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Marginal Abatement Cost of Sulfur Dioxide in Chinese Three Major Urban Agglomerations: A Parametric Meta-Frontier Analysis

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Abstract

In this paper, we use the quadratic directional distance function and the meta-frontier analysis, with the data of 48 prefecture-level cities in three major urban agglomerations: Beijing-Tianjin-Hebei, Pearl River Delta and Yangtze River Delta from 2003 to 2016. The estimate of production efficiency shows a U-shaped change, and the turning point of efficiency improvement in 2013. Both shadow price and production efficiency of the Beijing-Tianjin-Hebei urban agglomeration are inferior to the others. According to the potential production efficiency, the three major regions can achieve an annual reduction of 133,400 tons. The environmental tax collection standards in Beijing and Tianjin are greater than the shadow price, while the Hebei region is smaller. It needs to adjust the emission reduction policy.

Keywords

Meta-frontier, environmental protection tax, shadow price, urban agglomerations.

1. INTRODUCTION

Since the reform and opening up, China's economy has develop at a high speed for decades. 2018 is the 40th anniversary of reform and opening up. China's GDP has exceeded 90 trillion yuan, reaching 90.03 trillion yuan. China has become the country with the highest economic contribution rate in 30%. At the same time, environmental protection issues have gradually attract the focus of social attention. The National Ecological Protection “Thirteenth Five-Year Plan” outlines that: when it comes to 2020, the ecological space will be guaranteed, the ecological quality will be improved, the ecological functions will be enhanced, the rate of biodiversity decline will be curbed, and the unified supervision level of ecological protection will be significantly improved. Although environmental protection work has been continuously promoted in recent years and its effectiveness has been continuous,there is still a certain gap in achieving the environmental protection goal in 2020. According to 2017 Bulletin on the State of Ecological Environment, 99 of the 338 prefecture-level cities have achieved environmental air quality standards, only accounting for 29.3%. It can be seen that the task of reducing emissions cannot be delayed.

The environmental protection policies should not only take into account the total amount of emission reductions, but also consider the negative impact on the economy under environmental regulations. Only in this way can we achieve the double benefits of environmental protection and economic development. As a product of non-market transactions, the marginal impact of pollutants can be measured by the reduction of the amount of commodities when reducing one unit of pollutant. The marginal abatement cost of pollutants can also be called shadow price which is an important reference for emission reduction policies.

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For the measurement of the shadow price of pollutants, early articles did not classify it as part of the output. Considering the methods of Caves et al. (1982) and Dreschler et al(1973), Pittman (1983) proposes undesired outputs(bad output) relative to expected output of commodities (good output), and maximize the profit to solve the shadow price. The method of measuring the shadow price of a contaminant can be based on the Shepard distance function and the direction distance function. The distance function is first proposed by Shepard (1970) and is intended to solve the problem of efficiency evaluation of multiple inputs and multiple outputs. After inheriting the cost and production functions which are widely cited in 1953, the distance function is a deep summary of economic production techniques, including the input distance function and output. Fare (1993) uses the dual relationship between the income function and the output distance function to obtain the shadow price of bad output by the gradient of the distance function. The result of the Shephard distance function is not the optimal result expected by policy makers: while the output is increased, the bad output is reduced. Besides, the change of the good or bad output that may occur in the conventional enterprise cannot be described. The directional distance function proposed by Chambers et al. (1996) just makes up for this shortcoming. According to P. Zhou et al. (2014),consists more than 40 statistics on undesired output shadow price literature.The Shephard distance function is widely used between 1993 and 2002, but majorities chose the more flexible direction distance function between 2003 and 2013.

In solving the shadow price of pollutant, specific solutions can take the form of parameterization (Chung 1996; Fare et al. 2005; Cuesta et al. 2009) or non-parameterization (Boyd et al. 1996; Lee et al. 2002). For nonparametric methods, Boyd et al (1996) use a nonparametric method for the first time to calculate the shadow price. Compared with the result of only reducing the bad output by Turner (1994), they assume that the bad output under the environmental regulation is unchanged, but the output is increased. Lee (2002) assigns inefficiency observations to certain efficiency paths. The non-efficiency output can reach the frontier through different directions, and the direction vector of the direction distance function is calculated by the change between control group and the target group output. After the direction vector is fixed, the corresponding shadow price is calculated by a non-parametric method. In terms of parameter method, Fare et al. (2006) solved the shadow price of agricultural pollutants in the United States through the quadratic directional distance function. The results show that if the sample states eliminate the inefficiency, the pollution will be reduced by 7%.

The measurements of the shadow price of pollutants in China mainly include: Zhengge Tu (2009) calculates the shadow price of sulfur dioxide in industrial enterprises above 30 provinces by constructing a frontier function model. The distribution characteristics of shadow price reveal three stages: “steep slope zone ,"flat belt" and "plateau belt". Shiyi Chen (2010) uses the environmental directional distance function to calculate the carbon dioxide shadow price of 38 industrial double-digit industries. The results show that the shadow price of light industrial pollutants is higher than that of heavy industry. Both Industrial shadow prices have been increasing year by year. Peng Yuan et al. (2011) use the quadratic directional distance function to measure the shadow price of three pollutants in the industrial sector of China's 284 prefecture-level. Chu Wei (2014) calculates the carbon dioxide shadow price according to the quadratic directional distance function, and divides the 104 prefecture-level cities in China according to the eastern, central and western regions. Results conclude that the eastern region is higher than the western and central regions. The marginal abatement cost is U-shaped in relation to CO2 emissions per unit of GDP. In the process of calculating the shadow price of pollutants, the full sample data cannot take into account the problem of regional heterogeneity, which will cause deviations in the results. In the case of regional heterogeneity, the estimation of the shadow price of pollutants will use a meta-frontier approach. For example, Ning Zhang

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(2016) divides power generation enterprises into four groups, namely state-owned enterprises and foreign capitals. The results show that state-owned enterprises have the lowest production efficiency and can reduce carbon dioxide emissions by 44% under potential productivity.

The above documents have the following problems and the improvements in this paper:

Environmental technology:The shadow price represents the marginal abatement cost, which is the tangent slope of the observation point mapped to the frontier surface. The environmental technologies used in calculating shadow prices are different, and the results of shadow prices are different. For the marginal abatement cost estimation of specific cities in China, the shadow price calculated from the full sample data cannot be referenced (Yuan Peng et al. 2011, Wei Chu 2014), but appropriate environmental technology should be selected for measurement. In order to compare the performance of different frontier observation points, the meta-frontier used in this paper is a more reasonable choice.

Heterogeneity: Different human, capital, economic structure, social development, economic environment and other factors will lead to differences in production results (O'Donnell et al. 2008). Although several documents reflect regional heterogeneity through meta-frontier. The regional division of China is generally concentrated in the eastern, central and western regions or the division of industries, which cannot have a good effect on calculating the shadow price of pollutants in developed regions. China has a vast territory, and the economic development of the eastern, central and western regions is very different. Comparing the country under a large environmental technology does not reflect the marginal emission reduction characteristics of the major urban agglomerations themselves. It should be compared under the matching economic technology, such as the environmental technology formed by the three major urban groups in Beijing, Tianjin, Hebei, Yangtze River Delta and Pearl River Delta.

Measuring method: Although the non-parametric method does not require a priori assumption on the model, it cannot be derived from the intuitive parameter value and is greatly affected by the sample extremum. The slope of some projection points is not unique. The disadvantages of the nonparametric method need further study, so it is rarely used to estimate the shadow price of bad output (Fare et al. (1998). While the parameter method requires assumptions, it can be differentiated and algebraic. (Veeman et al. 2000) requires less sample size and is more suitable for estimating shadow prices. In addition, stochastic frontier analysis has endogeneity, multi-parameter estimation requires large samples, and violations of monotonic assumptions (Kumar and Managi, 2009), which is not adopted by this paper.

The remainder of the paper is organized as follows: Section 2 presents the methodology. Section 3 describes the data and division. Section 4 reports the basic estimation results. Section 5 contains the conclusion.

2. METHODOLODY

2.1. Environmental technology and Group Frontier

Production activities produce undesired outputs such as sulfur dioxide while producing the desired output. We first make assumptions about environmental technology. Following Fare et al. (2005) for the definition of environmental technology, we assume K prefecture-level cities adopte input $x = (x_1, \ldots, x_n) \in R_+^n$ to produce desire output $y = (y_1, \ldots, y_m) \in R_+^m$ and undesired output $b = (b_1, \ldots, b_I) \in R_+^I$ in period t.

The environmental technology could be:

$$P_t(x) = \{(x_t, y_t, b_t) : x_t can\ produce(y_t, b_t)\} \tag{1}$$

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The set of production possibilities should also satisfy the following assumptions: (i) if $(y, b) \in P(x)$ and $b = 0$, then $y = 0$. (ii) Joint weak disposition, if $(y, b) \in P(x)$ and $(y, b) \in P(x)$,then $(\theta y, \theta b) \in P(x)$. (iii) Strong disposition of good output, if $(y, b) \in P(x)$ and $y' \le y$,then $(y', b) \in P(x)$. (vi) Strong disposition of input: if $x' \le x$,then $P(x') \subseteq P(x)$.

Under the above environmental technology, we can express the direction distance function as:

$$\vec{D}(x, y, b; g_y, -g_b) = \max\{\beta : (y + \beta g_y, b - \beta g_b) \in P(x)\} \tag{2}$$

(g_y, g_b) represent the directional vector, β represents the ratio of good and bad outputs simultaneously increasing and decreasing.The greater β, the farther the observation point is from the potential production boundary. $\beta = 0$ represents production is already at the forefront of potential production, with an efficiency of 1 under this environmental technology.

We divide K cities into G groups,and the environmental technology of each g group can be described as:

$$P_t^g(x) = \{(x_t, y_t, b_t) : x_t can\ pruduce(y_t, b_t)\} \tag{3}$$

The distance function of g group can be showed as:

$$\vec{D}^g(x, y, b; g_y, -g_b) = \max\{\beta^g : (y + \beta^g g_y, b - \beta^g g_b) \in P^g(x)\}, g = 1, \ldots, G \tag{4}$$

The meat-frontier model is to envelop the several groups which are previously divided into a large environmental technology, so that the production activities of each group are compared under the same environmental technology. Then, we can derive the environmental technology and distance function of the meta-frontier:

$$P_t^M = \{P_t^1 \cup P_t^2 \cup \ldots \cup P_t^G\} \tag{5}$$

$$\vec{D}^M(x, y, b; g_y, -g_b) = \max\{\beta^M : (y + \beta^M g_y, b - \beta^M g_b) \in P(x)\} \tag{6}$$

In addition, the production frontier of the meta-frontier must be greater than, the each group boundary. Their gap is called the technical gap:

$$TG_k = \vec{D}^M(x, y, b; g_y, -g_b) - \vec{D}^g(x, y, b; g_y, -g_b) \tag{7}$$

The shadow price of a pollutant is obtained from the duality between the distance function and the profit function.Profit function is: $\pi(p, q, w) = py - wx - qb$.

Taking into account the direction distance function, we maximize the profit:

$$\pi(p, q, w) = \max\left\{py - wx - qb : \vec{D}^M(x, y, b; g_y, -g_b) \ge 0\right\} \tag{8}$$

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Shadow price could be described as:

$$q = -p\left[\frac{\partial \vec{D}(x, y, b; g_y, -g_b) / \partial b}{\partial \vec{D}(x, y, b; g_y, -g_b) / \partial y}\right] \tag{9}$$

The shadow price is the slope of the projection point of the observation point on the frontier surface, which represents the value of the good output that is abandoned to reduce the unit bad output which could be called marginal abatement cost (Fare et al., 1993).

In order to solve the parameters of the direction distance function, there are usually non-parametric data envelope analysis method(Lee 2002) and parametric SFA (Kumar and Managi, 2009; Lin and Du, 2013). As mentioned above, non-parametric methods may result in inability to obtain intuitive parameter values, misclassification of efficiency cases.While stochastic frontier analysis methods have endogeneity, multi-parameter estimation requires large samples, and violations of monotonic assumptions (Kumar and Managi, 2009). In the parametric form, there are generally quadratic functions and transcendental logarithmic functions for parameter solving. Noh et al. (2006) use the Monte Carlo method to compare the results of these two parameter methods, the transcendental logarithm method may violate some of the assumptions of the directional distance function, resulting in deviations in the estimation results. Quadratic functions could be a better choice.

In this study, we have 3 input, 1 good output and 1 bad output. We choose the direction(1,-1)which represent good output increases and bad output decreases. The expression of the quadratic function is as follows:

$$\begin{aligned}
\vec{D}^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1) &= \alpha_0 + \sum_{n=1}^{3}\alpha_n x_n^{kt} + \beta_0 y^{kt} + \beta_1 b^{kt} + \gamma_1 t \\
&+ \frac{1}{2}\sum_{n=1}^{3}\sum_{n'=1}^{3}\alpha_{n,n'} x_n^{kt} x_{n'}^{kt} + \sum_{n=1}^{3}\delta_{n0} x_n^{kt} y^{kt} + \sum_{n=1}^{3}\delta_{n1} x_n^{kt} b^{kt} + \sum_{n=1}^{3}\eta_n x_n^{kt} t \\
&+ \frac{1}{2}\beta_{00} y^{kt} y^{kt} + \beta_{01} y^{kt} b^{kt} + \mu_0 y^{kt} t + \frac{1}{2}\beta_{11} b^{kt} b^{kt} + \mu_1 b^{kt} t + \frac{1}{2}\gamma_{11} t^2
\end{aligned} \tag{10}$$

$\beta_0 - \beta_1 = -1$; $\beta_{00} = \beta_{01}$; $\beta_{01} = \beta_{11}$; $\delta_{n0} = \delta_{n1}$; $\mu_0 = \mu_1$.

$\alpha_{nn'} = \alpha_{n'n}, n, n' = 1, 2, 3.$

The first four expressions are obtained by the transformation of the quadratic directional distance function, and the latter two equations are obtained by symmetry. Referring to Fare et al (2005), we use parametric linear programming to calculate the parameters of the group direction distance function:

$$\min \sum_{k=1}^{K}\sum_{t=1}^{T}\left[\vec{D}_G^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1) - 0\right] \tag{11}$$

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$s.t$

$(i)\vec{D}_G^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1) \geq 0, k = 1, 2, \ldots, K; t = 1, 1, \ldots T; g = 1, 2, \ldots, G$

$(ii)\dfrac{\partial \vec{D}_G^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1)}{\partial y} \leq 0, k = 1, 2, \ldots, K; t = 1, 2, \ldots, T$

$(iii)\dfrac{\partial \vec{D}_G^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1)}{\partial b} \geq 0, k = 1, 2, \ldots, K; t = 1, 2, \ldots, T$

$(iv)\dfrac{\partial \vec{D}_G^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1)}{\partial x_n} \geq 0, k = 1, 2, \ldots, K; t = 1, 2, \ldots, T; n = 1, 2, 3$

$(v)\beta_0 = \beta_1 = -1; \beta_{00} = \beta_{01}; \beta_{01} = \beta_{11}; \delta_{n0} = \delta_{n1}; \mu_0 = \mu_1$

$(vi)\alpha_{nn'} = \alpha_{n'n}, n, n' = 1, 2, 3.$

(i) represents the direction distance function is non-negative and the sample point needs to be below the leading edge surface. (ii), (iii), and (iv) represent the monotony of good output, bad output, and input, respectively. (v) represents conversion, and (vi) represents symmetry.

After the frontier of the group boundary is determined, we calculate the meta-frontier . The meta-frontier is to enclose all group boundaries which means the meta-frontier must be above all group boundaries and at least coincide with it. We can determine the leading edge of the meta-frontier by minimizing the group boundary and the meta-frontier difference. The parametric linear programming describing the meta-frontier is:

$$\min \sum_{k=1}^{K} \sum_{t=1}^{T} \left[\vec{D}_M^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1) - \vec{D}_g^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1) \right] \tag{12}$$

$s.t$

$(i)\vec{D}_M^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1) \geq \vec{D}_g^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1), g = 1, 2, \ldots, G$

$(ii)\vec{D}_M^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1) \geq 0, k = 1, 2, \ldots, K; t = 1, 2, \ldots, T$

$(iii)\dfrac{\partial \vec{D}_M^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1)}{\partial y} \leq 0, k = 1, 2, \ldots, K; t = 1, 2, \ldots, T$

$(iii)\dfrac{\partial \vec{D}_M^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1)}{\partial b} \geq 0, k = 1, 2, \ldots, K; t = 1, 2, \ldots, T$

$(iv)\dfrac{\partial \vec{D}_M^{kt}(x^{kt}, y^{kt}, b^{kt}; 1, -1)}{\partial x_n} \geq 0, k = 1, 2, \ldots, K; t = 1, 2, \ldots, T; n = 1, 2, 3$

$(v)\beta_0 = \beta_1 = -1; \beta_{00} = \beta_{01}; \beta_{01} = \beta_{11}; \delta_{n0} = \delta_{n1}; \mu_0 = \mu_1$

$(vi)\alpha_{nn'} = \alpha_{n'n}, n, n' = 1, 2, 3.$

It can be seen that the direction distance function of the meta-frontier and the group boundary has the same constraint except (i), and the constraint (i) is the only difference between the meta-frontier and the group boundary area.

3. DATA AND DIVISION

In this paper, the parameter meta-frontier method is used to measure the shadow price of sulfur dioxide in three major urban agglomerations in China. The Beijing-Tianjin-Hebei urban

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agglomeration, the Yangtze River Delta urban agglomeration and the Pearl River Delta urban agglomeration contain 48 prefecture-level cities including 672 sample observation points . All data are from China City Statistical Yearbook, including good output GDP, bad output of sulfur dioxide, and three input factors: labor, capital, and energy.

3.1. Good Output

The good output is derived from the regional GDP of the local cities in 2003-2016, which is based on the gradual elimination of the price factor in 2003. We could have the actual GDP (GRP) of each city.

3.2. Bad Ouput

The bad output is industrial sulfur dioxide emissions from 2003-2016. Although the Chinese environmental tax system could be traced back to the environmental protection agency which is temporarily set up by the former State Council Environmental Protection Leading Group in 1978. However, in 2003, the State Council intends to strengthen the management of the collection and use of sewage charges. It promulgates the Measures for the Administration of the Collection of Sewage Charges, the Regulations on the Administration of the Collection and Use of Sewage Charges, and the Measures for the Administration of the Collection and Use of Sewage Charges. The introduction of these three documents truly indicates that China's sewage charges have officially entered the stage of full implementation of sewage charges (Lu Hongyou et al. 2018).Thus,we choose 2003 as the starting year for studying the shadow price of sulfur dioxide.

3.3. Input

As an input factor, labor time will be closer to production authenticity than the labor force, but it is not available to obtain the real labor hours of various industries. This paper selects the number of employees in prefecture-level cities in the yearbook as the proxy indicator of labor. Capital is calculated by the city's fixed capital stock. Since the energy statistics of different provinces and cities are not the same, we adopt standard coal as a proxy variable (Huang et al.2017)

3.4. City and Division

The 13 cities in the Beijing-Tianjin-Hebei urban agglomeration are selected from the concept and document:“Capital City Circle” ,the “Beijing-Tianjin-Hebei Coordinated Development Plan”. According to the different division concepts of transportation and ecology, the division of Beijing-Tianjin-Hebei city ranges from 10 cities to 14 cities. This paper takes 13 cities selected by common method and excludes the Xiong'an New District which is under construction. The selection criteria for the 9 cities of Guangzhou, Shenzhen and other cities in the Pearl River Delta urban agglomerations come from the “Guangdong, Hong Kong and Macao Dawan District Development Plan”. The selection criteria for the 26 cities of Shanghai, Hangzhou and Nanjing in the Yangtze River Delta urban agglomeration are from the “Development Planning of the Yangtze River Delta Urban Agglomeration”.

The concept of urban agglomerations originates from the French geographer Goldman. World-class urban agglomerations are highly concentrated representatives of regional economic, transportation, and cultural factors. Currently, the world-famous urban agglomerations include the Tokyo city group and the New York city group. The Central Committee of the Communist Party of China and the State Council issue the "Opinions on Establishing a More Effective Regional Coordination and Development Mechanism" on November 18, 2018, stating that the implementation of the regional coordinated development strategy is one of the major strategies of the new era. As mentioned earlier, the selection of different environmental technologies in the measurement of pollutant emission reduction will have an impact on the measurement results. The level of economic development, policy

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preferences, resource endowments and other factors between regions will cause significant heterogeneity between regions. The national sample calculation of shadow prices or simply dividing China into East, West and West as a classification will seriously affect the calculation of marginal abatement costs. As the three most developed urban agglomerations in China, the Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta urban agglomerations account for nearly 40% of China's GDP in 2016. In the process of formulating environmental policies, it is not appropriate to take the shadow price of pollutants on the common border across the country as a reference for emission reduction. The calculated shadow price in developed regions does not reflect the actual local conditions. From the regional perspective, the shadow price of pollutants in the eastern region is generally higher than that in the east and west (Chu Wei 2014). China has a vast territory, resource endowments, and huge economic structure. Regional heterogeneity cannot be ignored in calculating marginal abatement costs. The innovation of this paper is to use the three most developed urban agglomerations in China as a group to measure the shadow price of pollutants. Then, calculating the marginal abatement cost in meta-frontier.The results will be more in line with the actual situation of economic development.

Table 1. Descriptive statistics

		Mean	Max	Min	SD
Beijing-tianjin-hebei	GRP	2373.54	13366.96	234.98	2625.82
	SO2	10.66	33.19	2.02	7.52
	capital	3758.43	30734.97	207.47	4771.56
	Labor	114.63	878.05	21.00	180.49
	energy	3095.73	10700.00	456.45	2539.65
Yangtze River Delta	GRP	2479.11	20150.89	75.50	2962.27
	SO2	6.83	49.64	0.19	6.44
	capital	3276.19	18100.30	55.71	3403.30
	Labor	82.16	627.78	6.38	99.69
	energy	2192.44	12100.00	121.20	2326.93
Pearl River Delta	GRP	3250.54	14934.70	466.39	3161.19
	SO2	5.51	19.75	0.23	4.43
	capital	2525.43	12133.37	325.73	2291.41
	Labor	107.25	459.97	16.05	106.11
	energy	2299.63	7440.00	335.41	1845.29

As shown in Figure 1, we divide data into three major urban agglomerations of Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta. Although the three major urban agglomerations belong to the most developed areas of China, the GRP in the Pearl River Delta is the highest among the three major urban agglomerations, and the SO2 emissions are the smallest. In contrast, GRP and SO2 emissions in the Beijing-Tianjin-Hebei region are at a disadvantage compared to the other two regions. In terms of investment, the Beijing-Tianjin-Hebei region is at the highest level of capital, labor and energy. The Pearl River Delta invests more labor and energy than the Yangtze River Delta. Significant regional differences in input and output are bound to have a certain degree of impact on production efficiency and shadow price estimates.

4. MPIRICAL RESULTS

Using the above model method and collated data, we measure the production efficiency and shadow price of the three major urban agglomerations under the group boundary, and the meta-frontier. We conduct empirical analysis based on the differences in production efficiency under different boundaries, technical gaps, potential emission reduction targets, and policy

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impacts of shadow prices. The calculation process of efficiency and pollutant shadow price in this paper is carried out in GAMS. To ensure convergence of the calculations, we adopt Fare et al (2005) to standardize the data.

4.1. Inefficiency U-Shaped Feature

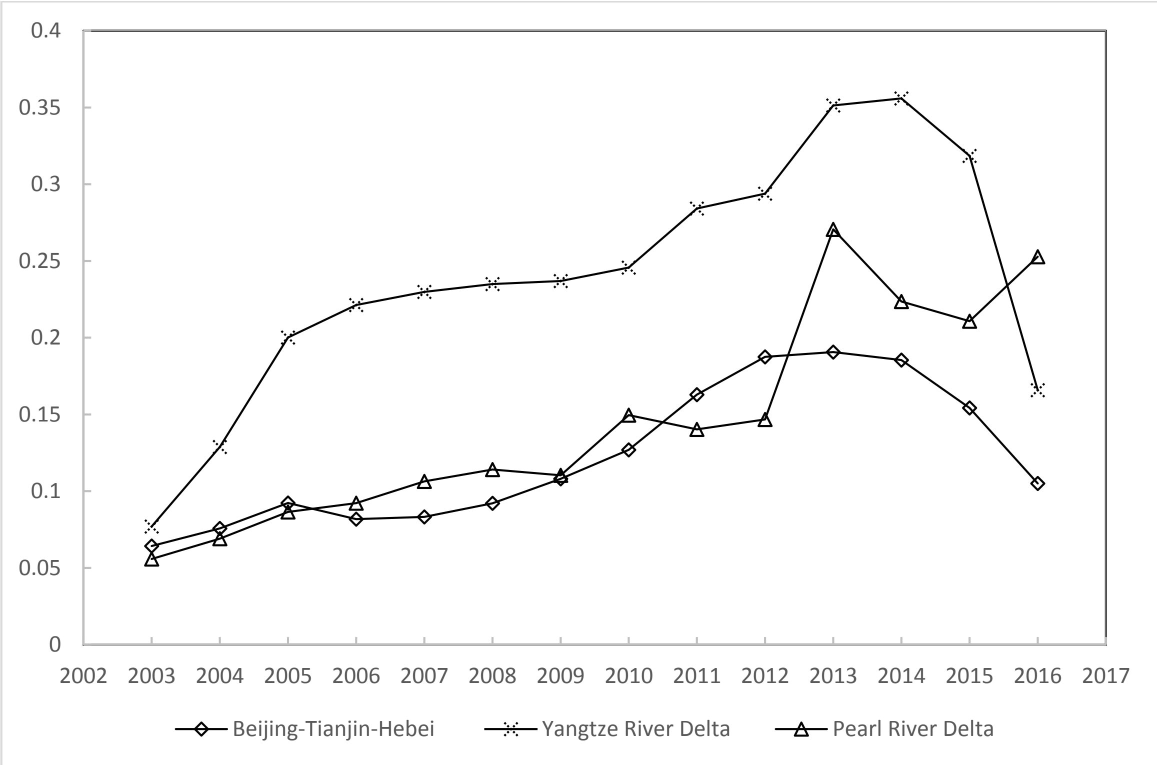

Figure 1. Group efficiency

From Figure 1, we can conclude that the average distance function of the medium- and long-angle urban agglomerations in 2003-2016 is 0.24, and the efficiency is at a low level. The Beijing-Tianjin-Hebei urban agglomeration is 0.12, and the efficiency is at a high level. Although the efficiency of the three is inconsistent from the figure 1, we should note that the efficiency levels of each group cannot be directly compared. Because of the regional heterogeneity, the environmental technologies of each group and the production frontiers are different. It does not mean that the efficiency of the Beijing-Tianjin-Hebei region is higher than that in the Yangtze River Delta region. Therefore, the efficiency of calculations under group boundaries can only be compared for observation points of the same group. For example, the efficiency of Shanghai in the Yangtze River Delta urban agglomeration is higher than that of Hangzhou, which means that Shanghai's production efficiency is closer to the production frontier of the Yangtze River Delta group than Hangzhou, and the efficiency level is higher.

From Fig. 2, we can see that the production efficiency of each urban agglomeration under the meta-frontier is lower than that of the group boundary, which is mainly due to the characteristics of the "big envelope" of the meta-frontier. Under the full sample data, the meta-frontier is always above and at least coincides with the boundaries of each group. From the trend point of view, the value of the direction distance function of the three urban agglomerations reflects the inverted U-shaped characteristics from rising to decreasing, and it becomes the turning point of efficiency growth around 2013. This is mainly due to the synergy between the regions. For example, the introduction of the "National New Urbanization Planning (2014-2020)" and other documents has promoted the coordinated development of large and medium-sized cities and the surrounding economic belt. In 2011, the coordinated development

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of the Beijing-Tianjin-Hebei region ended the previous research and entered the national level. "Beijing-Tianjin-Hebei integration" and "Capital Economic Circle" were included in the "Twelfth Five-Year Plan".

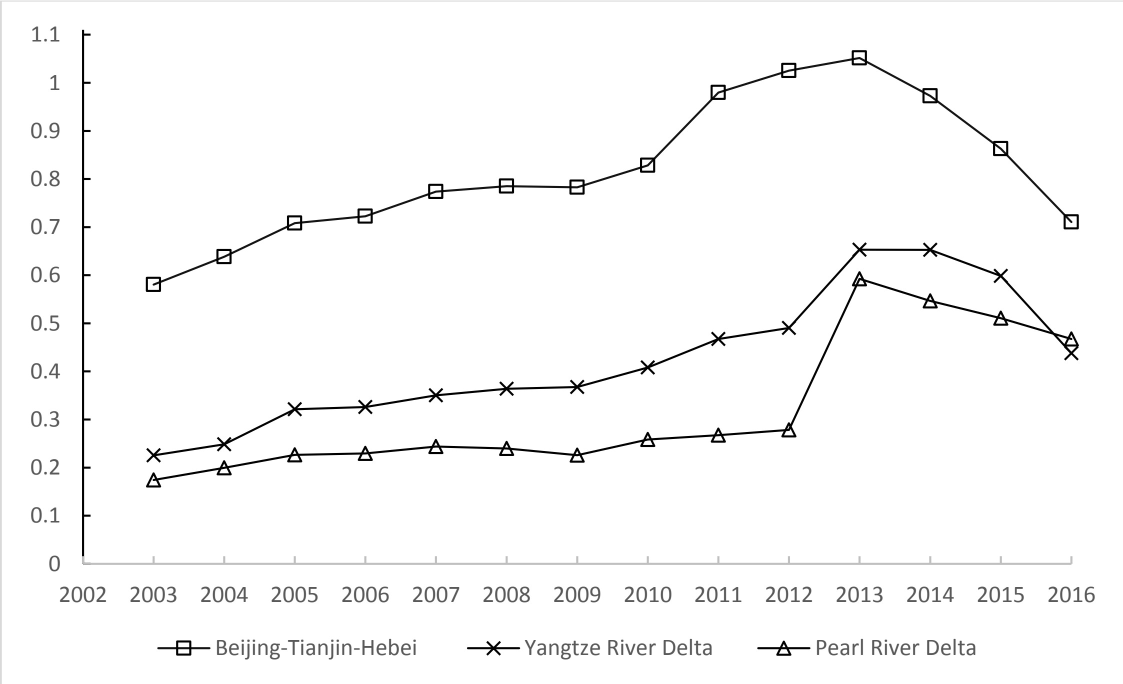

Figure 2. Meta-frontier efficiency

It is worth noting that the Beijing-Tianjin-Hebei region of the three major urban agglomerations has the lowest efficiency. The other two are closer to each other and converge around 2016. Significantly different from the results in the above group boundaries, when the three major urban agglomerations are at the meta-frontier, the efficiency of the Beijing-Tianjin-Hebei region is at a low level until 2016. It can be seen that the solution of the production efficiency of the region through the frontal group formed by the Beijing-Tianjin-Hebei region cannot truly reflect its economic development status. Whether the strong one should be placed in the same category of economic volume for comparison. In order to get real development, in the group boundary, the number of observation points on the front surface of the three groups of Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta are 10, 9 and 12. Among the meta-frontier, only Shanghai and Hangzhou in the Yangtze River Delta urban agglomeration have two observation points on the front surface. This shows that when the seemingly well-developed Beijing-Tianjin-Hebei urban agglomeration under the group boundary is compared with two urban groups of the same level under the meta-frontier, it is slightly inferior. The development of the Beijing-Tianjin-Hebei urban agglomeration began in the 1981 which is called North China Economic and Technological Cooperation Zone. After several decades of development, China promotes the coordinated development of Beijing-Tianjin-Hebei on the basis of the "Twin City Record" in 2013, The Beijing-Tianjin-Hebei urban agglomeration relies on a strong industrial base in the process of coordinated development, and there are many important public-owned enterprises. However, the coordinated development of the Beijing-Tianjin-Hebei region still has a certain gap compared with the Yangtze River Delta region of the Pearl River Delta (Weizhong Yang 2019). First, we can see from the descriptive statistics table above that the average GRP of the Beijing-Tianjin-Hebei urban agglomeration is at the lowest level. In addition, the level of urban development in the Beijing-Tianjin-Hebei region is significantly different. The siphon effect is obvious, and there are many low-level cities and

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towns nearby. The industrial structure convergence in Hebei is hard to be affected by Beijing and Tianjin. The Yangtze River Delta and the Pearl River Delta region have a relatively balanced urban development. Apart from the four first-tier cities of Shanghai, Guangzhou and Shenzhen, the development links between Hangzhou, Ningbo, Suzhou and other cities are growing (Xuliang Zhang et al. 2010). The relationship between the cities has gradually increased (Zhixiong Mei et al. 2012), and the synergistic development effect has been remarkable, driving the surrounding areas to prosper together.

4.2. Technology Gap Catching Up and Potential Emission Reduction Targets

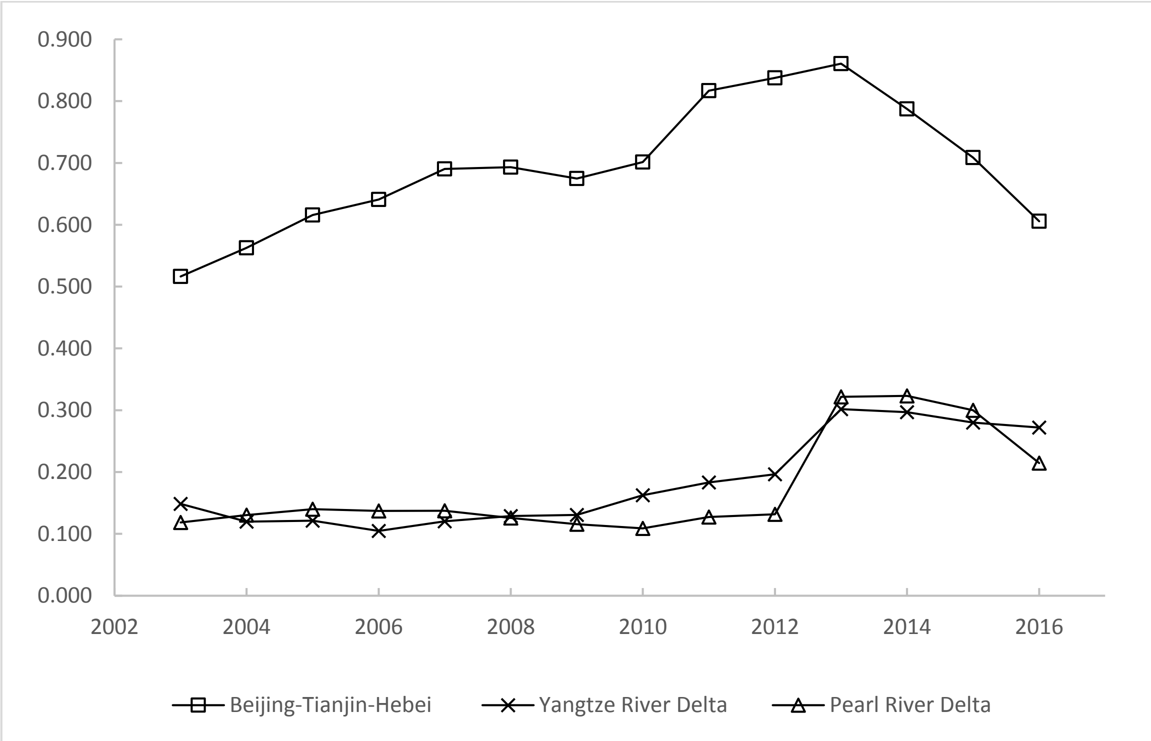

Figure 3. Technology gap

It can be seen from the figure 3 that the technical gap between the Pearl River Delta and the Yangtze River Delta region is not very obvious in 2003-2009. There is an inverted U-shaped change from 2010 to 2016. The technology gap in the Beijing-Tianjin-Hebei region is relatively large, and it is in a U-shaped change in 2003-2016, which is more obvious than the technical gap in the other two regions. It can be seen that after 2013, the technological gaps in the three major regions have decreased simultaneously, and the Beijing-Tianjin-Hebei region has shown a trend of catching up. This is just like the promotion of regional synergistic development strategies since 2013, which leads to the improvement of regional development efficiency and closer to potential production efficiency.

The value of the direction distance function of the three major urban agglomerations is the non-efficiency level of each region. For example, the average distance function of the Yangtze River Delta region from 2003 to 2016 is 0.4376, then the non-efficiency level of the Yangtze River Delta region is 43.76%. From this we can conclude that if the production is carried out according to the potential productivity level, the three major urban agglomerations of Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta can achieve SO2 emission reductions of 87,000 tons , 28,800 tons and 1.76 million tons respectively from 2003-2016.

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4.3. Shadow Price and Policy Impact

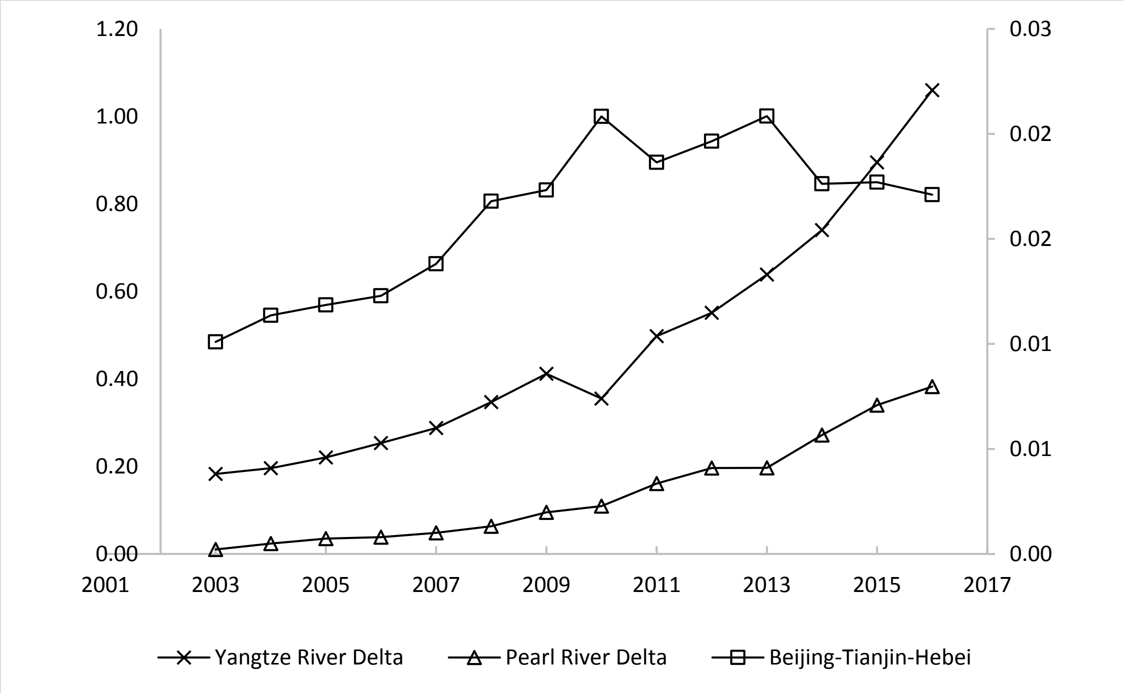

Figure 4. Group shadow price

From the overall trend of Figure 4, the shadow prices of the three major regions have increased year by year, which is consistent with the results by Zhengge Tu (2009) Chen Shiyi (2010) Murty et al. 2007 and Hettige et al (1996). In general, a more efficient company has a higher shadow price of pollutants, because there is less room for re-integration of resources to meet emission reduction targets under current conditions (LEE et al. 2002).

The Beijing-Tianjin-Hebei region has a huge gap between the average price of the shadow and the production efficiency compared to the Pearl River Delta and the Yangtze River Delta. In the same way as the efficiency in the previous article, the prices calculated by different frontiers cannot be directly compared. By comparing individual cities under the same group, we found that the shadow price in Beijing is significantly higher than in other regions. This is mainly because the Beijing-Tianjin-Hebei urban agglomeration has higher requirements for emission reduction standards. "Beijing's "13th Five-Year Plan" Air Pollution Prevention and Control Plan" , "Beijing's 13th Five-Year Plan for National Economic and Social Development" and other documents put forward strict control measures for air pollution. In addition, the "APEC" meeting, the "World Championships", the "Belt and Road" summit forum and other activities also force the Beijing region to implement stricter governance of air quality. In order to relieve the function of Beijing's non-capital industry, the heavy industry in Beijing and Tianjin has gradually shifted to Hebei, which will inevitably lead to the reduction of pollutants in Beijing and the substantial increase in marginal abatement costs.

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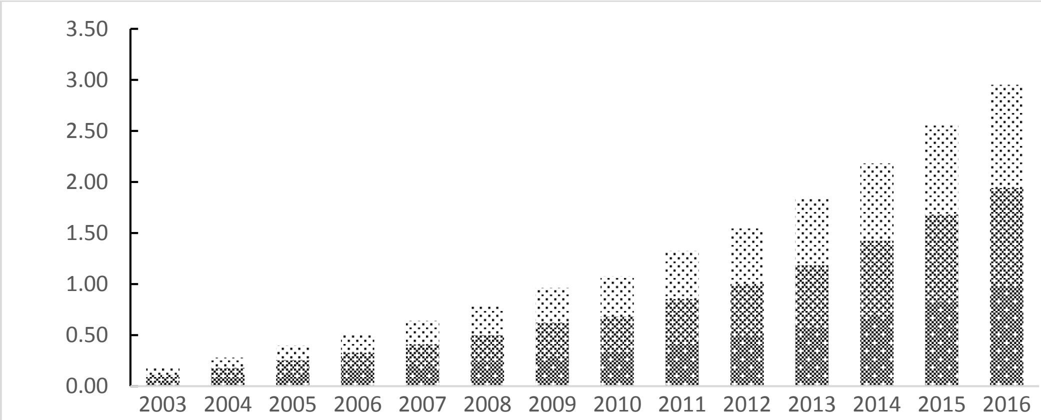

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
PRD	0.06	0.10	0.14	0.18	0.23	0.28	0.34	0.40	0.47	0.55	0.65	0.76	0.87	1.011
YRD	0.06	0.09	0.13	0.17	0.21	0.27	0.33	0.35	0.45	0.52	0.62	0.73	0.85	0.969
BTH	0.05	0.09	0.12	0.16	0.20	0.24	0.29	0.34	0.40	0.48	0.56	0.70	0.83	0.971

Figure 5. Meta-frontier shadow price

As can be seen from the figure 6, the shadow price gap of the meta-frontier of the three major urban agglomerations is smaller than that of the group, but the shadow price of the Beijing-Tianjin-Hebei region remains at the lowest level. This result is derived from Zhengge Tu (2009). The conclusion is consistent. He calculates the SO2 shadow price of industrial enterprises above designated size in 30 provinces and cities. The shadow price of sulfur dioxide depends on the emission level and productivity level. Combined with the efficiency comparison under the meta-frontier, the SO2 emission in the Beijing-Tianjin-Hebei region is the highest, the production efficiency is at the lowest level in the three places, and the shadow price of SO2 is also at the lowest level. Compared with the group price, the meta-frontier price is higher, and the result of the shadow price of power plant pollutants is higher than the group price under the meta-frontier drawn by Ning Zhang et al. (2016). If the environmental regulations are calculated according to the calculation results of the region alone, such as the calculation of prices in Beijing and Tianjin, the price will be underestimated. Calculating the three major urban agglomerations of China as a total sample, according to the current highest level of China's economic development, will reflect the authenticity of the shadow price of regional pollutants.

On December 25, 2016, the passage of the Environmental Protection Tax Law of the People's Republic of China markes the discharge of sewage charges collected for more than 30 years by environmental protection tax. The collection of environmental taxes can bring about the re-allocation of capital and other factors, making the economy develop towards cleanliness. Taxation of pollutants will reduce the negative effects of direct taxation on energy (Jianwu He et al. 2009). Andrea Baranzini (2004) argues that marginal abatement costs should be the optimal tax rate for environmental taxes. The shadow price of the pollutants calculates in this paper can provide an effective reference for environmental policy makers. According to the "Environmental Protection Tax , Taxation Schedule" , "Tourable Contaminants and Equivalent Values", the taxable standard for sulfur dioxide per pollution equivalent is 1.2-12 yuan/pollution equivalent, which is 1.26-2.63 yuan after conversion. The shadow prices of the 2016 Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta regions calculated in this paper are located within the levy range of sulfur dioxide, namely 9.72 yuan/kg, 9.70 yuan/kg and 10.12 yuan/kg. The environmental tax rate must be sufficient to change the behavior of the emitters in order to reflect the institutional value of environmental taxes (Chen Shiyi 2011). Under normal circumstances, each region should adjust the environmental tax according to the marginal abatement cost. Taking the Beijing-Tianjin-Hebei urban agglomeration as an example,

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the taxation fee in Beijing is the upper limit of the levy standard, which is 12.63 yuan/kg. It is greater than the marginal abatement cost calculated in this paper, The Tianjin environmental protection tax standard is 10.53 yuan / kg, slightly higher than the marginal abatement cost. While the environmental tax collection in Hebei Province imposes the third-rate tax standard, only one tax amount reaches the marginal abatement cost. From the perspective of emission reduction, the environmental protection taxation standards in Hebei Province are too low, which is less than the marginal abatement cost, and cannot impose emission reduction constraints on emitters.

Table 2. Tax Amounts of Environmental Protection Tax

Area	Jurisdiction	SO2 yuan/kg
Beijing	Citywide	12.63
Hebei	The 13 counties (cities, districts) adjacent to Beijing are Lishui County, Zhuolu County, Guangyang District of Langfang City, Anci District, Gu'an County, etc.	10.11
	Shijiazhuang, Baoding, Langfang and Dingzhou, Xinji City	6.32
	Tangshan, Qinhuangdao, Zhangzhou, Zhangjiakou, Chengde, Hengshui, Xingtai, Handan City	5.05
Tianjin	Citywide	10.53

5. CONCLUSION

In order to solve regional heterogeneity and SO2 emission reduction problems, the three major urban agglomerations with the most developed economies under the meta-frontier are measured. The shadow price and production efficiency of pollutants in the Beijing-Tianjin-Hebei urban agglomeration, the Yangtze River Delta urban agglomeration and the Pearl River Delta urban agglomeration have certainly exploratory. In this paper, 48 prefecture-level cities and 672 observation points were selected and divided into three groups. The differences between the shadow price and production efficiency of pollutants in the three major urban agglomerations under the meta-frontier were compared. The following conclusions are drawn: (1)The production efficiency and technological gap of the three major urban agglomerations show a U-shaped change from 2003 to 2016, and 2013 becomes the turning point of efficiency improvement. This is mainly because around 2013, the regions have strengthened synergistic development, increased inter-regional economic cooperation, and shared development results, resulting in a gradual increase in production efficiency. (2) although the shadow price and production efficiency of the Beijing-Tianjin-Hebei region are outstanding under the group boundary, they are always in the worst position in the meta-frontier. This shows that the Beijing-Tianjin-Hebei region will be slightly inferior to the same developed regions. It is necessary to deepen the industrial structure, reduce the siphon effect in the Beijing-Tianjin region, and promote regional prosperity. (3) According to the potential production efficiency, the 2003-2016 Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta can achieve an annual reduction of 87,000 tons, 28,800 tons and 17,600 tons. (4) The shadow prices of the three major urban agglomerations calculated in this paper are within the range of the sulfur dioxide levy standard in the Environmental Protection Tax and Taxation Schedule. Taking the Beijing-Tianjin-Hebei region as an example, the SO2 levy standards in Beijing and Tianjin are above the marginal abatement cost, but the levying standards in Hebei are much smaller than the marginal abatement costs. From the perspective of emission reduction, the tax collection should have an impact on the behavior of the emitters, and the Hebei region should increase the collection of environmental taxes.

It should be noted that the 2016 shadow price calculated in this paper is within the levy interval, but this is an intertemporal comparison. Since the 2017-2018 China Urban Statistical

Yearbook has not been updated, the spot price and policy comparison cannot be used. Therefore, the tax standards and marginal abatement costs implemented on January 1, 2018 will be further studied in the future.

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