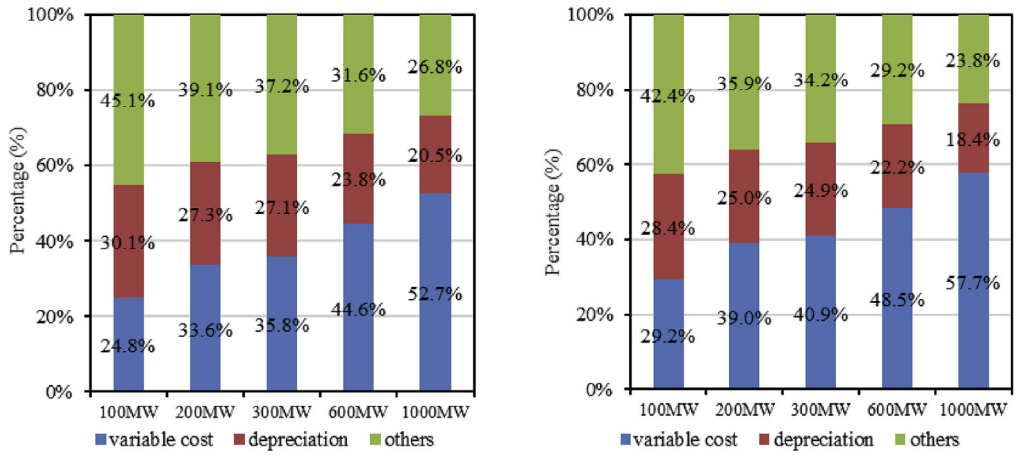


Fig. 1. The operating cost of different units meeting different standards.



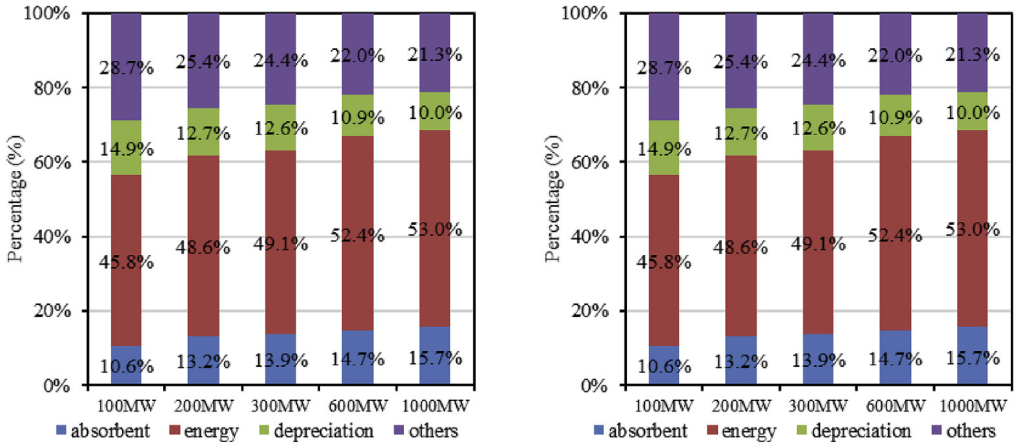
ultra-low emission standard GB13223-2011 emission standard

(a) NO_x control



Ultra-low emission standard (ESP + WESP system) GB13223-2011 emission standard (ESP system)

(b) PM control



ultra-low emission standard GB13223-2011 emission standard

(c) SO_2 control

Fig. 2. The proportion of sub-cost of multi-pollutant control of different units meeting different standards.

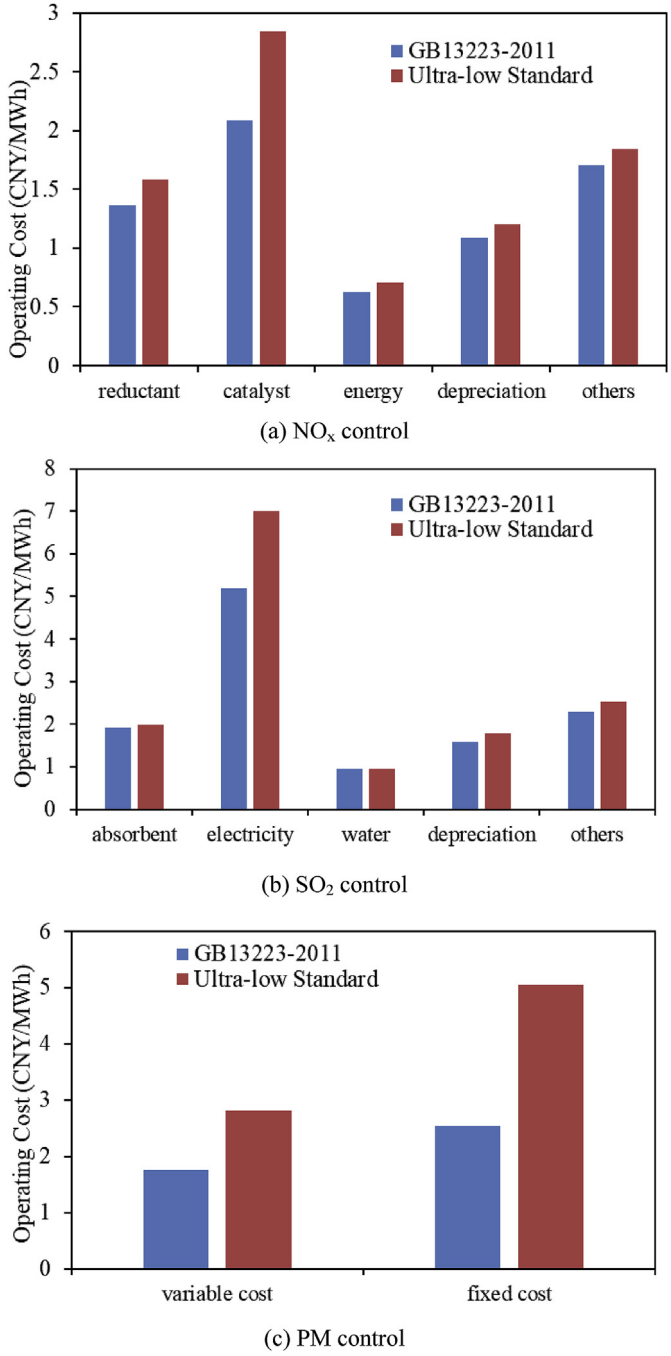


Fig. 3. The sub-cost of multi-pollutant control of a typical 300 MW unit meeting different standards.

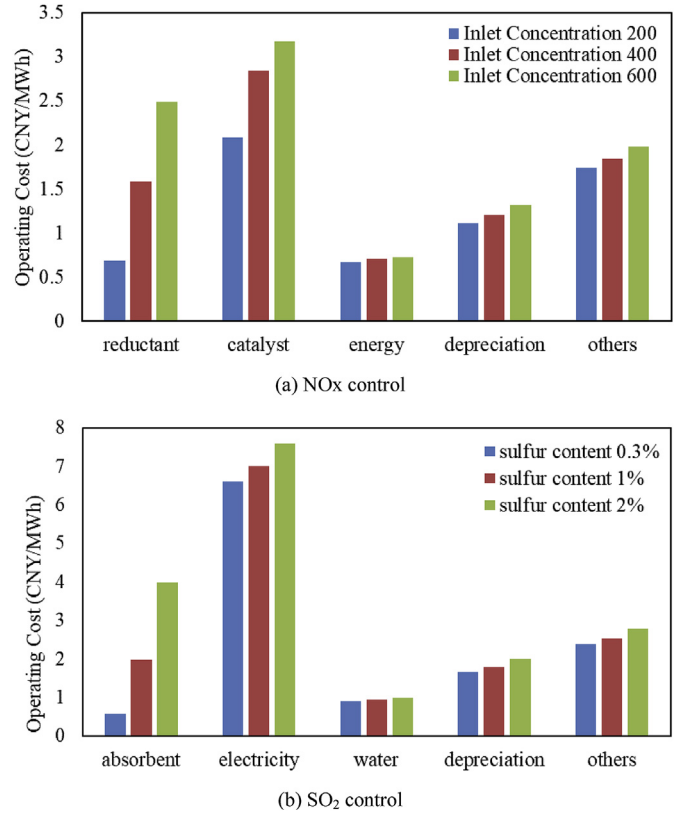


Fig. 4. The sub-cost of a typical 300 MW unit at different inlet concentration meeting Ultra-low emission standard.

because of the increase in reactor resistance caused by the additional catalyst. For SO_2 control, meeting ultra-low emission limits requires more energy than meeting the GB13223-2011 emission standard because an increase in the volume of slurry spray improves removal efficiency, which matches other stringent emission standards. Meeting ultra-low emission limits requires the application of ESP and WESP technologies, which increases fixed cost because the installation of WESP systems increases investment greatly.

The influence of inlet concentration on operating cost is depicted in Fig. 4. The removal effect of an ESP system with five electric fields is high and stable, and the emission concentration of PM can meet GB13223-2011 emission standards except for few special coals with high ash content. The field test from the case studies shows that the ESP system can adapt to the fluctuation of inlet concentration. High inlet concentrations of SO_2 and NO_x mainly increase the resource and energy consumption and remarkably influence on the design and construction of pollutant abatement systems. In addition, some extreme conditions should be avoided because each system is designed in a certain range of operating parameters. For example, the sulfur content of the design coal for limestone-gypsum WFGD system is 1%. If the sulfur content increases to 1.5%, then the manager can adjust the system to increase the volume of slurry spray. However, if the sulfur content increases to 3%, then the outlet concentration may not meet the emission standard.

Annual service hour indicates the effective operating time of a power unit in a year which is converted into operating time with a full load. Annual service hour has a pronounced influence on the operation economy. Fig. 5 shows that the additional generation cost of pollutant abatement systems can be reduced when the annual service hour increases. The additional generation cost of SO_2 control of a 300 MW unit decreases by 6.35% on the premise of meeting the ultra-low emission limits when the annual service hour increases from 5400 h to 6500 h.

3.2. Estimation of regional cost

The total cost of pollutant abatement in regional power sector can be estimated on the basis of the cost estimate of typical units and the distribution of coal-fired power units in China in 2013. The national inventory of desulfurization and denitrification equipment for coal-fired power units in 2013 is provided by China's Ministry of

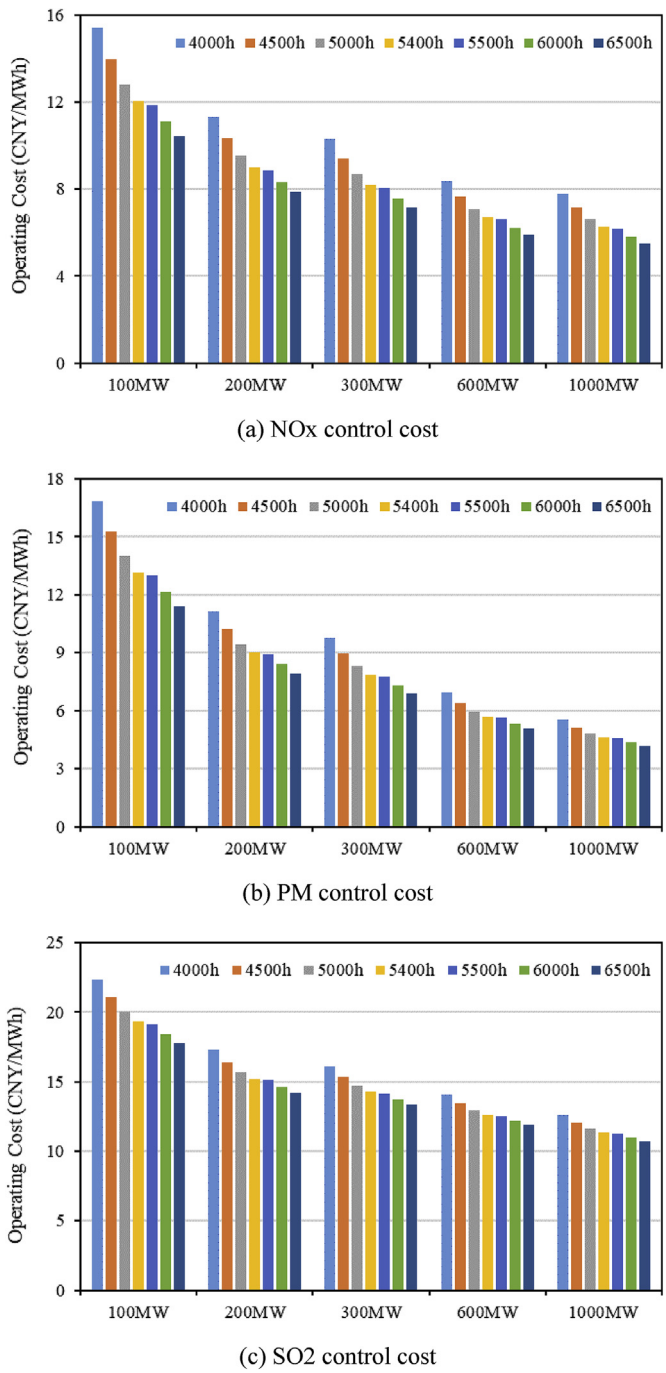
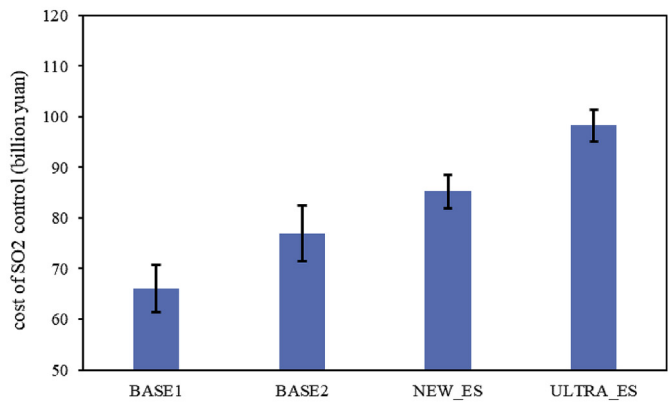


Fig. 5. The annual operating cost of different units at different annual service hour meeting Ultra-low emission standard.

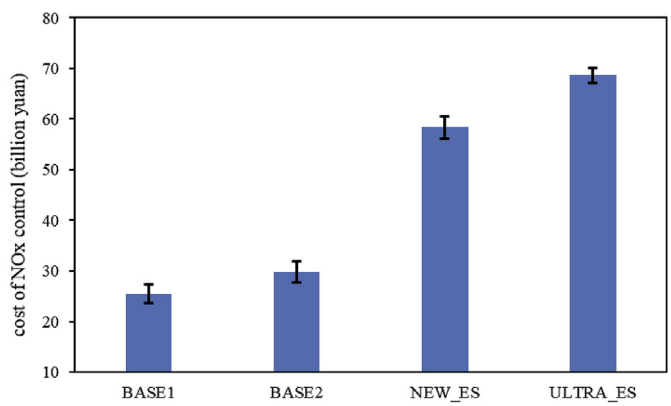
Environmental Protection. The detailed information of each unit with the installation of desulfurization and denitrification equipment is available in this inventory. The information includes the unit capacity, technology, and controlling company. Estimating the total cost of these units is difficult due to the lack of operating conditions of pollutant abatement systems. Most of them cannot meet the GB13223-2011 emission standard and ultra-low emission limits. Therefore, these systems should to be upgraded to improve removal efficiency. Additional investment should be made to upgrade pollutant abatement systems. The additional investment, as well as the high energy and resource consumption, will increase the operating cost when pollutant abatement systems are renovated to achieve high emission standard. Such additional investment depends on the current technological level. If the current removal efficiency is lower than the requirement of the GB13223-2011 emission standard, the pollutant abatement system will be upgraded comprehensively. Investment in pollutant abatement systems mainly causes the increase of depreciation and finance costs, which account for a large proportion of the operating cost. The resulting depreciation and finance cost for renovation projects are greater than those for new construction projects. The operating cost of a renovation project is calculated on the basis of case study because the additional investment depends on the current technological level and the initial investment in existing pollutant abatement systems is unknown.

Hence, four scenarios, namely, BASE1, BASE2, NEW_ES, and ULTRA_ES, are established to estimate the regional cost of emission control in the coal-fired power sector. BASE1 and BASE2 are based on the national inventory of desulfurization and denitrification equipment for the coal-fired power sector in 2013, which reflects the total operating cost of the units installed with pollutant abatement systems. The total operating cost per year in BASE1 and BASE2 is estimated when pollutant abatement system is upgraded to meet the GB13223-2011 emission standard and ultra-low emission limits, respectively. The cost of PM control is not estimated in this scenario due to lack of the information about the units installed with PM control equipment. NEW_ES scenario is based on the quantity and capacity distribution of coal-fired power units in China in 2015, which reflects the total operating cost of all the units that met the GB13223-2011 emission standard after the upgrade of existing pollutant abatement systems and construction of new pollutant abatement systems. The cost of PM control is estimated by considering all upgrades and new construction due to the lack of information regarding units installed with PM control equipment. ULTRA_ES scenario is similar to the NEW_ES scenario, but only the application of ultra-low emission limits is considered here. These scenarios are used to analyze the future operating cost of emission control in the power sector.

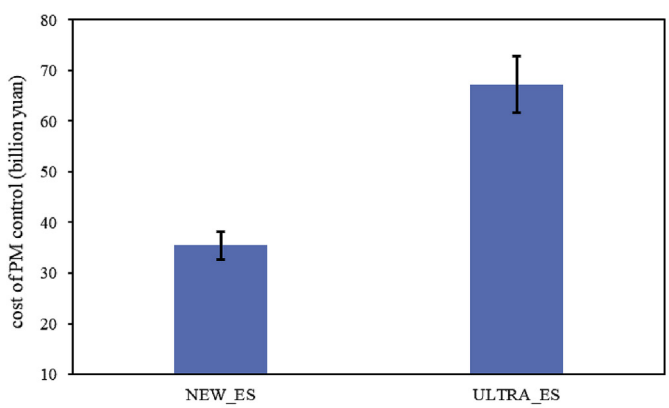
Fig. 6 (a), (b), and (c) show the costs of the coal-fired power sector in different scenarios. In BASE scenario, BASE1 represents the total cost of meeting the GB13223-2011 emission standard, and BASE2 represents the total cost of meeting the ultra-low emission limits. In BASE1, the total annual operating costs of NO_x and SO_2 control are approximately 23.63–27.26 and 61.34–70.77 billion CNY, respectively. In BASE2, the total annual operating costs of NO_x and SO_2 control are approximately 27.68–31.93 and 71.46–82.45 billion CNY, respectively. In NEW_ES scenario, the total annual operating costs of NO_x, SO_2, and PM control are approximately 56.2–60.5, 81.9–88.6, and 32.7–38.2 billion CNY, respectively. In ULTRA_ES scenario, the total annual operating costs of NO_x, SO_2, and PM control are approximately 67.2–70.1, 95.2–101.4, and 61.7–72.8 billion CNY, respectively. Desulfurization systems in the power sector are applied and installed widely. In 2013, the units with desulfurization system accounted for 61.9% of all units, and the percentage of capacity was 88.9%, indicating that future work will concentrate on the upgrading of existing desulfurization systems. Denitrification systems are not widely applied in the power sector and the quantity and capacity of units with denitrification system only accounted for 15.7% and 50.9% of all units based on the situation in 2013. As part of the effort to meet the seriously stringent emission standards, additional units without denitrification systems will be required to install SCR systems. The costs in the ULTRA_ES scenario increases to approximately 15.3%, 17.7%, and 89.7% for NO_x, SO_2, and PM control, respectively, compared with NEW_ES scenario. The cost of PM control in the ULTRA_ES scenario increases substantially compared with the NEW_ES scenario



(a) the cost of SO_2 control



(b) the cost of NOx control



(c) the cost of PM control

Fig. 6. The cost of multi-pollutants control in coal-fired power sector in different scenarios.

because the application of the WESP system is required to meet the standard of PM emission. The total annual operating cost in the ULTRA_ES scenario is approximately 224.1–244.3 billion CNY, representing approximately 0.35% of the GDP value of China in 2015.

Fig. 7 (a), (b), and (c) show the cost in the ULTRA_ES scenario in different provinces and the cost distribution of different capacity units. The advanced economy and dense population make the eastern region the demand side. This condition results in the aggregation of coal-fired power units and increased costs of pollutants control. For example, Shandong (SD) and Jiangsu Provinces (JS) show great economic aggregation and Henan Province (HN) has the largest population in China. Other regions, that are considered important power supply areas, such as the Inner Mongolia autonomous region (IN) and Shanxi Province (SX), also need to spend heavily on multi-pollutant control.

4. Feasible strategies for the cost reduction of ultra-low emission limits for regional study

The analysis of the regional cost of multi-pollutant control shows that the total cost of multi-pollutant control is still relatively high and will become an additional economic burden for the coal-fired power sector, although the environmental cost accounts for not more than 10% of the power generation cost. The high investment and operating costs of power generation are the main barriers in applying pollutant abatement systems in the power sector. As previously mentioned, the coal-fired power sector encounters the problem of excess capacity and the decrease of average annual service hour, both of which lead to the profit shrinkage of the power sector. Thus, feasible strategies for the cost reduction of multi-pollutant abatement are urgently required in addition to environmental subsidies for electricity price. Reducing control cost can mitigate economic burden and promote the installation and application of pollutant abatement systems in the power sector.

4.1. Operation management

The operating cost of the multi-pollutant abatement of power units can be reduced by adjusting the operating parameters to decrease the inlet concentration of pollutants. Resource and energy consumption can be reduced by decreasing inlet concentration. Burning low-sulfur coal is a common method to reduce the inlet concentration of SO_2. The inlet concentration of SO_2 can be reduced by purchasing low-sulfur coal or coal washing. However, the price of low-sulfur coal is relatively higher than that of high-sulfur coal, and its purchase will cause an increase in the power generation cost. Before applying low-sulfur coal, the impact of coal price and the additional desulfurization cost should be considered. Coal washing is a relatively effective method to reduce the sulfur content and remove other undesirable materials, such as ash. In the process of coal combustion, the inlet concentration of NOx can be reduced by approximately 50% by using the LNB system. The inlet concentration of NO_x can reach approximately 200 mg/Nm^3 by fuel reburning and air stage. The catalyst reductant dosage and consumption will be reduced compared with the inlet concentration 400 mg/Nm^3 and 600 mg/Nm^3, respectively. The reduction of the catalyst will reduce flow resistance, which decreases energy consumption.

Technological improvement in pollutant abatement systems is also an effective approach to reduce the operating cost of pollutant control. The application of high-frequency power converters for ESP systems is demonstrated to be an effective method to improve removal efficiency and reduce power consumption in PM control. Energy consumption is reduced by 60% when meeting the ultra-low emission limits according to the case study of a 600 MW power unit. Section 3 shows that the main cost of PM control is caused by energy consumption. Thus, high-frequency power converters can reduce the operating cost of PM control [36,37]. Catalyst reactivation technology can remove fly ash and certain components of flue gas on the catalyst surface, which block the surface pore and result in the deactivation of active components. Increasing poison-resistance of catalysts and catalyst reactivation can extend the service life of aged catalysts and the cost of this process is much lower than that of fresh catalyst production [38–40].

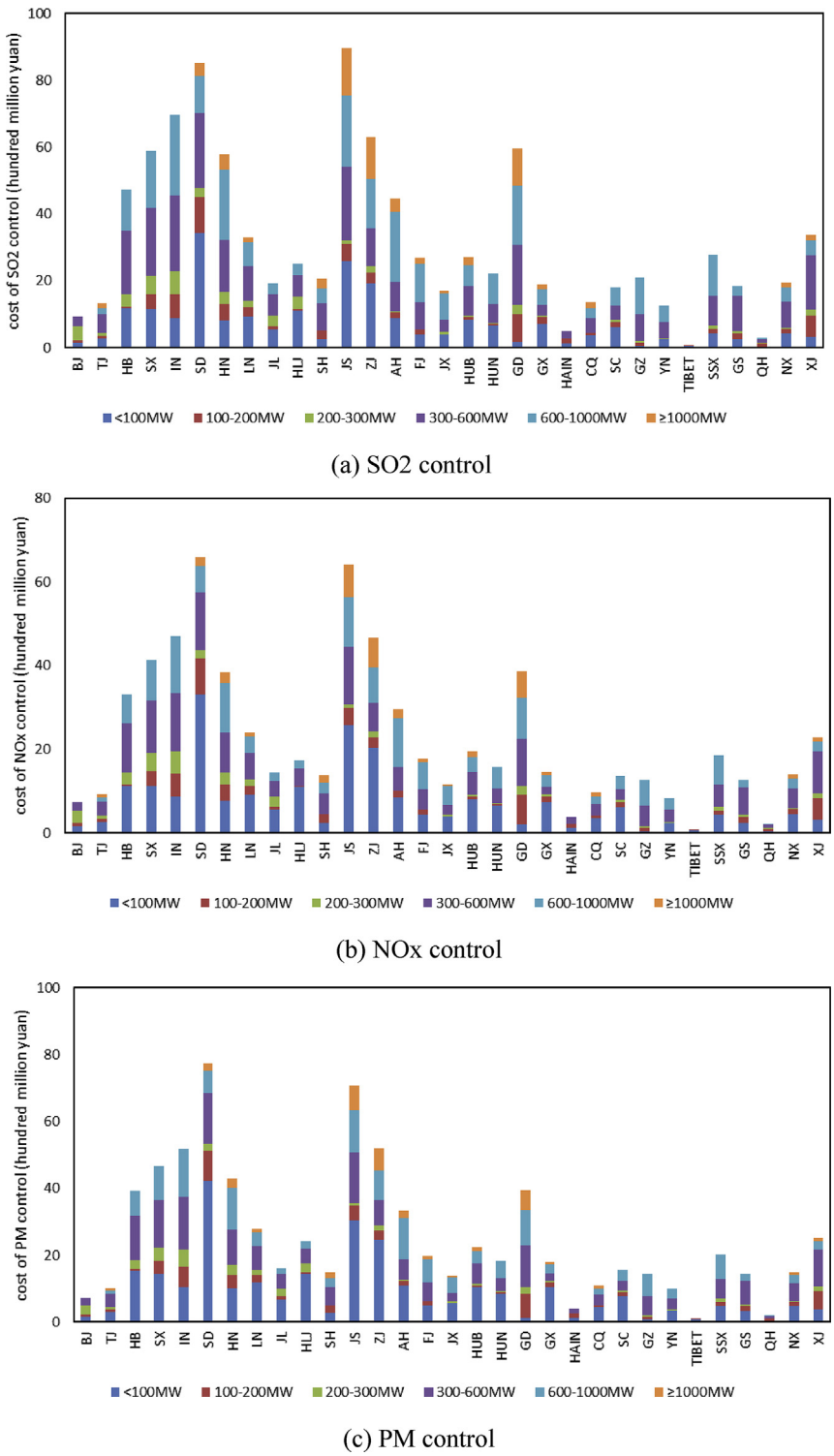


Fig. 7. The cost of ULTRA_ES scenario in different provinces and the cost distribution of different capacity units.

4.2. Sector planning

As previously stated, annual service hour exerts a great influence on the operation cost of pollutant abatement systems in power plants. However, operation managers cannot increase the operation time and unit load without following the regional power network dispatching. In China, power supply exceeds the total power demand, and the increase in power demand for the foreseeable future will not be high; this scenario leads to excess power supply [41,42]. A feasible solution is to impose restrictions on the construction of new coal-fired power units and to address the power demand by increasing the annual service hour of existing units.

In addition, there are still many small capacity units in China according to the distribution information of coal-fired power units.

Large capacity units for pollutant control are cheaper than small capacity units because of the scale effect, and the energy efficiency of small capacity units is generally poor. Fig. 8 indicates that the operating cost of small capacity units accounts for a large proportion of the total regional cost, whereas power generation only accounts for a small proportion of the total power generation. The application of pollutant abatement systems in small capacity units is not economical. Furthermore, some of these small units are used for hot water or steam generation, and their energy efficiencies are low. This phenomenon will create a greater economic burden for small units than for large units. Installing pollutant abatement systems in small units is not recommended. The government has actually started to implement regulations for reducing the number of small capacity units and replacing them with large capacity units. For example, six small capacity units have 100 MW capacity and can be replaced with new 600 MW unit. With this method, power generation is not reduced, and energy efficiency increases.

Suppose that all units in China whose capacity is below 100 MW are replaced 300 MW units. The total operating cost of this hypothetical scenario is depicted in Fig. 9. After replacing the small capacity units with 300 MW units, the cost of multi-pollutant control is reduced substantially. The costs of SO_2, NO_x, and PM control are reduced by approximately 73.6%, 80.3%, and 87.5%, respectively.

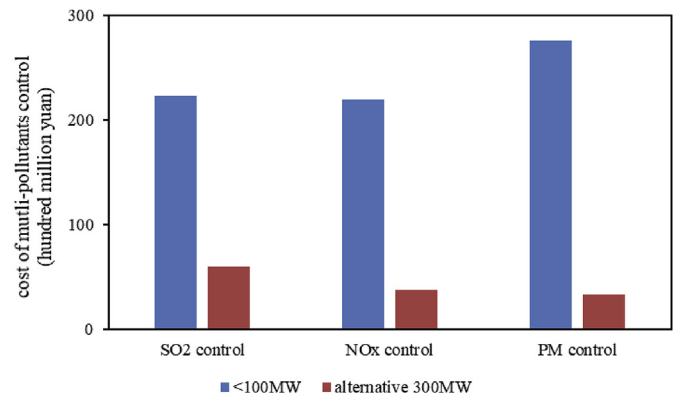


Fig. 9. The comparison of the cost of multi-pollutants control the replacement scenario and small capacity units.

5. Policy implications

Coal-fired power generation will maintain its dominant position in China's power generation structure for a long time, whereas the supply capacity of other clean energies, such as solar and hydropower, cannot meet the power demand. Therefore, the clean utilization of coal in the power sector is necessary due to the promulgation of emission standards and the installation and application of high efficient pollution control technologies. However, due to economic transformation, the growth rate of domestic power demand has been reduced, and the entire power sector is at overcapacity. In recent years, the annual average utilization hour of the thermal power industry has gradually declined, resulting in a decline in profits. As previously explained, the installation and operation of pollutant abatement systems increase the power generation cost, which can be the main barrier in the promotion and application of pollutant abatement systems in the coal-fired power sector. Thus, the accurate and comprehensive estimation of the additional power generation cost caused due to the operation of pollutant abatement systems and the effective cost reduction strategies can contribute to the rational implementation of pollution control technologies and the formulation of a reasonable electricity price subsidy policy.

In this study, the additional power generation cost (operating cost of pollutant abatement systems) of each power unit is estimated when different emission standards or limits are reached on the basis of an established cost database and operating cost estimation model of the pollutant abatement systems of the coal-fired power units. In addition, the regional cost can be estimated on the basis of the cost result of different power units and the distribution information of regional power units. The results can help managers understand the current additional power generation cost and provide effective cost reduction methods without reducing pollutant removal efficiency. Policy makers can also receive sufficient feedback to understand the economic impact of different environment-friendly policies on the power sector. For example, the current power price subsidy policy can improve the motivation of installing and operating pollutant abatement systems in the power sector, which can reduce the operating cost to some extent. A reasonable subsidy amount can ensure that the company will not lose too much money and that the government will not pay too much for the environmental bill due to the excessive power price subsidies. The research results on the emission control costs can also be combined with the health and environmental benefits and the regional air quality simulation to analyze the cost-effectiveness of different environment-friendly policies, by providing theoretical and data support.

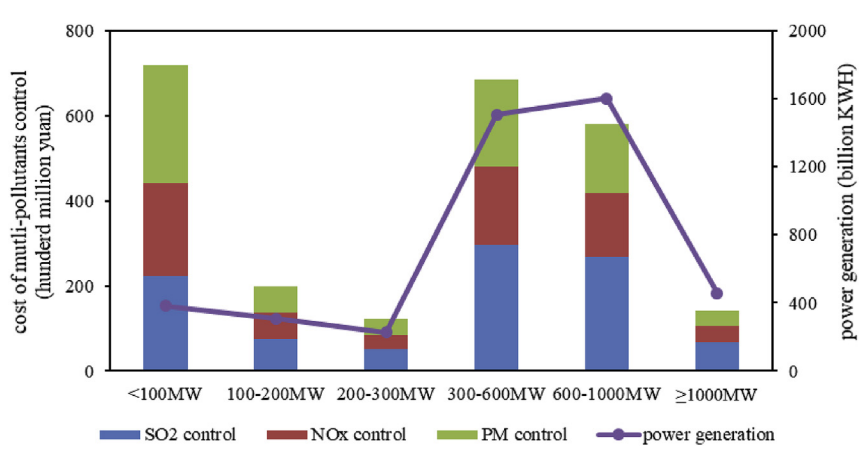


Fig. 8. The cost of multi-pollutants control and power generation of different capacity units.

6. Conclusions

This study provides a cost estimate model of multi-pollutant control in the coal-fired power sector in China and estimates the emission reduction cost of different typical capacity units with the application and operation of multi-pollutant control devices according to field survey and post evaluation of power units. The operating costs of NO_x, SO_2, and PM control of a typical 300 MW power unit when meeting the GB13223-2011 emission standard are 6.9, 11.7, and 4.3 CNY/MWh, respectively. The costs increase to 8.2, 13.8, and 7.9 CNY/MWh when meeting the ultra-low emission limits. The increase in operating cost is acceptable. Thus, the application of ultra-low emission limits can achieve remarkable emission reduction without paying a high price. The operating cost of pollutant abatement systems when meeting the ultra-low emission limits in coal-fired power plants accounts for approximately 8% of the total power generation cost. Depreciation cost is an important component of the total operating cost according to the analysis of sub-costs of different systems in Section 2. Energy consumption cost is the main component of SO_2 and PM control, whereas the catalyst and reductant cost are the main components for NO_x control.

Inlet concentration and emission standard are two of the main design specifications that affect not only energy and resource consumption but also investment. Although the operation of pollutant abatement systems fluctuates, which may lead to slight fluctuations of removal efficiency, technical indicators such as the removal efficiency of pollutant abatement systems should be improved to ensure the pollution removal effect. The influence of annual service hour on operating cost is also analyzed. The increase in annual service hour is an effective method to reduce the operating cost per power generation and to improve the operating economy.

The regional costs of different scenarios are estimated. Several scenarios are designed to estimate the current and future regional costs of multi-pollutant control. The total operating costs of multi-pollutant control when meeting the GB13223-2011 emission standard and ultra-low emission limits are approximately 170.8–187.3 and 224.1–244.3 billion CNY per year, respectively. The emission reduction cost per power generation of small capacity units is much greater that of other units. Considering that small units have an inferior energy efficiency, replacing these units will be an effective method to improve energy efficiency and reduce the emission control cost.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.energy.2018.07.164.

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