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Research on the Optimization of Capital for the Governance of Bulk Coal in Beijing-Tianjin-Hebei Region

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Abstract: Beijing, Tianjin and Hebei each contributed to the comprehensive governance of bulk coal to treat bulk coal pollution in a mutually beneficial way in 2017. The cooperative game theory is used in this paper to study the environmental benefits and cost effectiveness brought about by this comprehensive governance strategy, primarily focusing on the issue of how to maximize the environmental benefits by choosing an appropriate strategy since the benefits to Beijing, Tianjin and Hebei are closely related. Therefore, the linear optimization, game theory and Shapley value method in the cooperative game model are used to find the ways to minimize the total governance cost of bulk coal in the three areas. In addition, the issues of how to carry out rational distribution and transfer of governance capital among the three places are explored according to the actual amounts of consumption of bulk coal, the influence of the coal burning on the $PM_{2.5}$ and the actual cost of coal governance in Beijing, Tianjin and Hebei in 2017. The results show that the governance task in Hebei Province is the most onerous, and requires more investment than the other two cities. Thus, it requires the support from other two cities, with the amount of increased capital required of about 600 million Yuan. At the same time, the cost saved after optimization in Tianjin is calculated to be the largest, which thus can be adjusted appropriately and allocated to Hebei for the governance of bulk coal. The model constructed in this paper can not only be used to solve the issues related to bulk coal consumption in Beijing, Tianjin and Hebei, but also to carry out the effective distribution of capital, by which a win-win scenario among the three places can be achieved.

Key words: Beijing-Tianjin-Hebei region; bulk coal governance; cooperative game; Linear Optimization

1 Introduction

The former Ministry of Environmental Protection issued the *Action Plan for the Comprehensive Governance of Atmospheric Pollution in Autumn and Winter in 2017-2018 in Beijing, Tianjin and Hebei and Surrounding Areas* in 2017, and proposed to complete the task of replacing coal with electricity and gas in 2018. Beijing, Tianjin and Hebei also introduced a number of policies related to the comprehensive governance of bulk coal in 2013. Beijing promulgated and implemented the *Action Plan for Clean Air in Beijing in 2013–2017* (Action Plan for Clean Air), which carried out an in-depth analysis of the pollution sources, such as coal, motor vehicle, industrial production and dust, and decomposed the task by year in the implementation process. The bulk coal consumption in the main urban area of Beijing has been reduced by means of replacing bulk coal with gas and electricity and centralized heating, etc. as guided by the policy of "reducing coal and replacing it with alternative energy". The plan of "replacing coal with alternative energy", that is, replacing energy, such as coal which has pollutant discharges failing to meet the requirement, with clean coal products, has primarily been carried out in the rural-urban fringe zone. In 2013, Tianjin Municipal People's Government issued the *Notice of the Tianjin Municipal People's Government on the Action Plan for Fresh Air in Tianjin* (JZF No. [2013]35) and *requirements of the Command Post*

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of "Beautiful Tianjin No. 1 Project, which strives to implement the method of replacing bulk coal with clean energy and clean coal (anthracite briquettes) as well as combining the two ways of dredging and plugging, and finally realizing the comprehensive governance of bulk coal in Tianjin by replacing it with alternative energy. Beijing, Tianjin and Hebei also issued corresponding preferential policies and offered financial subsidies to residents who used advanced stoves and clean energy, such as briquettes. These three places jointly issued the *Action Plan for the Coordinated Development of Energy in Beijing, Tianjin and Hebei* (2017–2020) in 2017 to jointly promote the task of reducing bulk coal. However, there are two main problems with this non-cooperative command-control model. First, the cost per unit removal of pollutants in the Beijing-Tianjin-Hebei region varies greatly due to differences in pollution control technologies and levels, industrial structures and the composition of enterprise ownership. However, as the pollutant index is not allowed to be transferred across provinces, it is impossible to take advantage of the differences in cost and optimize the allocation of resources. Second, some areas in Beijing-Tianjin-Hebei region have idle pollutant treatment capacity, while others have insufficient pollutant treatment capacity, which prevents the social resources in the Beijing-Tianjin-Hebei region from being fully utilized and makes the resource allocation unreasonable, leading to the high total cost of control in the Beijing-Tianjin-Hebei region.

Cooperative game theory is widely used in pollution control research. Halkos established a static game model of acid rain in Europe by using game theory to allocate SO_2 emissions. Across the cooperation, the level of removal of cooperative pollutants is higher than that of non-cooperative ones. And the total cooperation benefit would be much greater than that of non-cooperative emissions. Krawczyk (2005) used the game model of coupling constraints to analyze the distribution and production situation of the three participants in the basin, and the existence of Nash equilibrium of emission behavior was proven and solved. Zhao Laijun (2005) established a model of transboundary water pollution cooperation and leveling in the basin taking the Taihu Lake Basin as an example. He also put forward the model of trans-border water pollution emission trading rights and the model of tax regulation and management in Huaihe River Basin.

The Shapley value method is one of the main cooperative income allocation methods in cooperative game theory, which is not based on either equal distribution or proportional distribution of investment costs. Instead, it is a distribution method based on the importance of each partner in the process of generating economic benefits. The method is scientific and widely used in the study of pollution control. Dinai et al. (1997) took the San Joaquin Valley, California, as an example of how to allocate the costs of cooperative treatment among polluters using the Shapley value method. Petrosjan et al. (2003) constructed a dynamic game model of inter- state cooperative pollution control according to the method of dynamic game theory, and calculated the eigenfunction values of various possible alliances. The Shapley value method was used to distribute the cost of cooperative pollution control fairly among the cooperative countries. Nir et al. (1997) simulated the non-cooperative and cooperative behaviors of water resource conflict subjects, and obtained the rational basis and necessity of cooperative behaviors based on the comparison of different behavioral results. Chen et al. (1999) applied cooperative game theory to study the cost allocation of pollutant treatment investment, and compared the effects of the Shapley value and CGA on the cost allocation scheme. Liu et al. (2011) adopted cooperative game theory to construct the environmental cooperative game model in various regions of a tidal river, and used the Shapley value method to determine the fair distribution of cooperative benefits. Tan et al. (2011) established the cost optimization model of the power generation side and the power supply side, and distributed the profits between the generation side and the power supply side by using the Shapley value method. Together, these studies have made a lot of advancements in the distribution of total amount of pollutants and cooperative income distribution, but there has been no administrative region to serve as the main body to build a cooperative game model, so as to control environmental pollution and achieve multi-level win-win results.

The cooperative game theory is used in this paper to study the environmental benefits and cost effectiveness brought about by the comprehensive governance of bulk coal in Beijing, Tianjin and Hebei in 2017, primarily focusing on the issue of maximizing the environmental benefits by choosing an appropriate strategy since the benefits of Beijing, Tianjin and Hebei are closely related. It is a theory to provide guidance for researchers on how to choose an appropriate strategy so as to balance the benefits of the three places in the course of concentration. The Shapley value method is a cooperative benefit distribution method in cooperative game theory, which allocates the income according to the degree of contributions of the parties in the concentration to the economic benefits (Shapley and Lloyd S., 1958). At present, many achievements have been made in environmental pollution at home and abroad by virtue of cooperative game theory, but there have been few studies applying it to the governance of bulk coal. Therefore, the linear optimization, game theory and Shapley value method in the cooperative game model are used in this paper to find ways to minimize the total governance cost of bulk coal in Beijing, Tianjin and Hebei. They are also used to explore the issues of how to carry out rational distribution and transfer of governance capital among the three places according to the actual amount of consumption of bulk coal, the influence of the coal burning on the $PM_{2.5}$ and the actual cost of coal governance in Beijing, Tianjin and Hebei in 2017.

2 Research methods and the construction of the Cooperative Game Model

The theoretical basis of the cooperative game model constructed in this paper is to reduce the target $PM_{2.5}$ concentration in 2020 by reducing the amount of coal consumption in Beijing, Tianjin and Hebei, thus reducing the overall $PM_{2.5}$ concentration in these cities. The influences of various provinces and cities on the air of Beijing-Tianjin and-Hebei region, the functional relation of the annual coal consumption and the $PM_{2.5}$ concentration, the governance cost function and the constraint function of governance are required in the process of construction of the model. The ways to reduce the total governance cost and allocate the capital reasonably can be found by virtue of analysis and optimization of the model.

2.1 Setting of the parameters

In view of the availability of data, this study focuses on the cost of fuel operation replacement and the cost of supporting infrastructure construction when conducting economic benefit analysis. Other fees are beyond the scope of this article. The following are the basic assumptions for the model. 1) The amount of bulk coal consumption in each province forms the direct proportion function relationship with the $PM_{2.5}$ concentration, and the scale is a constant. 2) The consumption of bulk coal in various provinces and cities will affect the overall $PM_{2.5}$ concentration in Beijing-Tianjin-Hebei region proportionally, and the scale is a constant. 3) The alternative methods adopted in different provinces and cities include "bulk coal to briquette", "coal to gas" and "coal to electricity". 4) The annual amount of bulk coal replaced in each province after the optimization is equal.

2.2 Construction of the Cooperative Game Model

2.2.1 To save the cost by optimizing the solution

The cost to meet the target $PM_{2.5}$ concentration is calculated based on the concentration among Beijing, Tianjin and Hebei and their differential governance costs, and its comparison with the established cost before optimization gives the cost reduction by optimization.

According to the assumption that the amount of bulk coal consumption is directly proportional to the $PM_{2.5}$ concentration in the air, the scale coefficient is *li*. The formula is as follows:

$$N_i \cdot l_i = \mathrm{a}_i \cdot \alpha_i \quad (1)$$

According to the constraint condition that the $PM_{2.5}$ concentration in Beijing-Tianjin-Hebei region shall not be higher than the target concentration in 2020, the constraint condition 1 is as follows:

$$\sum_{i=1}^{n} \frac{N_i l_i}{\alpha_i} \beta_i - \sum_{i=1}^{n} \frac{N_{0i} l_i}{\alpha_i} \beta_i \leqslant a_0 \quad (2)$$

At the same time, as the existing scheme is being implemented, it is assumed that the amount of coal consumption in Beijing-Tianjin-Hebei region should be reduced to at least 1/2 of the annual consumption of 2017, so the constraint condition 2 will be as follows:

$$N_i \geqslant N_{0i} \geqslant \frac{1}{2} N_i \quad (3)$$

Table 1 Symbols and parameters in the Cooperative Game Model

Name & unit	Symbols
Annual bulk coal consumption in a region (10^4 t)	N_i
The total amount of bulk coal replaced in a region (10^4 t)	N_{0i}
The annual amount of coal replaced in a region (10^4 t)	N_{ki}
The $PM_{2.5}$ concentration in a region (μg m^{-3})	a_i
The proportional contribution of bulk coal to the $PM_{2.5}$ concentration in the region	α_i
The proportional contribution of bulk coal of other places to the $PM_{2.5}$ concentration in Beijing, Tianjin and Hebei	β_i
The target $PM_{2.5}$ concentration in Beijing, Tianjin and Hebei in 2020 (μg m^{-3})	a_0
The unit cost for replacing bulk coal with clean briquette in a region (Yuan t^{-1})	X_{1i}
The unit cost for replacing bulk coal with gas in a region (Yuan t^{-1})	X_{2i}
The unit cost for replacing bulk coal with electricity in a region (Yuan t^{-1})	X_{3i}
The proportion of bulk coal replaced by clean briquette/gas/electricity respectively in a region	$\gamma_{1i}/\gamma_{2i}/\gamma_{3i}$
The proportional constant of the amount of bulk coal consumption and the $PM_{2.5}$ concentration	l_i
The cost per year in a region after optimization (10^4 Yuan)	T_{ki}
The total cost in a region after optimization (10^4 Yuan)	T_{0i}
The total cost after optimization (10^4 Yuan)	T
The total cost before optimization (10^4 Yuan)	T_0
The transfer volume of the fund (10^4 Yuan)	E_i

Note: the values of *i* are 1, 2 and 3, referring to Beijing, Tianjin and Hebei respectively; *k* refers to the year.

Then, the range of N_{0i} can be obtained.

The total amount of bulk coal consumption reduction needed from 2018–2020 is now obtained. According to the assumption, the equation relating the amount of bulk coal consumption reduction needed in each year and its total amount is:

$$2 \times Nk_i = N_{0i} \tag{4}$$

The relation between the annual cost and the total cost in a region is as follows:

$$\sum_{i=0}^{n} Tk_i = T_{0i} \tag{5}$$

The objective function is obtained by taking the lowest total cost as the object, by which the total cost T after optimization is obtained as follows:

$$\sum_{i=0}^{n} T_{0i} = T \tag{6}$$

n refers to the number of provinces and cities involved, so its value is 3. Ti is the cost for each province or city. The formula obtained by adding the cost of coal replaced with briquette, gas and electricity is as follows:

$$T_{1i} = X_{1i} \cdot \gamma_{1i} \cdot N_{1i} + X_{2i} \cdot \gamma_{2i} \cdot N_{1i} + X_{3i} \cdot \gamma_{3i} \cdot N_{1i} \tag{7}$$

Finally, the total revenue after optimization (reduced cost after optimization) is obtained as follows:

$$B = T_0 - T \tag{8}$$

2.2.2 The income distribution calculated by the Shapley value

After obtaining the optimized total income, the income is distributed by calculating the Shapley value. The income distribution scheme in Beijing, Tianjin and Hebei is $X = (X1, X2, X3)$, where Xi (i = 1, 2, 3) is determined according to its corresponding characteristic function V with the assumptions that Beijing, Tianjin and Hebei constitute a set $N = \{S1, S2, S3\}$ and $V(S)$ represents the income obtained when all or some of the provinces or cities participate in the game. Under these conditions there will be 7 kinds of $V(S)$: $V(\{S1\})$, $V(\{S2\})$, $V(\{S3\})$, $V(\{S1, S2\})$, $V(\{S1, S3\})$, $V(\{S2, S3\})$, and $V(S1, S2, S3)$ in the case of concentrations among Beijing, Tianjin and Hebei. Xi, the income of each province after the distribution obtained by the formula, is as follows:

$$X_i(V) = \sum_{S_i \subset S} W(|S|) \times [V(S) - V(S - S_i)] \tag{9}$$

$$W(|S|) = \frac{(n - |S|) \times (|S| - 1)}{n} \tag{10}$$

where n=3 (the sum of provinces and cities involved in the cooperative game), $W(|S|)$ is the weighting factor, and $V(S)$ is the cooperative benefit of the alliance when province i is included. $V(S\text{–}Si)$ is the cooperative benefit of the alliance when province i is removed and $|S|$ is the number of provinces and cities involved in the alliance. The reduced cost is transferred to other provinces and cities according to the above distribution scheme. The cost optimized by the Shapley value is obtained by reducing the cost before the optimization by the reduced cost.

$$T_{1i} = T_{0i} - X_i \tag{11}$$

The final optimized distribution plan of the capital is obtained by calculating the amount of cost transferred:

$$E_i = T_i - T_{1i} \tag{12}$$

If E_i is positive, the province or city needs to allocate capital to support the other provinces and cities; if it is negative, the province or city will need financial support from the other provinces and cities.

3 Data results

3.1 Actual value and cost function of each parameter

The data of 2017 are used, and the target $PM_{2.5}$ concentration is based on the compliance requirements for 2020 set up by Beijing, Tianjin and Hebei.

The replacement of bulk coal with electricity. The State Grid Beijing Electric Power Company plans to invest 27.5×10^9 Yuan and implement the project of "replacing coal with electricity" covering 6.74×10^5 households in 1521 villages during the "13th Five-Year" period. It can be estimated from the above that the average investment in power transformation is about 40000 Yuan per household. The total number of users who replace "coal with electricity" in urban and rural areas of Beijing is expected to reach 1.1 million by 2020. The cost of power grid transformation is about 44×10^9 Yuan, and the equipment subsidy is about 13.2×10^9 Yuan (as per subsidy of 12000 Yuan per household), with the comprehensive investment of 57.2×10^9 Yuan. The government needs to invest 770 million Yuan per year as per the average electricity consumption in the "valley period" in the heating season of 3500 kW h per household. If it is calculated as per the maximum subsidy of 10000 kw h per household, the subsidy will reach 2.2×10^9 Yuan. According to this calculation, the average input for "replacing coal with electricity" in the urban and rural areas of Beijing is about 55000 Yuan per household. There were 3.737×10^5 users in the rural areas of Beijing who had replaced coal with electricity, with the daily electricity consumption of 42.52 kw h per household, or 4.19 times as much as that before the transformation, and the average electricity consumption per household was 6300 kW h during the heating season of 2016–2017. The electricity expenditure per household, after the electricity subsidy was granted by the government, was 2027.66 Yuan.

According to the *Implementation Plan of Clean Heating in Winter in Rural Areas in 2017*, the cost for the reconstruction of internal and external pipelines per household was 23100 Yuan, all of which was borne by the government. The electricity price for those enjoying subsidies from 9:00 pm to 6:00 am of the next day during the heating season is 0.1 Yuan per kW h. The district government will grant an electricity subsidy of 0.1 Yuan per kW h according to the amount of electricity consumption during the peak period (6:00 am- 9:00 pm), with the maximum subsidy of 500 Yuan. Users who use the air source heat pump will be granted a subsidy of 200 Yuan per m^2 according to the actual heating area, and the maximum subsidy shall not be more than 24000 Yuan (100 Yuan per m^2 of which is granted by the Municipal Ministry of Finance, and the maximum subsidy shall not be more than 12000 Yuan).

The replacement of bulk coal with gas. The *Opinion on the Price Policy Related to Heating with Clean Energy in the North Area* was issued by the National Development and Reform Commission in September 2018, which made clear that the price of gas for residential use shall be implemented for residents adopting heating by gas instead of coal in the rural areas and towns. However, the heating cost for the residents after "coal replaced with gas" still rose sharply without taking the cost of the pipe network and equipment installation and so on into consideration, so the residents relied heavily on concentration and maintenance or gas-price-related subsidies. According to the calculation results, the cost of coal for heating in winter is about 1800 Yuan based on the national coal consumption in the heating season of 3 tons per household and the coal price of 600 Yuan per ton without taking the replacement-related cost into consideration. If the wall-hanging gas stove is used for heating, the fuel costs for heating will be about 3120 Yuan based on gas consumption of 1300 m^3 per heating season and the national gas price of 2.4 Yuan per m^3. The cost of fuel increases by about 1320 Yuan per household a year, an increase of more than 70%, without considering the procurement cost of equipment. According to the existing subsidy policy for cities involved in the "2+26" channel, the subsidy related to civil gas price in more than ten cities, such as Beijing, Langfang and Baoding, is up to 1000 Yuan per household, while in the rest of the cities it is 600 or 900 Yuan per household in each heating season. If the gas-price-related subsidy policy is taken into consideration, the heating cost for residents who have replaced "coal with gas" in nearly half of the cities involved in the "2+26" channel has increased slightly, yet it basically remains within the affordable range. However, there is still a certain gap between the cost of heating and the actual payment capacity of the remaining urban residents.

The replacement of bulk coal with clean briquettes. Taking the Beijing, Tianjin and Hebei market as an example, there are differences in subsidy standards for clean briquettes in Beijing, Tianjin and Hebei. The price of briquettes in Hebei Province was 800–900 Yuan per ton, the average subsidy standard of each city was 200–350 Yuan per ton in 2015, and the price of briquettes after the subsidy was granted was still higher than that of bulk coal. The price of briquettes in Beijing is more than 1100 Yuan per ton, with the subsidy at the municipal and district levels of more than 600 Yuan per ton; while the price of briquettes in Tianjin city is 1057 Yuan per ton, with the subsidy of 500 Yuan per ton. So for Beijing and Tianjin, the price of briquettes is equivalent to or below the price of the bulk coal after the subsidy is granted. As the common people are more concerned about price, the popularization of briquettes in Beijing and Tianjin has been rather smooth. In addition, due to the increased benefits brought about by the subsidy policy in Beijing and Tianjin, a siphoning effect has been produced, which directly affects the enthusiasm for sales and promotion of Hebei briquette enterprises in the local area. As a result, some of Hebei's production capacity has by-passed the market in Hebei Province and targets the markets in Beijing and Tianjin instead. The government will grant a one-time subsidy of 80% of the selling price for those using special briquette stoves, which shall not exceed 1600 Yuan.

Based on the above information, the unit cost of subsidies in various provinces and cities is estimated as shown in Table 2 below.

Table 2 The amount and proportion of subsidies in Beijing, Tianjin and Hebei (Unit: Yuan t^{-1})

Region	Subsidy	Coal to gas	Coal to electricity	Bulk coal to briquette	Total
Beijing	Input cost	4400	18330	1200	23930
	The amount of subsidy	1330	11866	600	13796
	Proportion (%)	30	64	50	/
Tianjin	Input cost	4400	18330	1000	23730
	The amount of subsidy	1330	11866	500	13696
	Proportion (%)	30	64	50	/
Hebei	Input cost	4400	15000	900	20300
	The amount of subsidy	1200	9800	300	11300
	Proportion (%)	27	65	33	/

According to formula (7), the cost functions of Beijing, Tianjin and Hebei are respectively expressed as:

$$T_{11} = 13796\ N_{11} \quad (13)$$

$$T_{12} = 13696\ N_{12} \quad (14)$$

$$T_{13} = 11300\ N_{13} \quad (15)$$

3.2 Linear optimization results

According to the existing consumption levels of bulk coal and the quality of coal in Beijing, Tianjin and Hebei, the proportional impacts of bulk coal pollution in Beijing, Tianjin and Hebei are estimated to be 3%, 3% and 40%, respectively. The period from 2018–2020 is 2 years, so with m=2, then the relationships among the amount of bulk coal to be replaced, the governance cost and the total amount for each province or city by 2020 are as follows:

$$2 \times N_{1i} = N_{0i} \quad (16)$$

$$6 \times T_{1i} = T_{0i} \quad (17)$$

According to the constraint conditions in equations (2)–(3) and the objective functions (4)–(7), the total cost after optimization is 178.9584×10^9 Yuan and the governance costs in Beijing, Tianjin and Hebei are 71.7392×10^9 Yuan, 71.2192×10^9 Yuan and 135.6×10^9 Yuan, respectively. The required amount of bulk coal replacement in each place is 5.2 million tons, 5.2 million tons and 12 million tons, respectively, as shown in Table 3.

The cost for 2018–2020 years without cooperation and optimization will be 274.5×10^9 Yuan, by estimating the cost for the transformation of industrial small boilers, civilian clean stoves and so on in Beijing, Tianjin and Hebei. A comparison between the costs before and after optimization of Beijing, Tianjin and Hebei, is shown in Table 4.

Therefore, according to the calculation, the cost saved after the optimization in Beijing and Tianjin will be 760.8 million Yuan and 780.8 million Yuan, with the total cost in the two decreased by 1.5416×10^9 Yuan; while the capital of Hebei will need to be increased by 600 million Yuan. On the other hand, it is found by calculation that more attention should be paid to the governance of bulk coal in Hebei, and the demand for governance should be improved. In addition, it is found that the total amount of bulk coal needing to be governed in Beijing and Tianjin is less than that in Hebei Province, while the amount of bulk coal needing to be replaced in Hebei Province is rather large, so the replacement process is expected to be an arduous task.

3.3 Distribution results of capital by cooperative game

The Shapley values are used to distribute governance capital and governance benefits. According to the above discussion, when the amount of bulk coal to be governed and governance capital in Beijing and Tianjin decreases, the two cities need to provide increased capital subsidies for Hebei. The specific amounts of the subsidies are shown in the following calculations: when Si refers to Beijing, S refers to {Beijing}, {Beijing, Tianjin}, {Beijing, Hebei} and {Beijing, Tianjin, Hebei} respectively; when Si refers to Tianjin or Hebei, S refers to {Tianjin}, {Tianjin, Beijing} and so on in a similar fashion. The distributions calculated by Shapley values after the governance of bulk coal by the above optimization scheme from 2018 to 2020 are shown in Table 5−Table 7.

According to the distribution by Shapley values, Beijing and Tianjin need to provide Hebei with subsidies of 76080–35863=40217 Yuan and 78080–31164=46916 Yuan, respectively. After the distribution, the costs saved in Beijing, Tianjin and Hebei are 359 million Yuan, 312 million Yuan and 25 million Yuan, respectively. At the same time, the three places will be able to achieve the target $PM_{2.5}$ concentration in 2020.

4 Conclusions

On the premise that the consumption of bulk coal in Beijing, Tianjin and Hebei and governance cost has been taken into full consideration, the total governance cost of the three places has been reduced in this paper by linear optimization by means of allocation of governance capital via cooperative game theory and Shapley value method. The analysis found in the process of governance by alternative energy, that the governance task in Hebei Province is the most onerous,

Table 3 Governance cost and the amount of bulk coal to be replaced

Region	Beijing	Tianjin	Hebei	Total
Governance cost (10^6 Yuan)	717.392	712.192	1356	2785.584
The amount of bulk coal to be replaced by 2020 (10^4 t)	520	520	1200	2240
The proportion of the amount of bulk coal to be replaced to the total amount for the region (%)	23	23	54	/

Table 4 Cost comparison before and after optimization (Unit: 10^8 Yuan)

Region	Beijing	Tianjin	Hebei	Total
Cost before the optimization	725	720	1350	2795
Cost after the optimization	717.392	712.192	1356	2785.584
Capital saved	7.608	7.808	–6	9.416

Table 5 The distribution of cooperative benefit in Beijing (Unit: 10^8 Yuan)

Region	{Beijing}	{Beijing, Tianjin}	{Beijing, Hebei}	{Beijing, Tianjin, Hebei}
$W(\|S\|)$	1/3	1/6	1/6	1/3
$V(S)$	0	7.7796	7.875	9.416
$V(S_i)$	0	0	0	–6.4844
$V(S) - V(S_i)$	0	7.7796	7.875	2.9316
$W(\|S\|) \times [V(S) - V(S_i)]$	0	1.2966	1.3125	0.9772
Total	3.5863			

Table 6 The distribution of cooperative benefit in Tianjin (Unit: 10^8 Yuan)

Region	{Tianjin}	{Beijing, Tianjin}	{Tianjin, Hebei}	{Beijing, Tianjin, Hebei}
$W(\|S\|)$	1/3	1/6	1/6	1/3
$V(S)$	0	7.7796	6.4152	9.416
$V(S_i)$	0	0	0	–7.1642
$V(S) - V(S_i)$	0	7.7796	6.4152	2.2518
$W(\|S\|) \times [V(S) - V(S_i)]$	0	1.2966	1.0692	0.7506
Total	3.1164			

Table 7 The distribution of cooperative benefit in Hebei (Unit: 10^8 Yuan)

Region	{Hebei}	{Beijing, Hebei}	{Tianjin, Hebei}	{Beijing, Tianjin, Hebei}
$W(\|S\|)$	1/3	1/6	1/6	1/3
$V(S)$	0	7.875	6.4152	9.416
$V(S_i)$	0	0	0	2.1991
$V(S) - V(S_i)$	0	7.875	6.4152	11.6151
$W(\|S\|) \times [V(S) - V(S_i)]$	0	1.3125	1.0692	3.8717
Total	6.2534			

and requires more investment than other two cities. Thus, it requires the support from the other two cities, with the amount of capital increase required being about 600 million Yuan. At the same time, the cost saved after optimization in Tianjin is calculated to be the largest, which thus can be adjusted appropriately following the allocation to Hebei for the governance of bulk coal. The model constructed in this paper can not only be used to solve the issues related to bulk coal consumption in Beijing, Tianjin and Hebei Province, but it can also carry out the effective allocation of capital, by which a win-win scenario among the three places can be achieved. In order to implement regional cooperation and governance in the Beijing-Tianjin- Hebei region, it is necessary to establish both an air pollution cooperation mechanism and an integrated policy system, including a joint monitoring system for air pollution, a system for co-construction of air pollution infrastructure, an emergency response system for air pollution, and an authoritative system. Such an organization will undertake the pollution control decision-making function; secondly, it will be beneficial to establish an information system for air pollution cooperation and governance, achieve information sharing, and enhance the synergy of Beijing-Tianjin-Hebei pollution control; and finally, a sound policy cost-benefit analysis technical guide or method would be established to guide the cooperation between Beijing, Tianjin and Hebei Province.

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京津冀地区散煤治理资金优化研究

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摘　要：2017 年京津冀三地联合开展散煤综合治理工作，全面治理散煤污染。本文采用合作博弈论研究 2017 年度京津冀区域散煤综合治理中如何选择合适的策略才能使环境效益最大化的均衡问题。本文根据 2017 年度京津冀地区散煤治实际使用量、散煤燃烧对 $PM_{2.5}$ 的影响情况以及散煤实际治理成本，利用合作博弈模型中线性优化、博弈理论和 Shapley 值法研究京津冀地区散煤的治理总成本最小化以及治理资金在京津冀三省市之间合理分配及转移的问题。研究结果显示，在治理的过程中河北省的任务量最大，所需资金也最多，需要得到其他两市的资金支持，增资额度约为 6 亿元。同时，经计算得出天津优化后节省的成本最多，可以适当调整资金额度给予河北省散煤治理工作。本文的模型构建可以探讨解决京津冀地区散煤使用量的问题，还能通过对资金的有效分配使得三个省市达到合作共赢。

关键词：京津冀地区；散煤治理；合作博弈；线性优化