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# Will joint regional air pollution control be more cost-effective? An empirical study of China's Beijing–Tianjin–Hebei region

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ABSTRACT

By following an empirical approach, this study proves that joint regional air pollution control (JRAPC) in the Beijing–Tianjin–Hebei region will save the expense on air pollution control compared with a locally-based pollution control strategy. The evidences below were found. (A) Local pollutant concentration in some of the cities is significantly affected by emissions from their surrounding areas. (B) There is heterogeneity in the marginal pollutant concentration reduction cost among various districts as a result of the cities' varying contribution of unit emission reduction to the pollutant concentration reduction, and their diverse unit cost of emission reduction brought about by their different industry composition. The results imply that the cost-efficiency of air pollution control will be improved in China if the conventional locally based regime of air pollution control can shift to a regionally based one.



## 1. Introduction

Environmental economists traditionally believe that if the cost heterogeneity of air pollutant control exists, market-based instruments can lead to cost savings compared to command-and-control policies for all involved jurisdictions (Tietenberg, 1985; Newell and Stavins, 2003; Rezek and Blair, 2005; Bergin et al., 2005). The cost-effectiveness of market-based instruments, inherently, depends on setting up the policy objective to minimize overall costs for reducing a given quantity of pollutant emissions. In China's environmental strategy, mitigation goals on pollutant emissions dominated the environmental agenda in the 11th and 12th Five-Year Plans (2006–2015) to suggest the potential application of market-based instruments. However, in order to address the mounting complaints about air quality from the general public, the Chinese central government in the *Action Plans on Air Pollution Prevention and Control* (announced in September 2013) switched the strategy to directly control air pollutant concentrations (State Council, 2013). Indeed, air quality is closely related to not only the quantity but also to the time and location of pollutant emissions as well as the meteorological conditions. Accordingly, the conventional wisdom on the cost-effectiveness of market-based instruments may not be directly applicable to cost-effectively improve air quality. A key factor for maintaining the applicability is the cost heterogeneity of reducing air pollutant concentrations, which will be empirically tested in the integrated Beijing–Tianjin–Hebei region (hereinafter called the 'Jing–Jin–Ji' region – Jing for Beijing, Jin for Tianjin, and Ji for Hebei), the most polluted of the three pollution centers distinguished in the 2013 *Action Plans on Air Pollution Prevention and Control*.

Marginal Abatement Cost (MAC) curves are often constructed to conduct analysis of emission reduction quantity with cost-effectiveness or potential cost savings from implementing a market-based instrument, for but not limited to pollution and climate change issues. The MAC curves can be constructed either by individually assessing the cost and abatement potential of abatement measures or investigating the relation between emission reduction quantity and the price of emission in system models, such as in computable general equilibrium models (Kesicki and Strachan, 2011). Given the consideration of more intuitively understanding the cost heterogeneity stemming from the heterogeneities embedded in the economic development differences across the region, the former approach, 'expert-based MAC' (Kesicki and Strachan, 2011), is derived in our study.

Aiming at air quality improvement, it is the pollutant concentration alleviation that ultimately indicates the quality changes but not the quantity of the emission reductions. In the integrated assessment model, such as RAINS (The Regional Air Pollution

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Information and Simulation) and GAINS (The Greenhouse gas-Air pollution Interactions and Synergies), pollutant concentration is used as the constraint to conduct optimization for making control schemes. However, pollutant concentration alleviation cost curves were seldom used in the past literature, according to the authors' acknowledge. The major reason may be that environmental economists can collaborate with the atmospheric physicists and atmospheric chemists while maintaining a large independency at the same time by using an integrated model as finding the control scheme with the lowest abatement cost. Despite cost optimization being fulfilled in the integrated model, pollutant concentration alleviation cost curves are still helpful for each individual jurisdiction in a region in order to understand the possibilities of its own actions. Hence, in this study, we try to further construct a marginal pollutant concentration alleviation cost (MCAC) curve based on the MAC curve.

The contribution of this study is to empirically test the cost heterogeneity in our targeted area by investigating the marginal cost curves. Therefore, we do not consider developing a methodology to measure the heterogeneity at a given level of cost but rather we focus on constructing cost curves. To explore a general relation between the cost heterogeneity and the magnitude of the potential cost savings, such as Newell and Stavins did in their 2003 paper, is not our emphasis. Because of that this study is based bottom-up and the magnitude of cost savings from implementing market-based instruments depends on a series of factors including the level of control target and the detailed policy setting etc.; the cost savings will not be quantified comprehensively but revealed in some specific case.

To address the severe regional air pollution status in China, it is necessary to put cost heterogeneity analysis into a regional framework. Studies in China show that the three major city clusters (the Jing–Jin–Ji region, the Yangtze River Delta and the Pearl River Delta) suffer from severe trans-boundary air pollution (He et al., 2009; Huang et al., 2010; Wang et al., 2008). Although there are no comprehensive and accurate results, basic conclusions concerning seasonal features of the regional impact of certain specific pollutants have been confirmed. The situation of our targeted region, the Jing–Jin–Ji region, will be introduced in the later paragraphs of this section.

In this study, we define all the possible regimes that allow each jurisdiction to improve its own air quality by abating pollutant emissions in the surrounding areas as the regime of "joint regional air pollution control" (JRAPC). On the contrary, the locally based approach is defined oppositely, *i.e.*, each jurisdiction can only improve its air quality by local emission abatement efforts. To demonstrate that there is heterogeneity of the concentration alleviation cost between the Jing–Jin–Ji cities is to prove that JRAPC can improve the cost-effectiveness in this region.

One thing which must be noticed is that there is a difference between pollution control with and without regional cooperation, although the emission reduction in the surrounding area could contribute to the air quality improvement in the center jurisdiction in both situations. Without regional cooperation, the center area cannot set control goals for the surrounding area so as to make it contribute to its own air quality, but it can do that if there is regional cooperation. From the perspective of the emission sources, with regional cooperation, the control scheme of one jurisdiction is constrained by both the control target that sets its own quality improvement and that set by the other jurisdictions which it cooperate with for enhancing their air quality.

Globally, there are several examples of pollution control regulations and regimes designed to address transboundary air pollution. These include, for example, the South Coast Air Quality Management District (SCAQMD) in California, U.S.A.; the Ozone Transport Region (OTR) in the eastern U.S.A.; and the Convention on Long-range Trans-boundary Air Pollution (CLRTAP) in Europe (Bergin et al., 2005; Wan et al., 2010). To cope with the regional compound air pollution problem, in May 2010, the Ministry of Environmental Protection (MEP) together with eight other ministries promulgated guidelines promoting multi-pollutant and regional air pollution control to improve regional air quality. The guidelines recommend the implementation of environmental impact assessments and improvements in inter-district coordination at the regional level as well as the facilitation of industry structure adjustments on a regional scale (MEP, 2010). In practice, however, few regional environmental management cooperation practices are in use in China due to the lack of institutional arrangements. In spite of recent efforts promoting regional level air pollution control initiatives aimed to ensure good air quality in Chinese cities hosting mega-events (*i.e.*, Beijing during the 29th Olympic Games in 2008, Shanghai during the 2010 World Expo, Guangzhou during the 16th Asian Games in 2010, and Shenzhen during the 26th Universidade in 2011), these initiatives were active only in the short term. Basically, the current regulatory system and regulations are still mainly applied as a patchwork of separate, locally based pollution control regimes in China. This paper aims to provide guidance for making regional control policies although it does not concentrate on the analysis of specific policy design.

In the Jing–Jin–Ji region, Beijing has invested significant efforts and resources in air pollution control since the late 1990s; the city's air quality, however, continues to worsen. The deterioration can be ascribed to two major factors: the significant increase in the number of motor vehicles in Beijing in the last ten years, and the rapid development of heavy-polluting industries in the surrounding provinces, accompanied by large amounts of pollutants being transported inadvertently to Beijing (Parrish and Zhu, 2009). Because the frequency and severity of the haze has worsened in the city, joint regional air pollution control in the Jing–Jin–Ji region has become an urgent issue. This region contains thirteen cities, but our study involves only the following nine: Beijing (BJ); Tianjin (TJ); Shijiazhuang (SJZ); Chengde (CD); Zhangjiakou (ZJK); Tangshan (TS); Langfang (LF); Baoding (BD); and Cangzhou (CZ). The spatial locations of the cities in the Jing–Jin–Ji region are shown in Fig. 1. The socio-economic status of this region is introduced in Appendix A.

## 2. Methodology

### 2.1. Cost estimation

Technologies involved in this study were chosen according to their applicability and universality in the energy-intensive industries as well as the available data. The industries are the coal-fired electricity industry; the iron and steel industry; the cement industry; the petrochemical industry; the chemical industry; the mining industry; and the heating industry. Fuel combustion in the above industries (apart from electricity) is an important contributor to pollutant emission. Therefore, the industrial boiler is also listed as a category here. A part of the technologies are specifically being used to affect the removal of pollutants, including $SO_2$, $NO_x$ and PM; and others can be classified as energy-saving technologies. The technologies involved and their corresponding industry category are listed in Appendix B.

For the energy-saving technologies, we kept them for analysis for three reasons. Firstly, as a result of policies regulations, energy saving will still be a key issue among the industries in the near future. In addition, we want to exhaust the measures that remove pollutant emissions. Secondly, in China, before 2009 (the baseline of the cost curve constructed in the study), energy-saving

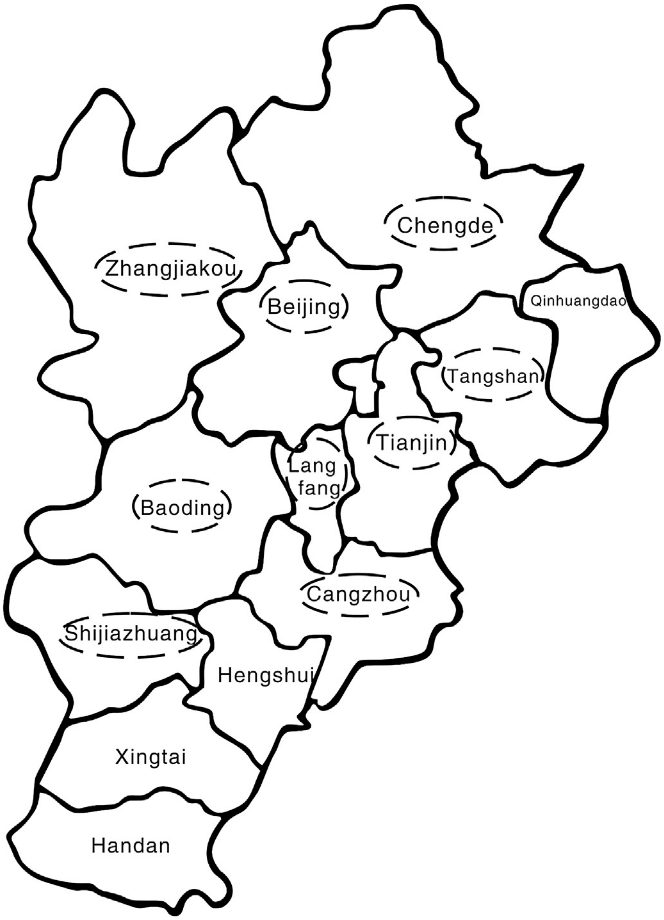



**Fig. 1.** The spatial location of the cities in the Jing–Jin–Ji region (circled cities are studied).

technologies were not broadly used in the industries. Thirdly, the energy-saving technologies involved in the study have been partly proposed in the 12th Five Year Plan for energy saving and pollution control in Hebei province, which plan was announced in 2012 (Hebei Property Rights Exchange Center, 2012). This also justifies the possible use of the technologies in the near future.

We estimated the annual cost of air pollution control technologies based on the initial investment and the operation and maintenance costs. The equivalent annual cost of the *i*th technology is represented by the following equation:

$$C_i = C_{F,i}\cdot\left((1+r)^n\cdot r/\left((1+r)^n-1\right)\right)+C_{V,i}$$

where $C_i$ is the equivalent annual cost of the *i*th control technology, $C_{F,i}$ represents the initial cost, $C_{V,i}$ represents annual operation and maintenance costs, *r* is the discount rate, and *n* equals the expected lifetime of the equipment. For some technologies, we used interview data to estimate $C_i$, while for other technologies, we used data from official sources and relevant literature for the estimation.

Based on the annual cost of technology *i*, $C_i$, the unit cost of the removal of pollutant *p* by use of the technology *i*, $uc_{i,p}$, is calculated in accordance with the following formula: $uc_{i,p} = C_i/A_{i,p}$. $A_{i,p}$ represents the annual pollutant emissions reduction of pollutant *p*. Similarly, the unit cost of coal savings by utilizing energy-saving technology *i*, $uc(s)_i$, is calculated by dividing $C_i$ by the annual coal savings, $s_i$, as shown in the following formula: $uc(s)_i = C_i/s_i$. It should be noticed that the revenue brought by energy-saving technologies is not considered in this study. When the unit cost of coal savings is available, it can be converted into the unit cost of the removal of pollutant *p*, assuming that reducing coal consumption by the percentage of $r_{i,p}$ can reach an equivalent removal rate of pollutant *p*, $r_{i,p}$, through the use of technology *i*. The parameter value is shown in Appendix B.

Compared to other technologies, central heating and the co-generation of power and heat are exceptional. The incremental costs of these two measures should be estimated based on previous heating conditions. Therefore, the incremental cost of central heating technology is estimated as the increased cost from the use of individual heating technologies. The incremental cost of power and heat co-generation is estimated as the increased cost from the use of separately generated power and heat. In addition, the substitution of coal with natural gas is analyzed based only on the investment cost of updating the facility.

### 2.2. Cost curve

In this study, the key indicator is the pollution control cost curve. Two cost indicators are used: the cost of pollution abatement, and the cost of pollutant concentration alleviation.

#### 2.2.1. Marginal pollutant abatement cost curve

A city's marginal pollutant abatement cost can be expressed as $MC_p = uc_{i,p}$ (when $x = \sum Q_{i,p}/E_p,\ i = 1,2,\ldots,m$). $Q_{i,p}$ is the emissions reduction of pollutant *p* by the use of technology *i* in those industries in which it can be applied. $E_p$ represents the total emissions of pollutant *p* from the city under analysis. $\sum Q_{i,p}/E_p$ is the cumulative percentage of the emissions reduction of pollutant *p* by applying technology 1 to *i* for the analyzed city.

The technologies applied in the corresponding industries are ranked in an order of lowest unit costs of pollutant removal to the highest one. The unit cost of pollutant removal, $uc_{i,p}$, is then projected to a cumulative percentage of the emissions reduction of pollutant *p* in each city, which is draw on the *x*-axis. The cumulative percentage of the emissions reduction is used as indicator; this is because we would like to address the reality of proportionally allocating the responsibility for pollutant emissions reduction among different regions in China.

The percentage of emission from a certain industry is calculated based on the emission data. The emission reduction percentage of using a certain technology in an industry is then calculated by multiplying the emission percentage and the removal rate of the technology.

#### 2.2.2. Regional emission-concentration contribution matrix

The regional emission concentration contribution matrix is required to convert the MAC curve into the MCAC curve. The regional emission concentration contribution matrix can be expressed as the following matrix **E**, where $e_{k,j}$ refers to the contribution of a unit of a certain pollutant emitted in city *k* ($k = 1,2,\ldots,n$, where *n* refers to the number of the cities) to the pollutant concentration in city *j* ($j = 1,2,\ldots,n$). The values in the diagonal (when $k = j$) represent the contribution effects of a unit emission of a certain pollutant on the pollutant concentration in the same area. The values located above the diagonal reflect the opposite effects of the emissions in one area on the pollutant concentration in another area, compared to the values symmetrically below the diagonal.

$$\begin{pmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ e_{n1} & e_{n2} & \cdots & e_{nn} \end{pmatrix}$$

#### 2.2.3. Marginal pollutant concentration alleviation cost curve

MCAC curves are constructed based on MAC curves. The $x$-axis of the MCAC curve is derived by multiplying the quantity of the emission reduction in all the cities and the corresponding emission-concentration contribution rate. In a regional framework, the regional emission-concentration contribution matrix is used to estimate the pollutant concentration alleviation in each individual city by considering the abatement of pollutant emissions from various cities. For each pollutant $p$, a matrix is used to represent the effect of pollutant emission reductions in one city on the others, which can be calculated by multiplying matrix $\mathbf{E}$ with matrix $\mathbf{Q}$. In matrix $\mathbf{Q}$, the value of the diagonal is $Q_k$ ($k = 1,2,\ldots,n$), which represents the pollutant emissions reduction in the $k$-th city. Thus, the product of $\mathbf{Q}_k \cdot e_{k,j}$ represents the contribution of pollutant emissions reduction in city $k$ to the pollutant concentration alleviation in city $j$. The concept of the regional conversion from pollutant emission abatement to pollutant concentration alleviation can be framed as the matrix below.

$$\begin{pmatrix} Q_1 & 0 & \cdots & 0 \\ 0 & Q_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & Q_n \end{pmatrix} \begin{pmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ e_{n1} & e_{n2} & \cdots & e_{nn} \end{pmatrix} = \begin{pmatrix} Q_1 \cdot e_{11} & Q_1 \cdot e_{12} & \cdots & Q_1 \cdot e_{1n} \\ Q_2 \cdot e_{21} & Q_2 \cdot e_{22} & \cdots & Q_2 \cdot e_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Q_n \cdot e_{n1} & Q_n \cdot e_{n2} & \cdots & Q_n \cdot e_{nn} \end{pmatrix}$$

The concentration alleviation in city $j$ will increase as technologies are successively added in city $k$. By using technology from 1 to $m$, the cumulative pollutant reduction in city $k$ is $\sum_i Q_{i,k}$ ($i = 1,2,\ldots,m$). $\sum_i Q_{i,k}$ can be calculated by the cumulative percentage of emission reduction in the MAC curves and the total emission of each city. Based on the above conversion, the $x$-axis of MCAC curve of city $j$ for each pollutant $p$ can be developed as $x = (\sum_i Q_{i,k}) \cdot e_{k,j}$, $i = 1,2,\ldots,m, k = 1,2,\ldots,n$; $i$ represents technology and $k$ represents the city in which abatement happens, and $j$ represents the city in which concentration is reduced.

To derive the $y$-axis of the MCAC curves for each city, the total cost of using the technologies in the corresponding industries in each city is calculated by successively summing up the cost in the industries that have used control technologies. The cost caused by using a technology in an industry is calculated by the unit cost of pollutant removal of the technology and the emission reduction quantity in the corresponding industry achieved by using the technology.

In the MAC curve, the unit cost of pollutant removal is projected on the pollutant emission reduction percentage, while in the MCAC curve, we project the total cost in city $k$ caused by using technologies from 1 to $i$ in the corresponding industries, $AC_{i,k}$, on the pollutant concentration reduction in each individual city, *i.e.*, $MC_{i,k} = AC_{i,k}$ (when $x = (\sum_i Q_{i,k}) \cdot e_{k,j}$, $i = 1,2,\ldots,m$, $k = 1,2,\ldots,n$; $i$ represents technology and $k$ represents the city in which abatement happens, and $j$ represents the city in which concentration is reduced).

The rankings of the technologies in the MCAC curves are the same as those in the MAC curves. The difference between the two types of cost curves in this study lies in the dimension of both the $x$-axis and the $y$-axis in the coordinate. The MCAC curves are used to show the heterogeneity of the regional cost and the cost savings resulting from an efficient regional responsibility allocation scheme for pollutant control.

### 2.3. Equi-marginal principle and its application

The regional air pollution control scheme with the least cost can be identified by using the Equi-Marginal Principle (EMP). The margin equilibrium achieved by a multi-city can be simplified into a two-city situation, *i.e.*, any two cities find their marginal cost equating to each other. The EMP applied in this study is illustrated in Fig. 2, which is framed as a two-city situation. In Fig. 2, the $y$-axis represents the pollutant concentration alleviation cost. The $x$-axis represents the pollutant concentration reduction in city A. The curve from the point O to the upper right-hand side of the coordinate system represents the marginal cost curve of city A, denoted by MC (A). The curve from the lower right-hand side to the upper left-hand side of the system represents the cost curve of city B, denoted by MC (B). The slope of MC (B) is steeper than MC (A) due to the lower contribution of emissions reductions in city B to city A, compared with the contribution effect in city A itself.

It is assumed that city A set a pollutant concentration reduction target ($\mathbf{O}'$). If city A achieves its target of $\mathbf{O}'$ completely through its own pollutant abatement efforts, then the additive cost can be estimated by calculating the area enclosed by MC (A) and the coordinate axis, *i.e.*, $\mathbf{ODO}'$. If city A achieves its target $\mathbf{O}'$ by collaborating with city B, however, it can find a pollutant control scheme with the least cost by seeking a marginal equilibrium point E, where MC (A) and MC (B) intersect. At this point, city A achieves the concentration reduction of $\mathbf{Q}$ through its own efforts with an additive cost of $\mathbf{OEQ}$, and city B contributes ($\mathbf{O}'-\mathbf{Q}$) through its local abatement with an additive cost of $\mathbf{O}'\mathbf{EQ}$. If city A and city B can make a deal to compensate city B with $\mathbf{O}'\mathbf{EQ}$, then the total cost for city A to achieve its pollutant concentration reduction of $\mathbf{O}'$ is $\mathbf{OEO}'$, which is lower than the original, $\mathbf{ODO}'$. The cost savings can be estimated by calculating the area of $\mathbf{DEO}'$. In the multi-city context, the equilibrium status will be achieved when all the cities find that their marginal cost is equal to the others.

### 2.4. Data and assumptions

The investments and the operation and maintenance costs which are used to estimate the annual cost of control technologies were obtained from different sources, including enterprise interviews, official government documents, and related literature. The enterprises considered in this study are the Huaneng Shang'an power plant, the Shijiazhuang No. 2 thermal power plant, and the Luquan Dingxin cement plant. The data obtained from the official government documents come mainly from the *'Experience Assembly*

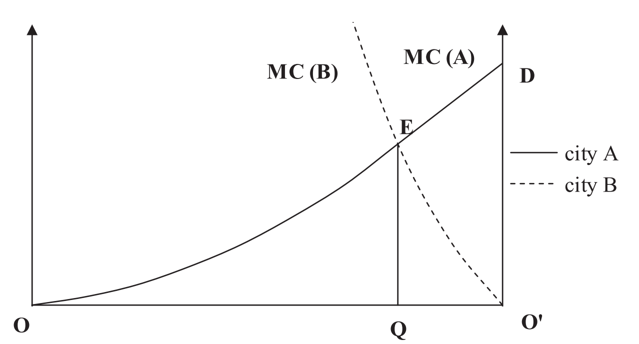



**Fig. 2.** Equilibrium of marginal pollutant concentration alleviation cost curves for two cities.

*of Energy Saving and Emission reduction in "Double Thirty" (thirty key areas and key enterprises)'* (abbreviated as 'Experience Assembly'), which was edited by the Hebei Environmental Protection Department in December 2010. The abbreviation of each control technology is shown in Appendix B, and the sources of the data for the estimation of each technology's costs are shown in Appendix C (China Electricity Council, 2009; Experience Assembly, 2010; Gao et al., 2007; He, 2010; Jia, 2007; Sang et al., 2004; Shi, 2006; Wang and Zhang, 2004; Xu, 2000; Xu et al., 2011). The data on pollutant ($SO_2$, $NO_x$, and PM) emissions at the industrial level in the Jing–Jin–Ji region in 2009 come from the 'Research on Strategy and Measure of Regional and Joint Air Pollution control' (RJAPC) project (IAPCAS, 2012), sponsored by the Beijing Science and Technology Commission.

In this study, the base scenario (or the starting point of the cost curves) for estimating the costs of control technologies is the situation in the Jing–Jing–Ji area at the end of the 11th FYP, which is also described in Appendix A. The value of the parameters for estimating control technologies costs are shown in Appendix D. In this study, the scale constraints of technologies application are not set. It is simply assumed that each technology can be applied by 100 percent in the corresponding industries. The unit pollutant removal cost of the technologies is assumed to be invariable across different scales of firms, fuel quality, and level of operation capacity of firms, etc. The residual value of any equipment is not considered when the cost is estimated. The co-benefit of multi-pollutant abatement by a certain technology is not considered. As stated previously, the revenue brought by energy-saving technologies is not considered when calculating the cost of the energy-saving technologies. It is also assumed that there is no 'spill-over' effect between the jurisdictions using the same technology, and, therefore, that the unit pollutant abatement costs of the same technology are the same across all the jurisdictions. The transaction cost of JRAPC is not considered through the whole analysis. Due to data limitations, the total pollutant emissions of the involved industries were used as the city's total emissions instead of the real total pollutant emissions. It is also implicitly assumed that the pollutant emissions from one city will uniformly affect the pollutant's concentration in the city and others without variation across different altitudes.

## 3. Results

### 3.1. Cost of control technologies

The control technologies cost is estimated based on the method developed in Section 2. The pollutant control technologies for $SO_2$ removal primarily comprise desulfurization technologies in the power sector and in the steel and iron sector. The pollutant control technologies for $NO_x$ removal comprise denitrification technologies in the power and cement sectors. The pollutant control technologies for soot (dust) are primarily newly used in the cement sector. Meanwhile, the PM control technology transformation is used in the steel and iron and power sectors.

The estimated results show that the $SO_2$ unit abatement cost for different technologies varies from 1000 to 400,000 CNY/ton of $SO_2$, among which the cost of control technologies that specifically address $SO_2$ ranges from 2000 to 5000 CNY/ton of $SO_2$. The $NO_x$ unit abatement cost for the use of different technologies varies from 1000 to 1,400,000 thousand CNY/ton of $NO_x$, among which the cost of the control technologies that specifically address $NO_x$ ranges from 1500 to 3000 CNY/ton of $NO_x$. The soot (dust) unit abatement cost of different technologies varies from 200 to 1500 CNY/ton of soot (dust).

The unit pollutant abatement cost of energy-saving technologies is much higher than the cost of the technologies used to specifically address pollutant removal. The reason is that energy-saving technologies generally abate less pollutant compared to the specific pollutant control technologies, but the total cost of energy-saving technologies is attributed to a specific pollutant when the unit pollutant abatement cost is calculated.

In real life, energy-saving technologies are often preferred to be implemented in plants due to their effect in reducing production costs (*e.g.*, fuel cost) or in generating economic profits by selling the recycled resources. Therefore, a plant is more likely to invest in energy-saving technologies than in pollutant-removal technologies. From this point of view, the 'net cost' would better represent the actual cost of an energy-saving technology; this aspect is not further explored due to the data constraints in this study.

The estimated results show that the unit PM abatement cost is comparatively higher than the unit $SO_2$ (or $NO_x$) abatement cost in the power industries. This is a result of setting the baseline scenario at the end point of the 11th FYP. By the end of the 11th FYP, all of the power plants had installed PM removal facilities. The PM control measures discussed in this case are related to technology transformation and are based on existing PM control technology. The unit PM removal cost of technology transformation is much higher than that of installing a new PM control facility, resulting from the rate of improvement in the PM removal rate being lower – not higher than 10% – when technology transformation is implemented.

### 3.2. City-level marginal pollutant abatement cost curves

The city-level pollutant abatement cost curves are constructed based on the estimation of the control technology cost. There are nine city-level cost curves in our case study area, all shown in Figs. 3–5, with the *x*-axis representing the proportion of the accumulative pollutant reduction to a city's total emissions, and the *y*-axis representing the unit pollutant abatement cost (thousand CNY/ton reduction) of corresponding control technology.

As a result of the variation in each city's industrial structure, each individual city's MAC curve is different. For each pollutant, the different industrial structures in each city lead to a correspondingly different industrial composition of emissions, meaning that the percentages of the industries are different between cities. Industries located in different cities may use the same control technology to abate the same type of pollutant, and may thus have the same unit pollutant abatement costs; however, at a certain point of accumulative emission reduction percentage of the cities (*i.e.*, at some point on the *x*-axis), the corresponding unit pollutant abatement costs that are caused by the technologies may diverge across the cities, which make the city-level pollutant abatement cost curves differ from each other. Besides, the sudden increase in the right-hand side of the curves can be mainly ascribed to the energy-saving technologies that have small potential for pollutant removal.

The $SO_2$ abatement cost curves of nine cities in the Jing–Jin–Ji region are shown in Fig. 3. The industry structure variations can be simply observed from the ranks of the cities before and after the point of 50% on the *x*-axis. When the city's total abatement proportion is less than 50%, Tangshan, Zhangjiakou, and Shijiazhuang have comparatively lower costs, and Cangzhou, Baoding, Langfang, and Beijing have comparatively higher costs. When the proportion is greater than 50%, Zhangjiakou, Shijiazhuang, and Tangshan have comparatively lower costs, while the costs in Cangzhou, Langfang, Baoding, and Tianjin are comparatively higher.

Likewise, the $NO_x$ and PM abatement cost curves for the nine cities are shown in Figs. 4 and 5. When the total abatement proportion of $NO_x$ in the cities is less than 50%, Shijiazhuang, Beijing, and Tianjin have comparatively lower costs, and Baoding,

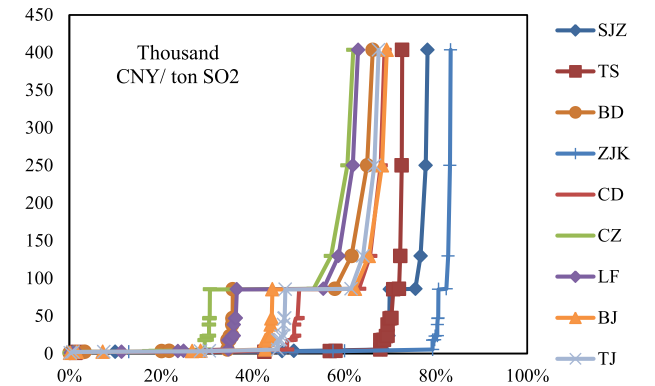



**Fig. 3.** Cost curve of unit $SO_2$ abatement for each individual city in the Jing–Jin–Ji region.

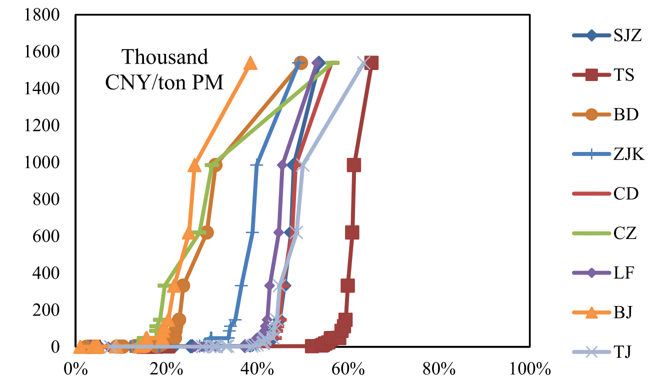



**Fig. 5.** Cost curve of unit PM abatement for each individual city in the Jing–Jin–Ji region.

Tangshan, Cangzhou, and Langfang have comparatively higher ones. When the proportion is greater than 50%, Tianjin, Cangzhou, and Shijiazhuang have comparatively lower costs, while Tangshan, Beijing, and Langfang have comparatively higher ones. When the city total abatement proportion of PM is less than 50%, Tianjin, Langfang, and Chengde have comparatively lower costs, and the costs in Cangzhou, Beijing, and Baoding are comparatively higher. When the proportion goes beyond 50%, Tangshan, Tianjin, and Chengde have comparatively lower costs, while Beijing, Cangzhou, and Baoding have comparatively higher ones.

The MAC curve varies between the cities, and thus it implies that related cities can find lower cost pollutant abatement solutions for themselves when seeking help from outside areas. Therefore, compared to the proportional allocation of emissions reduction responsibilities between the cities, the total pollutant abatement costs for this nine-city region could be decreased if a market-based instrument is implemented, such as a tradable permits system.

### *3.3. Regional emission-concentration contribution matrix*

The matrix for nine cities (Beijing, Tianjin, Tangshan, Chengde, Zhangjiakou, Baoding, Langfang, Shijiazhuang, and Cangzhou) in the Jing–Jin–Ji region was extrapolated by using the available data from the RJAPC project (IAPCAS, 2012), including the $SO_2$ concentration contribution matrix for the listed cities, expressed as a contribution percentage, which is estimated based on atmospheric physical model running by the Institute of Atmospheric Physics of Chinese Academy of Sciences; those cities' annual $SO_2$ emissions in 2009, and the average annual concentration of $SO_2$ from June 2009 to June 2010. Due to data limitations, only the regional $SO_2$ emission-concentration contribution matrix is extrapolated to construct the $SO_2$ concentration alleviation cost curve.

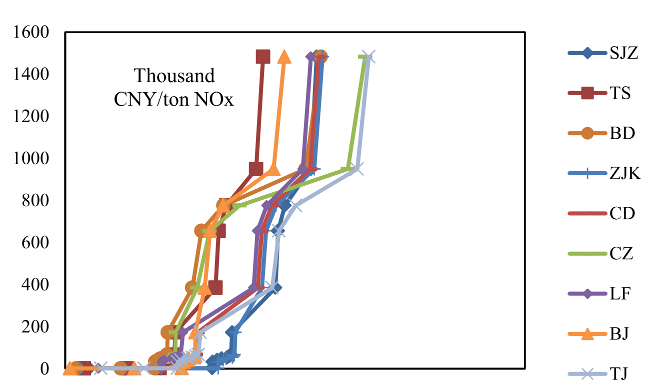



**Fig. 4.** Cost curve of unit $NO_x$ abatement for each individual city in the Jing–Jin–Ji region.

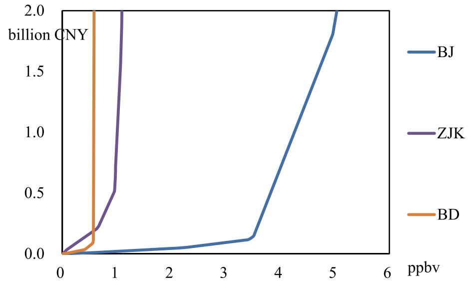
The $SO_2$ concentration contribution matrix for the cities expressed as contribution percentages is shown in Appendix E. Appendix F shows the data on the quantity of $SO_2$ emissions for the cities included in this study in 2009, and the average $SO_2$ concentration of the same year. To develop the regional $SO_2$ emission-concentration contribution matrix (Table 1), the $SO_2$ concentration contributions (ppbv) for each city were firstly calculated by utilizing the $SO_2$ concentration contribution matrix and the average annual $SO_2$ concentration. This estimation together with the 2009 $SO_2$ emission quantity from the cities involved is then used to calculate the regional $SO_2$ emission-concentration contribution matrix (the $SO_2$ emission-concentration contribution matrix is the transposed matrix of matrix **E** which is mentioned in Section 2.2.2, *i.e.*, $\mathbf{E}^{-1}$). The first column of Table 1 represents Beijing's per ton $SO_2$ contribution to the annual average $SO_2$ concentration in all other involved cities, with the unit being 1000 ppbv/ton. The remaining columns of the matrix may be deduced by the same logic.

### *3.4. City-level marginal pollutant concentration alleviation cost curve*

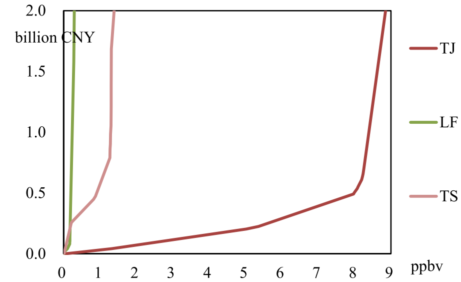
The $SO_2$ concentration alleviation cost curves for Beijing, Tianjin, Shijiazhuang, Chengde, Zhangjiakou, Langfang, Baoding, Cangzhou, and Tangshan are shown in Fig. 6 from (a) to (i). The curves indicate the change in costs as the center city's $SO_2$ concentration reduction changes. In this figure, the curves of those cities that have little concentration impact on the center city are neglected in order to better show the more impacting cities. For example, although Tianjin, Langfang, Cangzhou, and Tangshan also have a slight impact on Beijing's $SO_2$ concentration, only the curves of Beijing, Zhangjiakou, and Baoding are shown in the figure of Beijing. Because the cost curves are technology-based and the estimated

**Table 1**
Regional $SO_2$ emission-concentration contribution matrix (1000 ppbv/ton).

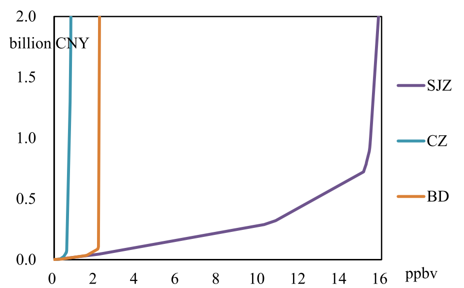
| | BJ | TJ | TS | CD | ZJK | BD | LF | SJZ | CZ |
|---|---|---|---|---|---|---|---|---|---|
| BJ | 0.135 | 0.000 | 0.000 | 0.001 | 0.013 | 0.012 | 0.004 | 0.000 | 0.000 |
| TJ | 0.006 | 0.075 | 0.009 | 0.001 | 0.000 | 0.002 | 0.009 | 0.000 | 0.003 |
| TS | 0.001 | 0.003 | 0.069 | 0.004 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 |
| CD | 0.006 | 0.001 | 0.001 | 0.150 | 0.002 | 0.000 | 0.002 | 0.000 | 0.000 |
| ZJK | 0.000 | 0.000 | 0.000 | 0.000 | 0.048 | 0.000 | 0.000 | 0.000 | 0.000 |
| BD | 0.022 | 0.000 | 0.000 | 0.000 | 0.008 | 0.375 | 0.008 | 0.003 | 0.006 |
| LF | 0.041 | 0.005 | 0.001 | 0.000 | 0.001 | 0.027 | 0.088 | 0.000 | 0.007 |
| SJZ | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 | 0.047 | 0.003 | 0.111 | 0.028 |
| CZ | 0.002 | 0.019 | 0.001 | 0.000 | 0.000 | 0.009 | 0.010 | 0.003 | 0.075 |



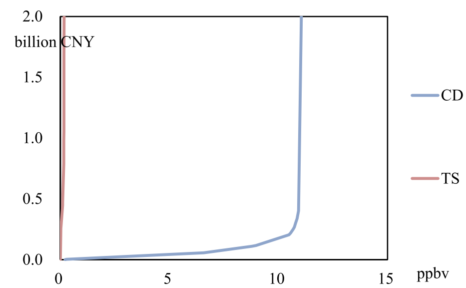

（a）：Cost curve of relevant cities for Beijing's $SO_2$ concentration alleviation



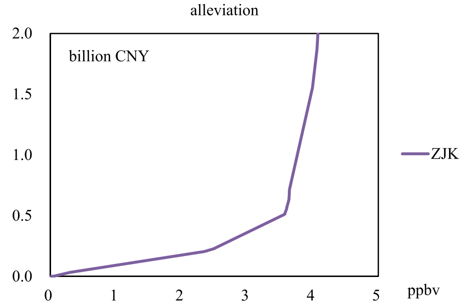

（b）：Cost curve of relevant cities for Tianjin's $SO_2$ concentration alleviation



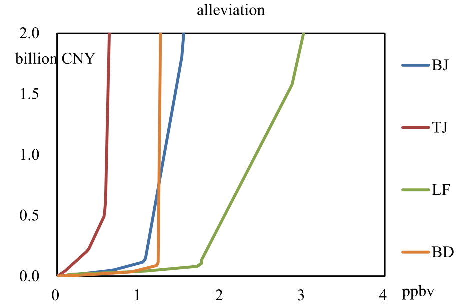

（c）：Cost curve of relevant cities for Shijiazhuang's $SO_2$ concentration alleviation



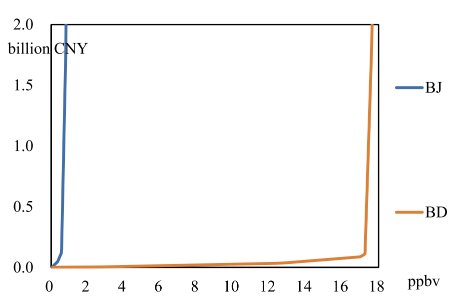

（d）：Cost curve of relevant cities for Chengde's $SO_2$ concentration alleviation



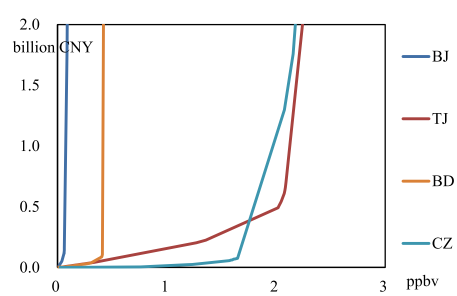

（e）：Cost curve of relevant cities for Zhangjiakou's $SO_2$ concentration alleviation



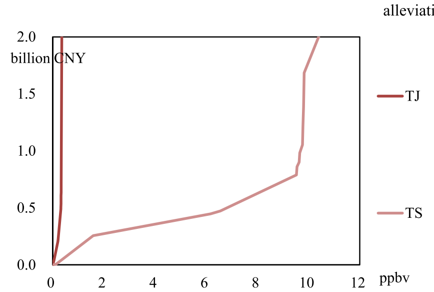

（f）：Cost curve of relevant cities for Langfang's $SO_2$ concentration alleviation




（g）：Cost curve of relevant cities for Baoding's $SO_2$ concentration alleviation




（h）：Cost curve of relevant cities for Cangzhou's $SO_2$ concentration alleviation




（i）：Cost curve of relevant cities for Tangshan's $SO_2$ concentration alleviation

**Fig. 6.** $SO_2$ concentration alleviation costs in 9 cities.

$SO_2$ unit abatement costs of part of the energy-saving technologies are much higher compared with others (such as technologies with the codes SI-TRT, SI-SPG2, SI-CDQ, SI-ESI, and HT-NG), the curves are almost vertical, especially on the right-hand side. In the figure, part of the curves located on the right-hand side were curtailed to highlight the lower level cost in the curves.

In Fig. 6, the disparity between the MCAC curve of the center city and that of the surrounding cities suggests a cost-saving potential which the center city can gain from collaborating with the others. The larger the disparity, the less is the marginal cost heterogeneity between the center city and its surroundings. For Chengde, Baoding, and Zhangjiakou, the larger disparity implies a comparatively smaller cost saving by joining the JRAPC program compared with that for Beijing, Langfang, and Cangzhou. Comparatively, Beijing, Langfang and Cangzhou can save more as a percentage of their total costs for improving their air quality by joining the JRAPC, e.g., paying for their surroundings at a price higher than the surroundings' abatement cost; this is especially so in the cases of Beijing and Langfang.

In addition, to respond to the EMP, which is illustrated in Section 2.3, we drew the pollutant concentration alleviation cost curves by letting the curve of the center city intersect with that of the surrounding cities (see Appendix G).

According to our results shown as Figure G (a) in Appendix G, if the assumed control target is set as reducing 6 ppbv of $SO_2$ in Beijing, it would cost Beijing 5.2 billion CNY to achieve the target. However, if the JRAPC regime is implemented in Beijing and its surrounding cities, the control scheme with least-cost would be achieved by Beijing cutting down 5 ppbv by itself together with Zhangjiakou contributing 1 ppbv reduction, with the cost of both Beijing and Zhangjiakou as about 1.8 billion CNY, which generate the total reduction cost of 3.6 billion CNY. Another option would be that Beijing cooperates not only with Zhangjiakou but also with Baoding, then Beijing only needs to abate approximately 4.5 ppbv of $SO_2$ by itself, and the remainder can be achieved by $SO_2$ emission reduction efforts from the other two cities (1.5 ppbv). It can be estimated that these three cities would spend a total of 2.4 billion CNY to meet the reduction targets, and that Beijing's cost savings from jointly controlling $SO_2$ concentration with Zhangjiakou and Baoding are approximately 2.8 billion CNY per year. The figures for the other cities may be deduced by using the same logic.

It should be noted that the abatement scheme with the least-cost feature in a specific city depends on the control target set for pollutant concentration. Different pollutant concentration control targets in a specific city will lead to different regional abatement schemes with different least-cost.

## 4. Discussions

### 4.1. The sources of cost heterogeneity

The differences in pollutant concentration reduction cost between districts may stem from three main sources. Firstly, the pollutant concentration reduction by unit pollutant emissions abatement varies across districts due to different contribution ratios of unit pollutant reduction to pollutant concentration, especially considering the transportation of pollutants in the region. Secondly, the marginal costs of unit pollutant emissions reduction differ in the area due to distinct industrial structures, thereby the composition of pollutant emissions vary across the districts. Thirdly, the costs of unit pollutant emissions reduction may vary with the differences in firms' socio-economic characteristics, such as scale, which we have not considered in this study. In this context, JRAPC can save greater expense when the heterogeneity of the marginal control cost is more significant.

### 4.2. Inconsistency between being more affected and achieving more savings

In our targeted area, the Jing–Jin–Ji region, the cities that could achieve more savings from JRAPC for improving their air quality are not always the ones that have been more affected by the surrounding areas. Two factors must be simultaneously effective to become great gainer cities from JRAPC, which is being both significantly affected by surrounding jurisdictions and detaching in the marginal abatement cost with others.

In terms of the calculation based on the emission-concentration contribution matrix and the constructed MCAC curves, the city that is most inconsistent between being affected and having a large cost-saving potential with respect to $SO_2$ control is Shijiazhuang. Shijiazhuang ranks second in the list of being significantly affected by others within the nine cities, while it ranks only fifth of the biggest gainers from JRAPC, estimated as the percentage of total control cost of their own.

### 4.3. Cost-effectiveness under city-oriented and region-oriented regimes

A JRAPC regime can either be city-oriented or region-oriented. City-oriented regimes give priority to assure the air quality in some specific cities or in one particular city, whereas region-oriented ones give priority to assure a quality standard across the cities. The cost-effective control scheme and the cost-saving potential under these two regimes may be different for a city as a result of its dual role of pollutant receptor and emission contributor. The pollutant concentration in one city could be significantly affected by the surrounding areas, while, on the other hand, this city could be an important contributor to the average concentration level of a region.

According to the results of the RJAPC project (IAPCAS, 2012), Shijiazhuang has the feature of dual roles with respect to $SO_2$. It means that the JRAPC regime oriented by assuring the $SO_2$ concentration in Shijiazhuang will result in a cost-effective scheme for Shijiazhuang, and this would be very different from that derived under a regime oriented by assuring that all the cities meet the same standard as Shijiazhuang. Regarding $NO_x$ and VOC, Beijing and Tianjin are contributors rather than receptors. Regarding $SO_2$, Tianjin is a contributor rather than a receptor. The role of being a contributor implies a loss when comparing participating in a region-oriented regime with not participating in it.

### 4.4. The biggest obstacle to hinder the launching of the JRAPC

Existing regional air pollution control regimes and relevant studies have indicated that developing effective cooperative relationships between jurisdictions is highly reliant on common interests, consensus, trust, the involvement of scientific knowledge, and supporting techniques, as well as proper institutional arrangements within the region (Bergin et al., 2005; Castells and Ravetz, 2001; Tuinstra et al., 2006; Victor, 2006; Wettestad, 1995). Among these factors, common interest is often regarded as the decisive factor in triggering regional cooperation. Interest-based analysis and explanations have emphasized two related factors: domestic ecological vulnerability (or environmental quality), and the cost of pollutant abatement (Sprinz and Vaahtoranta, 1998; Victor, 2006).

However, in the Jing–Jin–Ji region, the stage of and the appeal for economic development vary across the cities. The cities apparently do not share common interests, as has been mentioned previously. Beijing and Tianjin are comparatively more economically developed and have greater willingness to improve their air quality, but their marginal abatement cost is higher due to exhausting the local lower-cost measures. On the contrary, the cities in Hebei province, at this point of time, are less economically developed and have a comparatively minor willingness to improve the air quality, but their marginal abatement cost is lower.

In this context, applying the 'User Pays Principle' in this region may have an obvious advantage over the 'Polluter Pays Principe'. Specifically, we are referring to Beijing and Tianjin paying the relevant cities at a higher price than the abatement cost in their surroundings. By doing this, the JRAPC can be facilitated and cost savings can be realized as a result of giving more economic development opportunities to the further-development eager-demanders, as well as reducing the political resistances from them. This does not rationalize the legitimacy of polluting because implementing the JRAPC does not mean that other environmental regulations can be substituted. The JRAPC regimes are only aiming to provide supplemental instruments to internalize the externalities by balancing the environment and the economy from a regional point of view.

## 5. Conclusion

This study seeks to empirically demonstrate the cost savings through joint regional air pollution control in the Jing–Jin–Ji region. The pollutant removal or energy-saving effectiveness and the cost of the feasible air pollutant control technologies were investigated by interviewing firm representatives and relevant government officials as well as reviewing related studies. The MAC curves of $SO_2$, $NO_x$, and PM for nine cities in this region were developed to test the cost heterogeneity. The MCAC curves of $SO_2$ for nine cities were further constructed to test the cost heterogeneity and to investigate the potential cost savings for improving air quality. The heterogeneity of pollutant concentration alleviation cost comes from the cities' varying contributions of unit emission reduction to the pollutant concentration reduction, and diverse unit cost of emission reduction brought about by different industry composition.

The empirical results indicate that if the pollutant concentration-based pollution control strategy is implemented to respond to the *Action Plans on Air Pollution Prevention and Control*, which were announced in September 2013, joint regional control will generate potential for saving cost; despite that, the magnitude of the cost-savings generated would vary as the assumptions are changed in this study.

Our study follows a bottom-up analysis procedure and yields results of comparison between general cases of joint regional control and locally based control. The caveat of this paper is that the conclusion, *i.e.*, joint regional control in Jing–Jin–Ji is more cost-effective than locally based control, is confined to a general level, but it does not point to a detailed scheme. To determine a JRAPC scheme, more research should be done on associating the designed schemes that suggest specific control target and detailed policy setting with the magnitude of cost savings.

In the Jing–Jin–Ji region, the biggest obstacle to launch a JRAPC program to release the pollution control cost savings potential could be the conflict appeal for the air quality improvement and the economic development between more and less economically developed cities. We reckon that the more developed cities, *i.e.*, Beijing and Tianjin, paying the surrounding cities at a price higher than the marginal cost of those surrounding cities could be a second-best solution. By giving more development opportunities to the less developed cities, it could, on the one hand, facilitate joint regional air pollution control cooperation with less political resistance, and on the other hand, rebalance the polarized situation of the economic development in this region.

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## Appendix A. Supplementary material

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.jenvman.2014.09.032.

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