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Research article

Estimation of abatement potentials and costs of air pollution emissions in China

Fenfen Zhang [a,b], Jia Xing [a,b,*], Yang Zhou [c,d], Shuxiao Wang [a,b,**], Bin Zhao [e], Haotian Zheng [a,b], Xiao Zhao [f], Huanzhen Chang [f], Carey Jang [g], Yun Zhu [h], Jiming Hao [a,b]

[a] State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing, 100084, China
[b] State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing, 100084, China
[c] Tianjin Academy of Environmental Science, Tianjin, 300191, China
[d] Key Laboratory of Tianjin Air Pollution Control, Tianjin, 300191, China
[e] Pacific Northwest National Laboratory, Richland, WA 99352, USA
[f] School of Environment and Natural Resources, Renmin University of China, Beijing, 100872, China
[g] The U.S. Environmental Protection Agency, Research Triangle Park, NC, 27711, USA
[h] College of Environmental Science & Engineering, South China University of Technology, Guangzhou Higher Education Mega Center, Guangzhou, China

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ABSTRACT

Understanding the air pollution emission abatement potential and associated control cost is a prerequisite to design cost efficient control policies. In this study, a linear programming algorithm model, International Control Cost Estimate Tool, was updated with cost data for applications of 56 types of end-of-pipe technologies and five types of renewable energy in 10 major sectors namely power generation, industry combustion, cement production, iron and steel production, other industry processes, domestic combustion, transportation, solvent use, livestock rearing, and fertilizer use. The updated model was implemented to estimate the abatement potential and marginal cost of multiple pollutants in China. The total maximum abatement potentials of sulfur dioxide (SO_2), nitrogen oxides (NO_x), primary particulate matter ($PM_{2.5}$), non-volatile organic compounds (NMVOCs), and ammonia (NH_3) in China were estimated to be 19.2, 20.8, 9.1, 17.2 and 8.6 Mt, respectively, which accounted for 89.7%, 89.9%, 94.6%, 74.0%, and 80.2% of their total emissions in 2014, respectively. The associated control cost of such reductions was estimated as 92.5, 469.7, 75.7, 449.0, and 361.8 billion CNY in SO_2, NO_x, primary $PM_{2.5}$, NMVOCs and NH_3, respectively. Shandong, Jiangsu, Henan, Zhejiang, and Guangdong provinces exhibited large abatement potentials for all pollutants. Provincial disparity analysis shows that high GDP regions tend to have higher reduction potential and total abatement costs. End-of-pipe technologies tended be a cost-efficient way to control pollution in industries processes (i.e., cement plants, iron and steel plants, lime production, building ceramic production, glass and brick production), whereas such technologies were less cost-effective in fossil fuel-related sectors (i.e., power plants, industry combustion, domestic combustion, and transportation) compared with renewable energy. The abatement potentials and marginal abatement cost curves developed in this study can further be used as a crucial component in an integrated model to design optimized cost-efficient control policies.

1. Introduction

Air pollution has been one of the biggest challenges faced by China for the past two decades. Most regions in China have suffered from severe air pollution problems marked by high concentrations of fine particulate matter ($PM_{2.5}$) (van Donkelaar et al., 2015). The fast economic growth and urbanization in China have led to a rapid increase of anthropogenic emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x),

* Corresponding author. State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing, 100084, China.
** Corresponding author. State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing, 100084, China.
E-mail addresses: xingjia@tsinghua.edu.cn (J. Xing), shxwang@tsinghua.edu.cn (S. Wang).

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primary $PM_{2.5}$, non-volatile organic compounds (NMVOCs), and ammonia (NH_3), resulting in degraded regional air quality and visibility (Huang et al., 2014; Wang et al., 2014; Zhao et al., 2017, 2018a), adverse human health impacts (Heo et al., 2016; Lu et al., 2016; van Donkelaar et al., 2015; Wang et al., 2016), economic loss (Burke et al., 2018; Chestnut and Mills, 2005; Zhao et al., 2017), and global climate change over the last two decades (Bollen et al., 2009; Buonocore et al., 2015; Hill et al., 2009; Millstein et al., 2017). It has been assessed that the $PM_{2.5}$-mortalitirs in East Asia and South Asia increased by 21% and 85% respectively and correlations between population and $PM_{2.5}$ have become stronger in East Asia due to deteriorating air quality over the past two decades (Wang et al., 2016). The $PM_{2.5}$-mortalitirs was 0.96 million premature deaths per year, about 9.98% of total reported deaths in China, and the $PM_{2.5}$ exposure caused the economic loss of 101.39 billion USD (0.91% of GDP) in 2016 (Maji et al., 2018). Moreover, the contribution of China's emission to global radiative forcing was 10% (Li et al., 2016), which affects global climate change and regional air quality (Xing et al., 2016).

To improve the air quality, the Chinese government released a series of policies and legislations to implement end-of-pipe controls and adjust the structure of energy consumption. In September 2013, the Chinese government issued the Air Pollution Prevention and Control Action Plan (hereafter referred to as the "Action Plan") aiming to reduce $PM_{2.5}$ concentrations by 10% between 2013 and 2017 nationwide. A series of control measures were taken during the Action Plan, including the relocation or closing of highly polluting sources (e.g., steel factories and oil refineries), implementation of advanced end-of-pipe control measures with higher removal efficiency to meet more stringent emission standards for industrial facilities, and upgrades of numerous coal-fired boilers and domestic stoves to use natural gas instead of coal (Zhao et al., 2011, 2017). The effectiveness of the Action Plan has been verified by the considerable improvement in regional air quality. The annual averaged $PM_{2.5}$ concentrations of the Beijing-Tianjin-Hebei region (BTH), Yangtze River Delta region (YRD) and Pearl River Delta region (PRD) decreased from 110 $\mu g\ m^{-3}$, 70 $\mu g\ m^{-3}$ and 48 $\mu g\ m^{-3}$ in 2013 to 85 $\mu g\ m^{-3}$, 55 $\mu g\ m^{-3}$ and 34 $\mu g\ m^{-3}$ in 2015, respectively (Wang et al., 2017). However, the cost associated with the Action Plan control measures has been considerable; it was estimated as a loss of 4.8% of total GDP in the BTH region in 2017, which is forecast to10.25% in 2020 (Minjun Shi et al., 2017).

Studies have suggested that up to 80% of the cost associated with air pollution controls can be reduced by applying a cost-effective strategy (Amann et al., 2008). Cost-benefit analysis, which has been widely applied in the fields of environmental policymaking, has provided a unique framework to quantify the costs and benefits of proposed policy actions to select the optimal strategy since the late 1960s (Pearce, 1998). At present, several optimization frameworks have been developed to design least-cost strategies and control the multiple precursor emissions of air pollution; these frameworks include the Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) model developed by the International Institute for Applied Systems Analysis in Europe (Amann et al., 2001, 2008, 2011; Cofala et al., 2004; Kanada et al., 2013; Klimont et al., 2002; Klimont and Winiwarter, 2011; Liu et al., 2013; Schopp et al., 1999), the Control Strategy Tool (CoST) developed by the Environmental Protection Agency (EPA) in the United States (Alison Eyth et al., 2008; Loughlin et al., 2017), and the AIM/Enduse model developed by the National Institute for Environmental Studies in Japan (Hu et al., 2003; Xing et al., 2015). In recent years, a new policy-oriented integrated scientific assessment system, the Air Benefit and Cost and Attainment Assessment System (ABaCAS) was developed by Tsinghua University, the South China University of Technology, and the University of Tennessee with the support of the U.S. EPA to address the key question of the cost of the proposed control strategy (Xing et al., 2017). The International Control Cost Estimate Tool (ICET) module in ABaCAS was developed to calculate the cost of multi-pollutant control strategies by employing a linear programming algorithm to optimize the emissions reduction and control technologies for a certain sector. The ICET has been applied to the study of air pollution abatement in the Chinese coal-fired power industry (Sun et al., 2014) and a co-benefit analysis of energy efficiency improvement in the United States (Loughlin et al., 2017).

Studies conducting cost assessment in China have mostly focused on certain pollutants over various sectors or multiple pollutants in specific sector. Previous studies investigated the abatement potential and cost-effectiveness of SO_2 control policy in power plants or industry sectors at the national-wide scale in China (Zhang et al., 2017), in China's provincial-level regionals (Dong et al., 2015) and in Chinese mega cities (Kanada et al., 2013), respectively. For collaborative control of multiple pollutants, Sun et al. (2014) assessed the maximum abatement potential and total costs of SO_2, NO_x, and $PM_{2.5}$ for power generation sector in the YRD region in China using the ICET. Furthermore, the impacts of incorporating air quality and environmental co-benefits into the climate policy for SO_2, PM, NO_x, and CO_2 have been evaluated in Chinese cement (Yang et al., 2013; Zhang et al., 2015), iron and steel industries (Zhang et al., 2014).

Coordinated control of multiple pollutants across various sectors is critical to maintaining air quality in China. However, few studies have investigated the costs associated with control efficiency of multiple pollutants, particularly for sectors such as the iron and steel, cement, transport, and industry processes, or the end-of-pipe controls and potential applications of NMVOCs and NH_3 in China. Moreover, previous studies have reported that increasing energy efficiency and applying renewable energy could significantly reduce air pollution control costs (Dai et al., 2016). For instance, approximately 17–35% of the costs of SO_2 emission reduction have been reduced due to the application of renewable energy in China (Boudri et al., 2002).

This study therefore sought to rebuild the ICET model based on high resolution inventory by updating the local database with the cost of end-of-pipe technologies and renewable energy application in China. Different from previous study, the costs of multiple pollutants and sectors from a provincial perspective were investigated. Furthermore, the end-of-pipe technologies, potential applications, and costs of NMVOCs and NH_3 were comprehensively analyzed associated with SO_2, NO_x, and primary $PM_{2.5}$ in this study, which were rarely mentioned in previous studies. Such information can be valuable for policy maker to understand the future control potentials and design cost-effective control strategy.

2 and 345The structure of this paper is as follows: Section 2 describes the cost model methodology, data sources and end-of-pipe control options for each pollutant by sectors. The results of the abatement potential analysis and marginal abatement cost curves are given in Section 3. Section 4 and 5 presents the discussion and conclusion.

2. Method and data

2.1. Control cost of end-of-pipe technologies

The cost of end-of-pipe control technology *i* for pollutant *p* in a sector s is estimated using following equations. First, the total cost is the sum of the capital cost, fixed operating and maintenance (FOM) costs, and fuel costs, as presented in Eq. (1).

$$TCost_{i,p,s} = CC_{i,p,s} + FOM_{i,p,s} + FUEL_{i,p,s} \quad (1)$$

where $TCost_{i,p,s}$ is the total cost of the end-of-pipe measure *i* for a pollutant *p* in a sector s; $CC_{i,p,s}$ is the annual average capital cost of end-of-pipe measure *i* for a pollutant *p* in a sector s; $FOM_{i,p,s}$ presents the FOM costs of the end-of-pipe measure *i* for a pollutant *p* in a sector s; $FUEL_{i,p,s}$ is the fuel cost per year of the end-of-pipe measure *i* for a pollutant *p* in a sector s. The unit is CNY/kW for power plants and CNY/t for steelmaking and cement.

Second, the annual average capital cost is estimated from the initial investment cost, the discount rate, and the lifetime of the end-of-pipe measures, as presented in Eq. (2).

$$CC_{i,p,s} = Cost_{i,p,s}\frac{\alpha(1+\alpha)^t}{(1+\alpha)^t - 1} \tag{2}$$

where $Cost_{i,p,s}$ is the initial investment cost of the end-of-pipe measure i for a pollutant p in a sector s; α is the discount rate; t is the lifetime of the end-of-pipe measure i.

In this study, the discount rate and lifetime were assumed in Table S1 according to previous studies (Cofala and Syri, 1998; Sun et al., 2014; Zhang et al., 2014). The initial investment cost and FOM cost were gathered from government documents, reports, literature review and field investigation (Table S2). The unit cost of the end-of-pipe measure i for a pollutant p (SO_2, NO_x, primary $PM_{2.5}$) was calculated for different types of end-of-pipe technologies in 10 major sectors (i.e., power generation, industry combustion, cement production, iron and steel production, other industrial process, domestic combustion, transportation, solvent use, livestock rearing, and fertilizer use). The capital cost and the FOM costs of emission control technologies in coal-fired power plants, iron and steel production, and cement production are summarized in Table S3, Table S4, and Table S5 in Supplementary Information, respectively. For oil-, gas-, and biomass-fired boilers, the FOM costs were investigated from literature review (Table S6); thus, overall, the costs of four types fossil-fuel boilers were computed. The specific unit costs were simply estimated based on the ratios compared with coal-fired boilers in this study. The unit cost of most NMVOCs-related (Table S7) and NH_3-related (Table S8) sectors was directly collected from literature review or field investigation, which aimed at studying the end-of-pipe technologies and abated emissions of VOCs thought interviewing industries in BTH region (Zhao et al., in preparation).

For consistency with other pollutants, the NH_3 abatement cost in per unit of live animal, which was derived from a literature review, is transformed to be per unit of removed NH_3 emission through the following equation (Klimont and Winiwarter, 2011).

$$uc_{ij} = \frac{ua_{ij}}{n_{ij} \cdot ef_j} \tag{3}$$

where n_{ij} is removal efficiency of a technology i for the livestock sector j; ef_j is the emission factor for the livestock sector j; ua_{ij} is the unit cost per live animal; and uc_{ij} is the unit cost per abated NH_3 emission.

2.2. Control cost of renewable energy application

In addition to end-of-pipe controls, renewable energy application measures were considered in this study. Renewable energy, such as hydropower, solar power, wind, nuclear and biomass energy were considered as replacements for fossil fuels to be applied in the power generation, industrial combustion, and domestic sectors to reduce pollutant emissions. Similar to end-of-pipe technologies, the emission reductions and associated costs for renewable energy application measures were mainly based on the levelized cost published by the International Renewable Energy Agency in 2014 (The International Renewable Energy Agency, 2015). In sum, the abatement potential and associated costs of renewable energy were estimated as follows.

First, the potential reduction emissions of each renewable energy were simply assumed to be equal to the emissions from coal-fired power plants and industry combustion when the same amount of electricity or heat is produced, and the associated levelized cost of renewable energy was considered as the unit cost of each abated pollutants.

Second, renewable energies can only partly replace related fossil fuels, and the maximum substitution rate was determined based on the potential power generation of each renewable according to the latest China 2050 High Renewable Energy Penetration Scenario and Roadmap Study reported by the Energy Research Institute of the National Development and Reform Commission in 2015 (Energy Research Institute of National Development and Reform Commission, 2015).

Third, renewable energy application was treated as an optional control technology. The unit cost of pollutant reduction associated with renewable energy application was calculated and implemented into the development of marginal cost curves for all pollutants.

2.3. Estimation of marginal abatement cost and abatement potential

Marginal abatement cost curves for pollutant emissions were established based on the ICET module in the ABaCAS system. First, the unit cost per ton of pollutant emission for each control technology was calculated based on the control cost and emission abatement. Second, the control technologies were classified by unit cost per ton from low to high, implying that most cost-efficient control technologies will be first to apply with their maximum application rate. Subsequently, the maximum abatement potential of each pollutant was estimated as the maximum abatement rate of emission when all available control technologies are applied.

Current control applications, as well as the unit cost, potential application rate, and emission control efficiency of different control technologies are calculated as follows.

$$TCost^r_{i,p,s} = UC_{i,p,s} \times \Delta Emis^r_{i,p,s} \tag{4}$$

$$\Delta Emis^r_{i,p,s} = (1 - CE_{i,p,s}) \times \left(AppR^r_{i,p,s} - Cur\_AppR^r_{i,p,s}\right) \times Unabated\_Emis^{r,s}_p \tag{5}$$

$$Cur\_AppR^r_{i,p,s} \le AppR^r_{i,p,s} \le \max\_AppR_{i,p,s} \tag{6}$$

where $TCost^r_{i,p,s}$ is the total cost of technology i for pollutant p (i.e., NO_x, SO_2, NH_3, NMVOCs and primary $PM_{2.5}$) in a region r; $UC_{i,p,s}$ is the unit cost of the technology i for a pollutant p; $\Delta Emis^r_{i,p,s}$ is the potential emission reduction by the technology i for a pollutant p in a region r; $CE_{i,p,s}$ is the control efficiency of the technology i for a pollutant p; $AppR^r_{i,p,s}$ is the control application rate of the technology i for a pollutant p in a region r; $Cur\_AppR^r_{i,p,s}$ is the current control application rate of the technology i for a pollutant p in a region r; $Unabated\_Emis^{r,s}_p$ represents the unabated emissions of a pollutant p in a region r in a sector k where the control technology i is applied; and $\max\_AppR_{p,i}$ is the maximum application rate of the technology i.

In this study, the data of $Unabated\_Emis^{r,k}_p$, $Cur\_AppR^r_{i,p,s}$ and $CE_{i,p,s}$ were derived from the study of the province-level bottom-up unit-based emission inventory developed by Tsinghua University (Wang et al., 2011, 2014; Wei et al., 2008, 2011; Zhao et al., 2018b). The inventory includes detailed point source information, such as energy consumption, geographical location, capacity, boiler type and the emission control technologies of SO_2, NO_x and primary $PM_{2.5}$ derived from the related industrial associations. The anthropogenic emission of NO_x, SO_2, primary $PM_{2.5}$, NMVOCs, and NH_3 in China of 2014 were estimated to be 23.10, 21.40, 9.63, 23.23, and 10.71 Mt, respectively (Zhao et al., 2017). The total cost of the control technologies for pollutants was estimated from annualized investment, FOM costs, and fuel cost over lifetime. Part of the parameters of $UC_{i,p,s}$ and $\max\_AppR_{i,p,s}$ referred to the dataset of the ICET (Sun et al., 2014) and GAINS-Asia model (Amann et al., 2008) with updates for power generation and industrial processes from the literature and surveys.

When cost-efficient measures are selected in an optimal sequence, the marginal costs ($MCost^r_{i,p,s}$) are calculated by Eq. (7) which provides a ranking of the available emission control measures.

$$MCost^r_{i,p,s} = \frac{TCost^r_{i,p} - TCost^r_{i-1,p}}{\Delta Emis^r_{i,p} - \Delta Emis^r_{i-1,p}} \tag{7}$$

The marginal abatement cost and abatement potential were estimated for five pollutants, namely SO_2, NO_x, primary $PM_{2.5}$, NMVOCs, and NH_3 individually. Specifically, the abatement potential and cost of NMVOCs and NH_3 were investigated and comprehensively analyzed in association with SO_2, NO_x, and primary $PM_{2.5}$ from a regional disparity perspective in China. The abatement potential of multiple emission sources and the control cost associated with certain emission reduction target were calculated in this study to provide a basic dataset for policy makers to design cost-effective control strategy in China.

To analyze the relative contribution from end-of-pipe measures and renewable energy application, we designed two hypothetical scenarios in addition to the baseline 2014 emissions (referred to as the BAL scenario). First, the emissions were estimated with maximum application of end-of-pipe measures (referred to as EOP scenario). Second, the emissions were estimated with the maximum application of both end-of-pipe measures and renewable energy (referred to as REN scenario). The difference between the BAL and EOP scenarios indicated the abatement potential of air pollutants with the maximum application of end-of-pipe measures. The difference between the EOP and REN scenarios indicated the abatement potentials of air pollutants with the application of renewable energy. Moreover, the difference between the BAL and REN scenarios indicated the overall maximum abatement potential of air pollutants.

3. Results

3.1. Renewable energy application

The abatement costs of renewable energy sources are summarized in Table 1. To simplify estimating the cost of renewable energy, some hypotheses were tested, as mentioned in Section 2.2. Renewable power is the major replacement option for fossil fuel. By 2050, 86% of total power generation will be renewable power in China according to the latest China 2050 High Renewable Energy Penetration Scenario and Roadmap Study reported by the Energy Research Institute of National Development and Reform Commission in 2015 (Energy Research Institute of National Development and Reform Commission, 2015). Wind, solar, hydropower, biomass and geothermal energy could meet more than 60% of primary energy demand. According to this report, the potential application of renewable energy was estimated. By 2050, coal power generation will decrease to below 7% of total power generation, and the wind, hydropower, solar, nuclear power, natural gas, and other sources of energy (e.g., biomass, geothermal) could replace 35.2%, 14.4%, 28.4%, 4.3%, 3.1%, and 7.9% of the power generated by coal-fired power plants, respectively. Furthermore, approximately 60% of the coal used in industrial combustion, residential heating, and lighting could be replace by solar energy by 2050. The unit cost of wind, hydropower, solar, and natural gas are 0.40, 0.43, 0.42, and 0.47 CNY/kWh, respectively, which are cheaper than that of coal-fired power generation at 0.53 CNY/kWh.

3.2. Estimation of emission abatement potential in China

To analyze the abatement potential of multiple pollutants, the EOP scenario was designed assuming that the application rate of end-of-pipe control technologies reached its maximum. Fig. 1 presents the changes of pollutants by sectors under three scenarios. The emissions of SO_2, NO_x, primary $PM_{2.5}$, NMVOCs, and NH_3 decreased by 69.2%, 56.1%, 53.8%, 56.6%, and 80.3%, respectively, under EOP scenario. Under the REN scenario, by applying renewable energy, the emissions of SO_2, NO_x, primary $PM_{2.5}$, and NMVOCs decreased by 89.7%, 89.9%, 94.6%, and 74.0% lower than those in the BAL scenario. The total abatement potential of SO_2, NO_x, primary $PM_{2.5}$, NMVOCs, and NH_3 in 2014 was thus estimated as 19.2, 20.8, 9.1, 17.2, and 8.6 Mt, respectively.

Regarding end-of-pipe control measures, the industrial sector, including cement plants, iron and steel production, and other industrial processes, demonstrated the largest abatement nationwide, with SO_2, NO_x, primary $PM_{2.5}$, and NMVOCs reduced by 31.7%, 32.5%, 72.5%, and 36.5%, respectively. In particular, the application of advanced technology including SNCR or SCR for NO_x control and high efficiency de-duster for PM control in cement production, as well as the activated carbon adsorption technology for the collaborative reduction of SO_2 and NO_x during iron and steel making, could bring substantial emission reductions. The application of EOP in industrial combustion and power generation sectors could reduce SO_2 emissions by 39.5% and 23.3%, and reduce $PM_{2.5}$ emissions by 16.8% and 9.1%, respectively. The abatement potential of NO_x largely resulted from EOP controls in power generation (26.7%) and transportation (20.7%). The petroleum and solvent use sectors exhibit the largest abatement potentials for NMVOCs with 32.5% and 39.2% emission reduction, respectively. The livestock sector reached 62.2% NH_3 abatement due to the application of large-scale rearing and breeding farms.

Table 2 summaries the abatement potential and the total cost of multi-pollutants in each province of China. Shandong province exhibited the largest abatement potential with SO_2, NO_x, primary $PM_{2.5}$, and NMVOCs reduced by 1993.4, 2268.8, 798.0, and 1667.4 kt, respectively. Furthermore, Henan province, as one of the major agricultural provinces exhibited the largest abatement potential of NH_3 with 748.2 kt, followed by Sichuan and Shandong provinces. In the BTH region, the abatement ratio of SO_2, NO_x, primary $PM_{2.5}$, NMVOCs, and NH_3 was 85.6%, 89.8%, 94.4%, 71.8%, and 78.1%, respectively. In the YRD region, the abatement ratio of SO_2, NO_x, primary $PM_{2.5}$, NMVOCs, and NH_3 was 93.4%, 90.6%, 96.9%, 67.3%, and 79.2%, respectively. In the PRD region, the ratio was 92.9%, 88.2%, 96.5%, 71.1%, and 81.0%, respectively.

Identifying the key provinces and sectors that exhibit the largest potential for air pollutant abatement is useful for policymakers to select specific sectors or provinces to control air pollution priority over others. From our analysis, the provinces of Shandong, Hebei, Henan and Sichuan exhibited the largest abatement potential for SO_2, NO_x, and primary $PM_{2.5}$. For NMVOCs, the YRD region has substantial abatement potential. Compared to power generation and industrial combustion sectors, cement production, steelmaking, and other industrial processes with larger abatement potential (e.g., oil refining, glassmaking, and chemical industry) should be considered as the priority industrial sectors to reduce emissions.

Table 1
The potential application of renewable energy sources in China.

Renewable energy	Renewable technology	Sector replaced	Fuel replaced	Substitution ratio (%)	Unit Cost[a] CNY/kWh
Wind	Wind turbine	Power	Hard coal	35.2	0.40
Hydro power	Hydro power station	Power	Hard coal	14.4	0.43
Nuclear power	Nuclear power station	power	Hard coal	4.3	0.58
Natural gas	Power plant	power	Hard coal	3.1	0.47
Others				7.9	0.6
Solar	Flat plate collectors	Power	Hard coal	28.4	0.42
	Flat plate collectors	Industry combustion	Hard coal	60	1.12
	Photovoltaic cells	Residential	Electricity	60	0.42

Unit Cost[a]: cost value is from the leveling cost of reports by International Renewable Energy Agency (IRENA) and calculated by exchange rate conversion of 6.8.

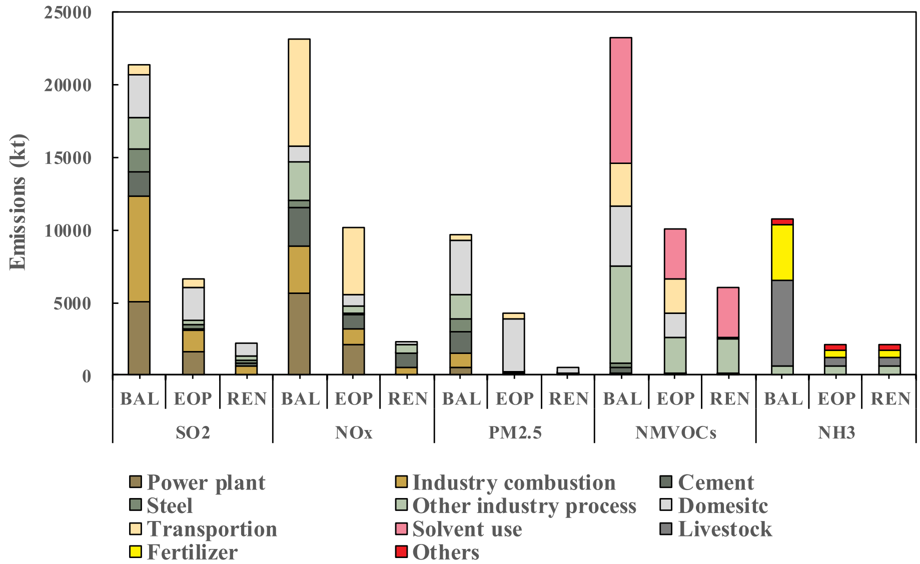

Fig. 1. The analysis of emission reduction from sectors: BAL-baseline scenario; EOP-end-of-pipe scenario; REN-renewable energy scenario.

3.3. Estimation of marginal abatement cost curves

Fig. 2 displays the relationship between the total abatement costs and reduction rates by five pollutants in China. Both the end-of-pipe measures and energy structure adjustment were applied in the development of the marginal abatement cost curves. As the reduction rates increase, the total abatement costs also increase in all pollutants.

For SO_2 controls, the marginal abatement cost curve increased sharply when the reduction ratio reached 10% and 83%. The low efficiency end-of-pipe measures in power plants, including turning off some power plants with an installed capacity less than 100 MW, were replaced by high-efficiency FGD technology when the reduction ratio reached 10%. The raise of the marginal abatement cost curve after the inflexion point of 83% was caused by higher unit cost of FGD by using nature gas and liquefied petroleum gas for boilers and domestic stoves. In addition, application of energy structure adjustment by replacing fossil fuel with wind or solar energy could further reduce SO_2 emissions, which indicates that renewables may be a solution for pollutant abatement in the future.

For NO_x, three inflexion points appeared as the marginal abatement cost curve rose. When the reduction ratio was less than 58.0%, LNB + SCR technologies and energy structure adjustment were mainly applied in power generation, industrial combustion, and domestic sectors. Subsequently, the marginal cost increased sharply with the higher cost of the activated carbon absorbing method used in sintering process or the SCR technology in gas-fired or oil-fired boilers and domestic stoves. Subsequently, the large-scale upgrade in the quality of gasoline products and the promotion of new energy electric vehicle policies resulted in further abatement of NO_x when the reduction ratio reaches 77.1%.

For primary $PM_{2.5}$, when the reduction ratio was larger than 29.3%, the substitution of renewables in coal-fired power plants was more expensive than conventional technologies (i.e., ESP, FF, and ESP + FF), as depicted in the cost curve of $PM_{2.5}$. The de-dusting in gas- or oil-fired boilers was difficult and costly after a reduction ratio of 90.5%.

For NMVOCs, the processing of synthetic materials, paints, chemicals, plant oils, as well as solvent use exhibited large potential abatement and marginal costs with a reduction ratio of 42.6%–62.0%. When the reduction ratio was larger than 62.0%, the marginal cost was up to 267.3 billion CNY because of the implementation of new energy electric vehicle policies.

For NH_3, urea substitution was used in fertilizer when the reduction ratio was under 38.4%. In addition, it demonstrated the larger potential abatement and marginal costs of NH_3 in livestock if the reduction ratio exceeds 40%.

Further reduction of air pollutants should therefore depend on adjustment of the energy structure (e.g., increase of renewable energy generation proportion, closure of high-emission plants), which could bring considerable social benefit. According to the marginal cost curves of multiple pollutants (Fig. 2) and typical end-of-pipe technologies (Fig. S1), The cost-effective pathways are designed to control air pollution in China. However, there is quite limited end-of-pipe technologies of ammonia over the world except Europe. Hence, the large limitation about ammonia controls still exists even though we applied related database of ammonia controls in Europe to supply a gap in China.

Fig. 3 illustrates the emission abatement potential and cost in different sectors. Industrial combustion exhibited the most abatement potential for SO_2 with 35.0% in all sectors, and also had the highest abatement cost of 34.4% (31.9 billion CNY). The power generation and domestic sectors exhibited the considerable abatement potential and cost. However, the industrial processes sector, including cement production, iron and steel production, and other industry production, not only exhibited a larger abatement potential (24.5%) but has a lower abatement cost which account for 14.9 billion CNY (16.2%). Compared with power generation and industrial combustion, the controls of cement production, steelmaking production and other industrial processes are more cost-effective. Similarly, the potential reduction of NO_x emission in the industrial processes was 4209 kt (20.3% of total potential abatement emission) with a cost of 35.2 billion CNY (7.5% of total cost). Approximately 69.5% of the abatement cost of NO_x was from transportation sector because of the high technology cost and requirement for new energy vehicles. For primary $PM_{2.5}$, the most economical abatement sector was other industrial processes with 0.1% abatement cost (i.e., lime production, building ceramic production, glass and brick production), with an abatement potential of 1624 kt. The largest abatement potential of $PM_{2.5}$ (3388 kt) was in the domestic sector; the total cost was 31.1 billion CNY. For NMVOCs, the solvent use, other industrial processes, domestic, and transportation sectors had the highest abatement potential and costs resulting from disordered management of controls and high investment costs. Up to 25.6% NMVOCs could be reduced in the other industrial processes sector (e.g., car manufacturing, vehicle refinishing), with an 18.0% abatement cost (80.9 billion CNY). According to previous research (He, 2018), electric vehicles are a cost-effective means to alleviate air pollution from a life-cycle perspective, noting that vehicles could reduce VOCs and NO_x emissions by 1770–2354 g/year per vehicle and 930–1354 g/year per

Table 2
Potential for reducing emissions and total cost of multi-pollutants with respect to 2014.

Province	SO_2					NOx					$PM_{2.5}$					NMVOCs					NH_3^c				
	MPR[a] kt (%)		Total Cost[b]			MPR kt (%)		Total Cost			MPR kt (%)		Total Cost			MPR kt (%)		Total Cost			MPR kt (%)		Total Cost		
			low	high	mean			low	high	mean			low	high	mean			low	high	mean			low	high	mean
Beijing	55.8	(79.4)	0.3	0.4	0.4	173.3	(89.7)	8.9	9.4	9.1	34.5	(85.7)	0.2	0.2	0.2	233.6	(68.7)	4.6	9.5	7.0	26.0	(63.1)	0.0	1.4	1.4
Tianjin	212.0	(88.4)	1.0	1.5	1.2	264.4	(91.1)	6.6	7.4	7.0	88.2	(94.6)	0.5	0.7	0.6	226.5	(69.1)	3.4	8.0	5.7	37.3	(73.2)	0.0	1.8	1.8
Hebei	729.1	(85.3)	3.1	4.3	3.7	1084.3	(89.5)	31.6	34.4	33.0	661.7	(94.9)	3.6	5.2	4.4	1025.0	(73.2)	17.1	34.7	25.9	461.3	(77.0)	0.0	18.4	18.4
Shanxi	833.6	(87.9)	3.8	5.1	4.4	776.9	(91.2)	15.7	17.9	16.8	453.7	(94.4)	1.9	2.6	2.3	522.1	(79.9)	6.6	12.4	9.5	111.4	(62.5)	0.0	4.5	4.5
Neimeng	945.1	(85.8)	4.8	6.1	5.5	1035.3	(91.7)	15.8	18.8	17.3	347.3	(87.4)	2.5	3.1	2.8	459.2	(76.2)	6.4	13.3	9.8	312.1	(77.3)	0.0	9.9	9.9
Liaoning	754.2	(89.9)	2.7	5.6	4.1	914.1	(91.2)	17.4	21.0	19.2	377.3	(96.6)	2.3	3.2	2.7	731.4	(70.3)	8.5	24.7	16.6	288.0	(80.1)	0.0	13.5	13.5
Jilin	324.8	(90.5)	1.2	1.9	1.6	500.1	(91.3)	9.3	11.0	10.2	248.2	(95.8)	1.5	1.8	1.6	331.2	(76.2)	5.5	13.0	9.2	233.7	(80.3)	0.0	8.9	8.9
Heilongjiang	255.0	(90.0)	1.1	1.9	1.5	585.5	(91.6)	11.2	13.1	12.2	287.1	(93.2)	2.3	2.4	2.3	418.3	(78.4)	6.7	17.0	11.8	273.3	(78.8)	0.0	10.8	10.8
Shanghai	453.5	(89.5)	1.6	4.3	2.9	283.7	(91.7)	6.9	7.9	7.4	77.6	(93.7)	0.3	0.7	0.5	438.5	(62.8)	3.2	14.7	8.9	19.2	(63.1)	0.0	1.1	1.1
Jiangsu	900.6	(93.3)	3.6	5.0	4.3	1170.1	(90.1)	28.0	30.7	29.4	461.8	(97.4)	4.2	5.3	4.7	1371.9	(70.2)	19.6	52.8	36.2	403.7	(78.1)	0.0	13.9	13.9
Zhejiang	1079.4	(95.2)	3.9	5.1	4.5	835.4	(91.0)	20.1	21.9	21.0	226.6	(96.9)	2.2	2.6	2.4	1114.5	(65.7)	12.9	40.0	26.4	148.9	(75.7)	0.0	7.3	7.3
Anhui	529.6	(91.8)	1.6	2.7	2.2	946.4	(91.6)	25.4	27.7	26.6	431.9	(97.7)	3.9	4.5	4.2	784.3	(82.2)	13.7	33.8	23.8	329.0	(77.7)	0.0	13.9	13.9
Fujian	448.1	(93.1)	1.6	2.3	1.9	622.0	(86.8)	9.7	12.0	10.8	170.7	(96.0)	1.6	1.9	1.7	473.2	(69.7)	6.0	16.7	11.3	178.3	(79.7)	0.0	8.6	8.6
Jiangxi	344.4	(90.8)	1.0	1.6	1.3	471.9	(86.8)	9.3	10.6	10.0	222.0	(96.6)	1.9	2.4	2.2	354.1	(75.6)	6.3	13.3	9.8	242.3	(80.0)	0.0	14.4	14.4
Shandong	1993.4	(90.4)	7.8	10.8	9.3	2168.8	(91.3)	41.5	48.4	45.0	798.0	(95.3)	4.7	5.9	5.3	1667.4	(70.7)	26.5	60.3	43.4	579.2	(76.7)	0.0	24.4	24.4
Henan	837.9	(90.0)	3.0	4.2	3.6	1458.2	(90.8)	32.8	36.6	34.7	660.6	(95.4)	4.4	5.2	4.8	1033.6	(77.7)	18.9	40.5	29.7	748.2	(78.9)	0.0	30.7	30.7
Hubei	971.8	(87.4)	3.6	6.0	4.8	858.3	(87.8)	17.6	20.6	19.1	470.0	(92.8)	3.4	4.0	3.7	710.7	(76.9)	10.0	25.7	17.9	440.5	(76.7)	0.0	19.9	19.9
Hunan	683.6	(87.5)	2.5	3.7	3.1	667.6	(87.3)	14.1	16.1	15.1	325.1	(91.1)	2.9	3.4	3.1	512.6	(74.0)	8.6	19.0	13.8	471.6	(81.4)	0.0	26.9	26.9
Guangdong	885.4	(92.9)	3.5	5.1	4.3	1253.5	(88.2)	27.2	31.2	29.2	357.4	(96.5)	3.3	3.8	3.5	1182.8	(71.1)	18.8	43.7	31.2	350.6	(78.5)	0.0	16.6	16.6
Guangxi	571.4	(91.3)	2.0	2.8	2.4	493.5	(87.7)	10.0	11.5	10.7	319.6	(96.9)	2.6	3.0	2.8	506.0	(77.5)	11.1	22.4	16.8	322.3	(81.0)	0.0	16.0	16.0
Hainan	71.7	(95.2)	0.2	0.3	0.3	97.9	(89.3)	1.7	2.0	1.8	28.6	(96.7)	0.4	0.4	0.4	96.0	(70.7)	1.4	3.7	2.5	56.8	(77.1)	0.0	2.7	2.7
Chongqing	816.4	(87.3)	3.4	4.6	4.0	393.1	(88.0)	8.9	10.1	9.5	186.2	(93.4)	1.7	1.9	1.8	311.0	(79.3)	4.7	12.5	8.6	203.7	(78.7)	0.0	9.6	9.6
Sichuan	1388.6	(90.1)	5.1	7.6	6.3	848.4	(87.4)	16.3	19.3	17.8	522.6	(97.4)	4.8	5.4	5.1	1002.0	(83.2)	17.0	45.1	31.0	714.5	(80.2)	0.0	35.1	35.1
Guizhou	856.7	(84.1)	3.9	5.0	4.4	500.1	(87.3)	7.6	9.0	8.3	313.9	(87.1)	3.0	3.3	3.2	301.5	(84.2)	4.7	9.7	7.2	202.0	(72.9)	0.0	9.2	9.2
Yunnan	375.9	(87.9)	1.0	1.7	1.4	438.8	(87.9)	9.4	10.5	9.9	240.3	(93.0)	2.2	2.6	2.4	334.3	(80.5)	6.7	12.3	9.5	393.8	(80.2)	0.0	17.3	17.3
Xizang	3.3	(92.8)	0.0	0.0	0.0	22.1	(94.1)	0.8	0.8	0.8	6.0	(98.1)	0.1	0.1	0.1	13.0	(88.2)	0.5	0.7	0.6	70.9	(78.9)	0.0	2.6	2.6
Shaanxi	622.2	(87.9)	2.9	3.5	3.2	592.0	(89.7)	11.5	13.0	12.3	301.1	(95.0)	2.5	2.9	2.7	430.4	(78.5)	6.0	13.4	9.7	210.2	(76.3)	0.0	6.4	6.4
Gansu	247.4	(88.8)	0.9	1.5	1.2	320.6	(88.9)	8.6	9.3	8.9	166.7	(93.8)	1.4	1.7	1.5	206.9	(80.7)	3.8	7.5	5.7	158.0	(76.8)	0.0	5.6	5.6
Qinghai	42.6	(88.5)	0.1	0.3	0.2	97.7	(88.5)	2.1	2.4	2.2	43.9	(91.9)	0.4	0.4	0.4	46.2	(81.0)	0.9	1.6	1.3	65.6	(76.8)	0.0	2.6	2.6
Ningxia	238.0	(93.9)	1.1	1.4	1.2	190.4	(91.5)	3.5	4.0	3.8	80.1	(97.2)	0.4	0.6	0.5	71.3	(79.7)	1.3	2.2	1.7	46.0	(74.7)	0.0	1.2	1.2
Xinjiang	721.3	(93.9)	2.7	3.9	3.3	696.3	(93.5)	9.6	11.8	10.7	209.1	(95.5)	1.4	1.8	1.6	272.5	(76.6)	4.2	8.5	6.3	260.7	(76.8)	0.0	6.5	6.5
Total	19192.9	(89.7)	75.0	110.0	92.5	20760.5	(89.9)	439.0	500.4	469.7	9117.6	(94.6)	68.3	83.0	75.7	17181.9	(74.0)	265.5	632.4	449.0	8359.3	(78.0)	0.0	361.8	361.8

MPR[a]: Maximum potential reduction emissions, unit: kt; (%) represents the reduction ratio to that in 2014.
Total Cost[b]: Calculated by average cost and the range of cost is in supplementary information, unit: billion.
NH_3^c: the low cost of ammonia is zero for uncontrolled in China at present.

vehicle, respectively. Specifically, the reduction potential of VOCs emissions for vehicle material cycle mainly focuses on vehicle fluids (i.e., windshield washer fluid) and vehicle manufacturing (notably the painting process). The maximum potential reduction of NH_3 in the livestock and fertilizer applications was 5352 and 3254 kt with a total cost of 347.7 billion and 14.1 billion, respectively. The unit cost of NH_3 in livestock was the highest in all sectors which indicated it was more difficult and expensive to reduce NH_3.

In summary, the total abatement cost of the five major air pollutants was up to 1448.6 billion CNY (219.6 billion USD), of which 801.5 billion CNY (121.5 billion USD) went toward the EOP scenario (Table 3). Under REN scenario, the abatement costs of NO_x and NMVOCs were five to six times higher than SO_2 and $PM_{2.5}$, at 469.7 billion CNY and 449.0 billion CNY compared with 92.5 billion for SO_2, 75.7 billion CNY for $PM_{2.5}$, and 361.8 billion CNY for NH_3. The total cost for SO_2, NO_x, primary $PM_{2.5}$, and NMVOCs under REN scenario was 2.2, 4.8, 1.8, 1.8 times higher than that of the EOP scenario, respectively. High NO_x and NMVOCs costs were associated with lower removal percentages and utilization rates with higher marginal abatement costs for denitrification and NMVOCs extraction.

3.4. Relationship between abatement cost and local economy

We also investigated the relationship between unit abatement costs and the local economy at a provincial level, as displayed in Fig. 4. The R was the percentage of national GDP produced in each province in 2014. The lager the R value, the higher the ratio of GDP. The slope represents the unit cost of abated emissions (the purple line represents the national average). Generally, the total abatement cost increases along with the total abatement potential. However, differences in slopes are still noticeable among provinces.

For SO_2, two types of regions exhibited cost-effective reduction emissions; one represents high GDP province with intensive industries (i.e., Zhejiang, Shandong), and another represents lower GDP province with high sulfur content of coal that facilitates reduction of SO_2 emissions (i.e., Sichuan). A better quality of coal with low sulfur constant results in a higher unit cost of emission abatement, as in Inner Mongolia, which is the main coal mining and renewable energy supply areas, as explained in previous study (Dong et al., 2015). In addition, the less cost-effective regions were Beijing, Tianjin, and Shanghai, which showed relatively lower potential reduction. That is because the end-of-pipe measures have been fully implement in those developed eastern regions, and the unit cost raise for further reduction is highly depended on the renewable energy application.

For NO_x, the cost-effective reduction regions were Inner Mongolia, Xinjiang, and Guizhou provinces. The least cost-effective regions were located in the provinces with high potential abatement and high population density and vehicle population, including Beijing, Shandong, Henan, Hebei, Guangdong, Jiangsu, Anhui, and Zhejiang.

For primary $PM_{2.5}$, Shandong, Henan, and Hebei provinces exhibited considerable potential abatement and high costs to control. The most cost-effective region was Shanxi, whereas the least cost-effective regions included Hainan, Tibet, and Qinghai.

For NMVOCs, higher potential abatement and total cost were recorded in developed areas, such as Shandong, Jiangsu, Guangdong, Sichuan, Henan, and Zhejiang province.

For NH_3, the potential abatement regions included some major agricultural provinces, such as Sichuan, Henan, Hunan, and Shandong. In summary, it is crucial to focus on regional disparity, different economic levels and energy structures in the policy-making process to improve general air quality in China.

4. Discussion

4.1. Power generation

Up to 67.1% of China's power generation comes from coal-fired plants according to the inventory of power plants in 2014 (Zheng et al., 2019). For SO_2, the flue gas desulfurization (FGD) is the major control measure in China with an installed capacity of 824 GW in 2014. As the share of FGD technology installed in coal-fired unit increased from 12.0% in 2005 (Wang et al., 2014) to 97.0% in 2014, SO_2 emission from power generation sector have been substantially reduced by 67%. For NO_x control, low-NO_x burners (LNB), selective catalytic reduction (SCR), and selective non-catalytic reduction (SNCR) are the major control technologies used in China's coal-fired power plants, and their installed capacity was approximately 289 GW, 15.9 GW, and 534 GW in 2014, respectively. The share of installed denitrification facilities in coal-fired unit increased to 63.0% in 2014 from 1.1% in 2005 (Wang et al., 2014), resulting in a considerable reduction in NO_x emissions from the power generation sector by 22.5%. The control technologies for primary $PM_{2.5}$ in China's power generation sector include fabric filter (FFs), electrostatic precipitators (ESPs) and a combination of FFs and ESPs, and their installed capacities are 9.1% (7.5 GW), 77.1% and 13.8% (11.4 GW) in 2014, respectively, reported by National Bureau of Statistics of China (NBS) (National Bureau of Statistics, 2015). The average removal efficiency of primary $PM_{2.5}$ was over 99.75% from the coal-fired power sector in 2014, which signifies in a limited reduction potential in primary $PM_{2.5}$ from the coal-fired power sector.

4.2. Iron and steel plants

Emissions of SO_2, NO_x, and primary $PM_{2.5}$ are generated from multiple processes in the iron and steel industry. Up to 70% SO_2 emission in the industry are from the sintering process where end-of-pipe measures such as FGD, circulating fluidized bed technology (LJS-FGD) and activated carbon absorbing technology can be implemented (National Bureau of Statistics, 2015). SCR is selected to control NO_x during the production process. Primary $PM_{2.5}$ is emitted mostly during iron-making, steel-making and steel-rolling processes. In this study, the capital cost and FOM cost were collected for each end-of-pipe control measure during the whole process of production. The unit cost of the end-of-pipe measures per pollutant abatement was calculated based on the cost and emission inventory. The activated carbon absorbing method for SO_2 has been employed at several steelmaking plants as listed in Table S4. Compared with conventional FGD technology, activated carbon absorbing exhibits a higher efficiency for its simultaneous reduction of both SO_2 and NO_x, providing potential for achieving further reduction in the future (Yang et al., 2011). Different cost parameters can be applied in different sectors even for the same measures of each pollutant. For example, the unit cost of SCR in iron and steelmaking was 24300–27070 CNY/t, which was much higher that of in other sectors, such as, the average unit cost of SCR in power generation was 9733 CNY/t. This is because many more procedures are required in the whole process for iron and steelmaking than for power generation.

4.3. Cement production

In 2012, the demand for cement in China was recorded at 2184 Mt, which accounts for 58% of the total consumption worldwide (National Bureau of Statistics, 2013). Consequently, cement manufacturing has a notable environmental impact and contributes considerably emissions in China (Zhang et al., 2015). For SO_2, combustion of fuel with high sulfur content was the major source of emission (Zhang et al., 2015). FGD devices can be equipped to reduce SO_2 levels. In 2014, approximately 668 denitrification facilities for cement clinker production were equipped with SNCR technology to reduce NO_x emissions (National Bureau of Statistics, 2013). The primary sources of $PM_{2.5}$ emissions in

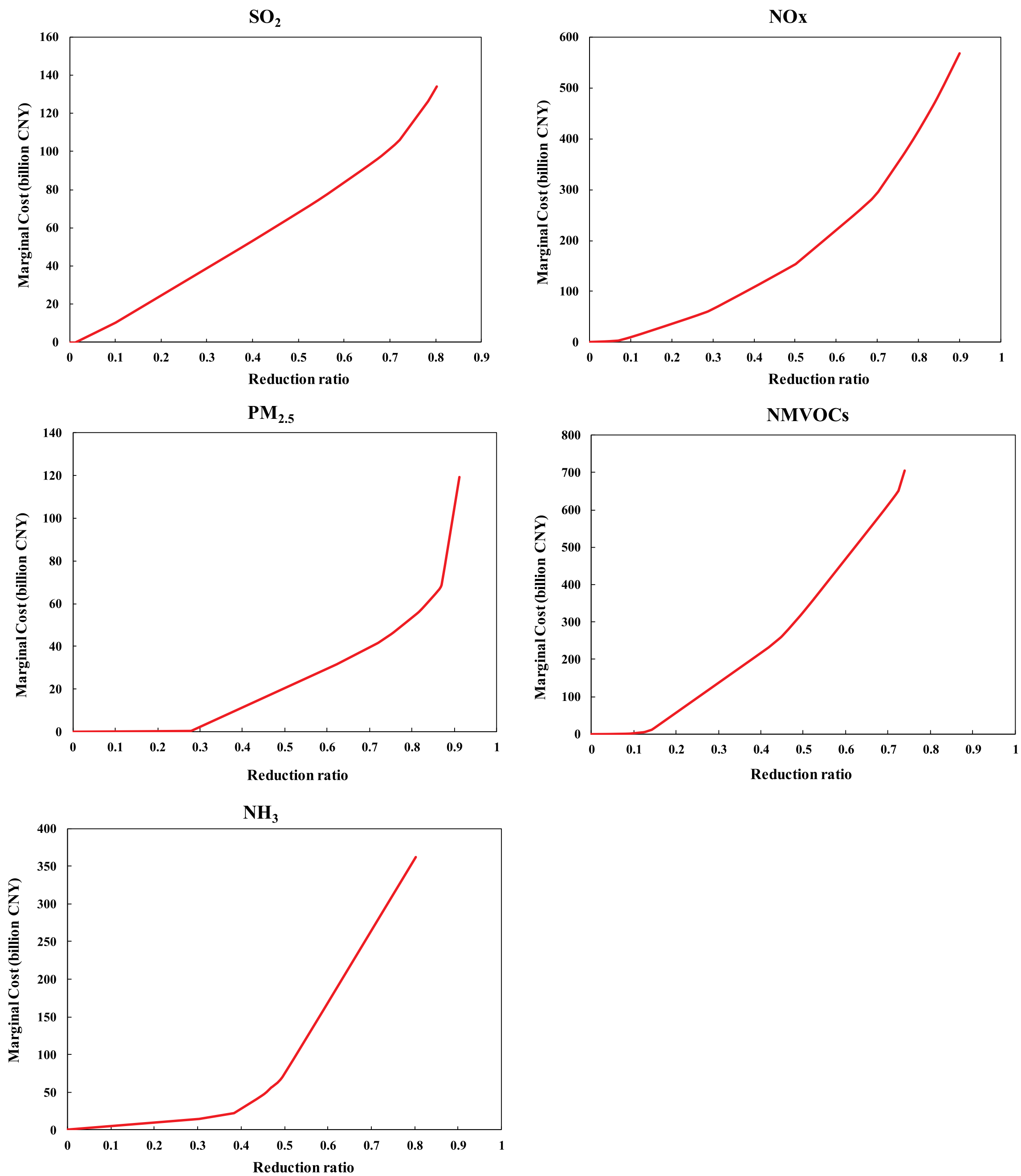

Fig. 2. The marginal abatement cost of multi-pollutants in China.

cement production are mainly the grate cooler, kiln inlet, coal mill and cement mill. ESP and FF technologies can be implemented to capture the primary $PM_{2.5}$ during production process. The initial investment cost and FOM cost were investigated from field investigation of nearly 150 cement plants in this study (Table S9). Similarly, the annual average capital cost and total cost of measures implemented in cement, were listed in Table S5, were calculated by Eqs. (1) and (2), respectively. The total cost of unit cement clinkers was estimated between 10.98 and 12.99 CNY/t, which is consistent with that reported by Ministry of Ecology and Environment (MEE) of China in 2012, which was 12–15 CNY/t for the combination of denitrification and de-dusting (Ministry of Ecology and Environment, 2012).

4.4. Transportation sector

The government issued a series of emission standards for new vehicles in China and the implementation times are listed in Table S10. For light duty vehicles, the China I, II, III, IV, V standards came into effect nationwide in 2000, 2005, 2008, 2011 and 2017 respectively. The China Ⅵ standards will be adopted in 2020. For megacities such as Beijing and Shanghai, vehicle standards went into force 2–3 years earlier than other provinces because of the more severe air pollution problems in such regions. In general, control measures of NO_x and VOCs from vehicle emissions in China include improvement of catalyst and fuel injection methods, improvement of the construction of engine combustion chambers, and updates to on board diagnostics systems. As summarized in Table S11, the unit cost and emission abatement tend to increase with the vehicle standards revision, according to the database of Tsinghua University, government documents, and the GAINS-Asia dataset. The stricter the standards are, the higher the unit cost of removing vehicle exhaust is. The unit cost with implementation of China VI instead of China V in the transportation sector will be approximately

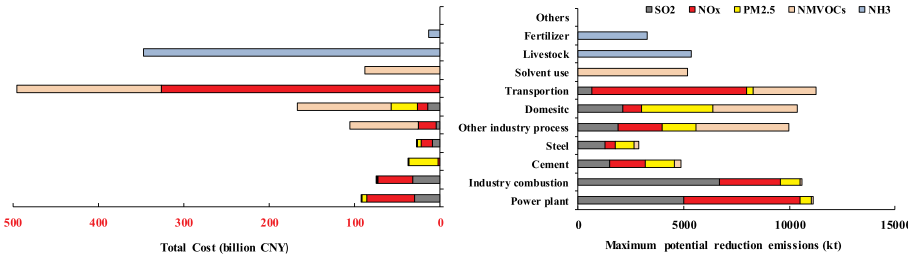

Fig. 3. The abatement potential and total cost in sectors.

1100–1700 CNY per vehicle, and the total cost will be over 25.5 billion CNY/year for light duty vehicles (China VI), as announced by the MEE in 2016 (Ministry of Ecology and Environment, 2016). For NO_x, the unit cost of diesel vehicles will be much higher than that for gasoline vehicles, especially for diesel high-duty trucks (HDT-D). Moreover, the unit cost for diesel vehicles to remove VOCs is approximately four times that of gasoline vehicles. The VOCs of vehicles are more difficult and expensive to control than NO_x. The unit cost for ships are approximately 10 times than that for automobiles, which means that the shipping sector is facing considerable challenges in controlling emissions.

4.5. NMVOCs-related sector

The major anthropogenic sources of NMVOCs are solvent use and fossil fuel distribution which accounted for 37.3% and 33.7% of the total NMVOCs emission in 2010, respectively (Fu et al., 2013). China's government issued national standards to control NMVOCs in 2000, and these controls subsequently gained considerable research interest (Wei et al., 2011). Nevertheless, the end-of-pipe technologies listed in Table S7 are still not widely used. For examples, control measures for NMVOCs are only implemented in areas related to fossil fuel exploitation and distribution in China, where the applicate rate increased from 5% in 2010 to 12% in 2014 (Wang et al., 2014; Zhao et al., 2017). In addition, there is still a lack of highly-efficiency measures in most industrial process (Wei et al., 2008).

In this study, the end-of-pipe measures were assumed to be fully applied in the chemical industrial process, solvent use, transport and industrial combustion when we calculated the maximum potential reduction emissions. Based on our previous studies (Fu et al., 2013; Wang et al., 2014; Wei et al., 2008, 2011), the activity data including annual product, technology and pollution control facilities, as well as the unit cost of end-of-pipe technologies were collected from statistical yearbook, surveys, and the dataset in GAINS-Asia model. Because of the uncertainty of control measures used in the production of coke oven, painting, adhesive, ink, pharmacy, as well as in food processing, the control technologies were all treated as end-of-pipe control measures, and the related cost were referenced to the database in the GAINS-Asia model, as summarized in Table S7. Direct incineration, activated carbon adsorption, substitution, and primary measures (i.e., leak detection and repair program, and good housekeeping) are the main end-of-pipes measures for most NMVOC-related sectors. The range of unit cost was from 0 to 83,200 CNY/t and the average unit cost was calculated from 9642 to 25,111 CNY/t NMVOCs in different sectors, which indicates that NMVOCs are more expensive than other pollutants (i.e., SO_2 and primary $PM_{2.5}$) in terms of air quality management.

Table 3
The potential reduction emissions and total cost of EOP and REN scenarios.

Pollutants	EOP		REN	
	Reduction emission/Mt	Total cost/ billion CNY (USD)	Reduction emission/Mt	Total cost/ billion CNY (USD)
SO_2	14.8	42.2 (6.4)	19.2	92.5 (14.0)
NO_x	13.0	97.8 (14.8)	20.8	469.7 (71.2)
$PM_{2.5}$	5.4	43.2 (6.5)	9.1	75.7 (11.5)
NMVOCs	13.1	256.4 (38.9)	17.2	449.0 (68.1)
NH_3	8.6	361.8 (54.9)	8.6	361.8 (54.9)
Total Cost/ billion CNY	–	801.5 (121.5)	–	1448.6 (219.6)

Note: At the average exchange rate (6.5962) form the year of 2008–2018.

4.6. NH_3-related sector

Livestock rearing and fertilizer use are the dominant sources for NH_3 emissions, accounting for 88% of NH_3 emissions in China in 2000 (Wang et al., 2015). Currently, limited NH_3 controls have been instigated in China. In this study, we investigated all available NH_3 emission control measures from the database of GAINS-Asia model because of the lack of local information. The range of unit cost for reducing NH_3 was from 8905 to 66,241 CNY/t in the livestock sector; we selected high-efficiency technologies ($\geq$80%) including animal house adaption, low NH_3 application, covered outdoor storage of manure, and a combination of the aforementioned, to calculate the maximum potential reduction emission. For fertilizer use, urea substitution is suitable for reducing NH_3 and economically with a unit cost of 4348 CNY/t.

5. Conclusion

The results revealed that the total maximum abatement potentials of SO_2, NO_x, primary $PM_{2.5}$, NMVOCs, and NH_3 in China are 19.2, 20.8, 9.1, 17.2, and 8.6 Mt, respectively. For the end-of-pipe control measures, the industrial sector, including cement production, iron and steel production, and other industrial processed (i.e., oil refining, glassmaking and the chemical industry), remains the largest source of abatement potential nationwide. Compared with other regions, Shandong province has the most abatement potential followed by Sichuan, Hebei, and Henan provinces.

The application of renewable energy can further reduce the pollutants but with much higher costs though end-of-pipe controls. The results suggest that the emission of SO_2, NO_x, $PM_{2.5}$, and NMVOCs will be further decreased by 89.7%, 89.9%, 94.6%, and 74.0% under REN scenario based on 2014 emission level. Comparing the limitations of conventional EOP technologies, the application of renewable energy to replace fossil fuel could result in further reduction of pollutants, which signifies that renewable energy can be alternative to end-of-pipe measures in the future.

Different control measures should be implemented based on the local industrial structure and economy level. For SO_2 and NO_x, the end-of-pipe technologies employed in industrial processes were more cost-effective than those employed in fossil fuel-related sectors. The application of renewable energy could significantly increase the marginal

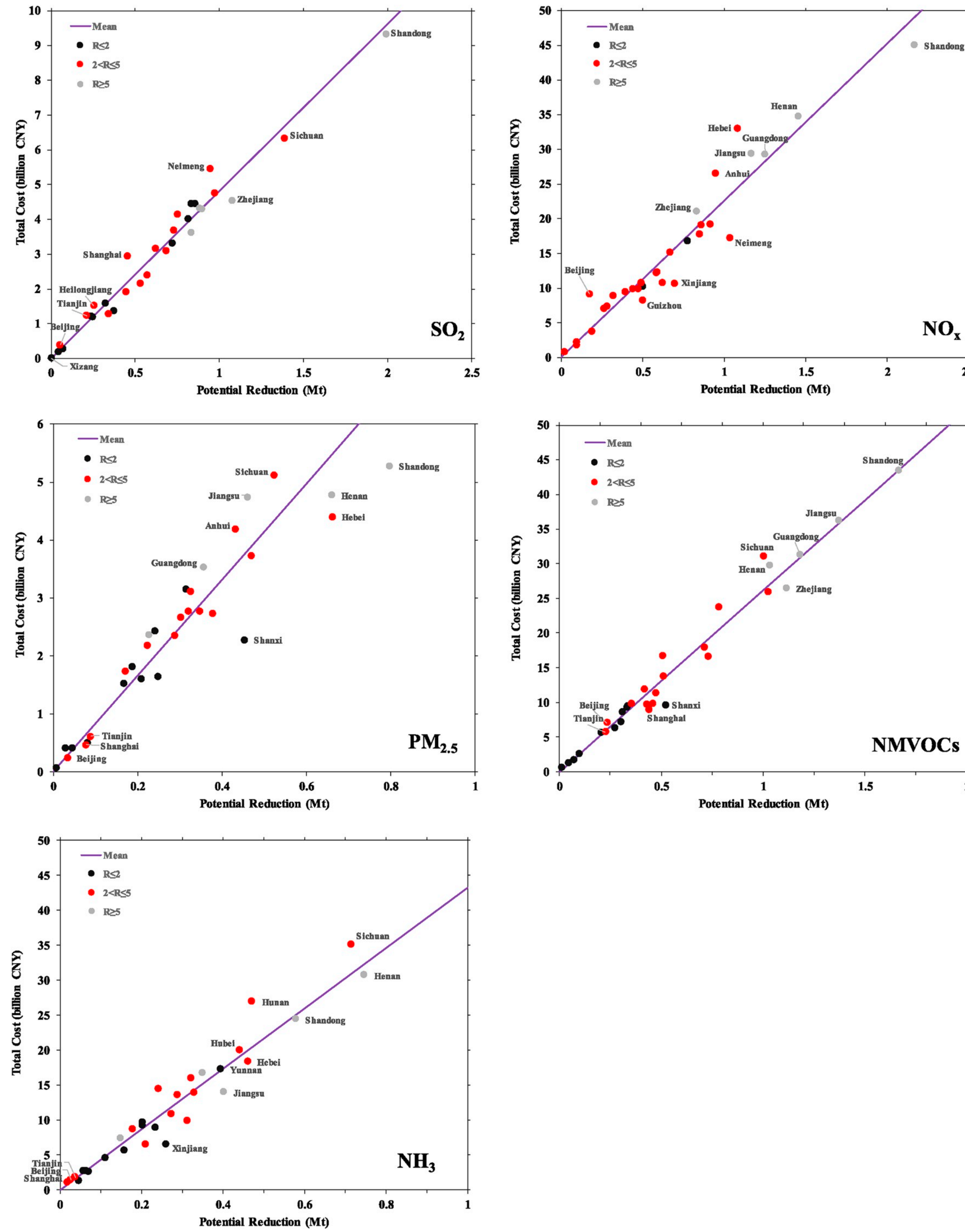

Fig. 4. The unit costs of abated air pollutants at provincial level with local economy.

abatement cost for further reduction, especially for SO_2 and NO_x. For primary $PM_{2.5}$, the total cost in cement plants was still higher than in other sectors, suggesting the need to implement more stringent end-of-pipe controls. However, end-of-pipe technology, as a matter of priority, can still be a cost-efficiency way to control NMVOCs and NH_3, which both have considerable abatement potential in China. Differences in the economic level among provinces should also be taken into consideration when designing control policies. Provinces with higher potential abatement emissions are developed regions with higher GDPs, such as Shandong, Jiangsu, Henan, Zhejiang, and Guangdong provinces. However, the least-effective regions with high GDP, including Beijing, Shanghai, and Tianjin, have high unit abated costs because of the limited potential reduction.

This study gathered available information regarding marginal abatement costs and the application rate of control measures, and it further calculated the corresponding emission abatement and associated costs in China. This analysis and costs assessment can contribute to an integrated assessment model (e.g., ABaCAS) to design cost-effective control strategies for policymakers to improve air quality. The marginal abatement cost curves developed in this study can also be used in combination with an air quality model simulation, to further evaluate the cost-effectiveness of abatement policies designed to achieve certain ambient air quality targets.

CRediT authorship contribution statement

Fenfen Zhang: Methodology, Writing - original draft. **Jia Xing:** Methodology, Writing - original draft, Writing - review & editing. **Yang Zhou:** Writing - review & editing. **Shuxiao Wang:** Writing - review & editing. **Bin Zhao:** Writing - review & editing. **Carey Jang:** Writing - review & editing. **Yun Zhu:** Writing - review & editing. **Jiming Hao:** Writing - review & editing.

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Appendix A. Supplementary data

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