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Ying Qu, Yingmin Yuan, Lingling Guo, Yusha Li

Institutions: Dalian University of Technology

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Ying Qu
Dalian University of Technology
Yingmin Yuan
Dalian University of Technology
Lingling Guo (guolingling_517@163.com)
Dalian University of Technology https://orcid.org/0000-0001-6409-178X
Yusha Li
Dalian University of Technology

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Initial Allocation of SO_2 Emission Rights Based on the Combination Weighting Method: Evidence from China's Thermal Power Plants

Abstract

Emission trading system is an effective market-oriented means to control pollutant emission and reasonable initial allocation of emission rights is the premise of its smooth implementation. However, at present, the initial allocation of emission rights depends largely on the amount of emissions, which leads to weak positive guidance effect for enterprises. So to explore the optimal initial allocation method of SO_2 emission rights, this paper takes 8 thermal power plants in Dalian, China as the research objects to calculate the initial allocation of SO_2 emission rights. Because SO_2 is the main cause of acid rain, which is one of the most serious air pollution in China, and thermal power plants are among the main SO_2-emitters. Firstly, an indicator system is established considering enterprise size, pollutant discharge and social contributions, as well as pollution control capacity. Then, the combination weighting method is developed through integrating the subjective methods G1 and G2 with the objective ones, entropy and maximum deviation. The empirical results show that the enterprises with more desulfurization equipment or large heating supply are supposed to get more emission rights; the actual emission value of SO_2 in half of the enterprises exceeds the theoretical ones; SO_2 removal rate, desulfurization equipment quantity and heating supply exert the most positive effects on the initial allocation of emission rights. The constructed model can be used as a reference for future research of initial allocation of other pollutants' emission rights. Also, the implications have been proposed for the government, industry, and enterprises.

Keywords: *Initial allocation; Emission rights; SO_2; Combination weight; Power industry*

1. Introduction

The rapid development of China's economy consumed a large amount of energy, which significantly increased in emissions of CO_2, SO_2, particulate matter (Zeng et al. 2019; Luo et al. 2019). Because of the aggravation of the greenhouse effect, most existing research focuses on CO_2 emission rights, while research on SO_2 emission rights is relatively underrepresented. However, compared with other atmospheric pollutants, SO_2 is an important cause of acid rain, which not only leads to air pollution, but also pollutes rivers, corrodes buildings, acidifies arable land and even damages the human health (Li et al. 2015). China's SO_2 emission was 2.578 million tons in 2018, and the area affected by acid rain accounts for 30% of the total land area. According to the statistics released by China Economic Network in 2015, China had 624 thousand industrial boilers, more than 80% of which are coal fired, with a resulting annual consumption of standard coal of 490 million tons. To resolve the detrimental environmental effects, many countries have adopted a variety of measures conducive to reducing SO_2 emissions. Prominent examples are e.g., banning small thermal power plants, strengthening cleaner production audits, and promoting clean energy (Li et al. 2013; He et al. 2016). Among these measures, the emission trading system has become the favorite pollution control policy, since it realizes the pollution reduction at the lowest cost (Lin et al. 2011; Tang et al. 2020). The emission trading system has been first proposed by USA in the 1970s, and China formally implemented it in 2007 (Jiao et al. 2017; Hou et al. 2020). In the process of the allocation of SO_2 emission rights, the first-level government determines the total amount of emissions according to the local economic and environmental conditions; then, this amount is allocated to the second-level government, and from there to each enterprise according to its size and characteristics. The emission trading system is a type of market trading system based on environmental compensation, which can either indirectly or directly benefit enterprises. Compared with the means of publicity and education, it imposes a stronger guiding effect on enterprises. Data showed that China's SO_2 emissions have gradually decreased since 2007, from 36.6 million tons in 2007 to 2.57 million tons in 2018. The implementation of a SO_2 emission trading system exerts a significant effect on the SO_2 emission control; however, there is still a long way to go (Shin 2013). Thus, it is meaningful both for theory and praxis to develop a reasonable mechanism for the initial allocation of SO_2 emission rights (Ji et al. 2017; Lee 2019).

In addition to the practices of emission trading systems of many countries, the academic circle has conducted extensive research on the topic. Rathnayake et al. (2018) studied the improvement means of cleaner production and pollution control from a technical perspective. Lin et al. (2011) studied the means of the reasonable implementation of SO_2 emission rights from a managerial perspective. In the 1990s, several researchers proposed that the initial allocation of emission rights was the main barrier for the implementation of emission rights trading (Van Egteren and Weber 1996), which was later corroborated by many other studies (Guo et al. 2012; Hang et al. 2019). For example, Li (2013) studied the strategy of enterprises under the background of emission permits and the results indicated that the production inventory strategy of enterprises will be reasonably adjusted, which is more conducive to enterprise development. Conclusions diverse in the study of the factors that need to be considered in the enterprise's SO_2 emission right. Taking Fujian power plants as research object, Lin et al. (2011) studied four independent methods for the initial allocation of SO_2 emission rights: the historical emission method, the calorific value method, the production value method, and the emission performance method. The results indicated that the emission performance method and the production value method are the most suitable methods for Fujian power plants. Mahdiloo et al. (2018) proposed a model for the allocation of pollutant emission rights based on the ecological efficiency score of power producers. Their model involved reward and punishment strategies for ecological efficiency behaviors of power producers. However, there is currently no clear research on the key factors that affect the initial allocation of SO_2 emission rights in thermal power plants. Therefore, this paper builds a multi-dimensional index system for the initial SO_2 emission rights allocation and explores the key influencing factors. This will help to understand the gap between the theoretical and actual emission values of enterprises, which is of great significance for both theoretical research and practical production. Dalian is an important city in the northeast old industrial base, whose power is mainly supplied by thermal power plants. In 2017, Dalian's thermal power generation was 19.77 billion kwh, accounting for 44.6% of the total power generation. Dalian currently changes from a heavy industrial city to an ecological civilization city. Therefore, by focusing on Dalian as study location, the research results can accelerate the process of green transformation of Dalian, and also provide experience for other industrial cities in China. Despite the gradually increasing proportion of new energy power generation, the growth rate remains slow; therefore, thermal power generation will still remain the main mode of power generation for Dalian in the foreseeable future. So this paper takes eight thermal power plants of Dalian as research objects.

The contributions of this paper can be divided into two aspects. Theoretically, the optimal combination weighting method including two subjective weighting methods and two objective weighting methods, is used to enhance the reliability of the research results. Furthermore, this study not only considers the status of enterprise emissions, but also takes the social benefits into account, which enriches the relevant research on the initial allocation of SO_2 emission rights. Practically, the model is applied to conduct an empirical study using the panel data of eight thermal power plants in Dalian, which is helpful to identify the main influencing factors of SO_2 emission right. Also, through the comparative analysis of the actual and theoretical emission value of each enterprise, this paper provides managerial and industrial implications accordingly, helping Dalian government to make relevant decisions and take corresponding measures.

The rest of paper is organized as follows. Section 2 reviews and summarizes the related literature in this field. Section 3 establishes the allocation model constructed in this paper. Section 4 is an empirical study of thermal power plants in Dalian. The results and discussion of the study are presented in Section 5. Finally, Section 6 provides conclusions and implications.

2. Literature review

With the increasing severity of environmental pollution, the awareness of the need for environmental protection has gradually enhanced. The concept of emission rights was first put forward by Dales, who believed that an emission right is the right of the obligee to discharge pollutants into the environment within the scope permitted by law (Dales 2002). However, the initial allocation of emission rights has not attracted much attention until the emission trading system has been implemented by the United States, where it achieved remarkable results (Zhu et al. 2012). Subsequently, this theory was used by the National Environmental Protection Agency for the management of atmospheric and river pollutant discharges; other countries have also carried out relevant practices and research. The theory of emission trading is mainly based on the Coase Theorem, the purpose of which is to encourage enterprises to improve technology, reduce the amount of pollution and optimize the allocation of environmental resources (Gurianov 2015; Venmans 2016). Later, economists put forward the concept of “environmental capacity resources”, whose property rights are emission rights, so it becomes necessary to define the ownership of emission rights (Wang and Wang 2016).

However, previous studies have hardly considered the impact of initial allocation on emission trading. With the accumulation of theories and practices associated with emission trading, economists and policy makers gradually realized the importance of the allocation of initial emission right (Gurianov 2015). Among these, Lyon (1982) first studied the allocation of initial emission indicators in 1982. Later, Hahn (1984) showed that, in an incomplete competitive market, the efficiency of emission trading is, to some extent, affected by the initial allocation. Woerdman (2000) studied the impact of initial emission allocation and quantitative allocation on emissions trading. These studies revealed that the effect of the reduction of pollutant emissions not only depends on emissions trading, but also, to a large extent, on the initial allocation of emission rights. Therefore, it has become urgent to study the initial allocation of emission right and provide scientific suggestions for future emission reduction.

At present, there are two main types of research. On the one hand, the initial allocation of emission rights is determined by mathematical models. Shi et al. (2017) established a cross-border air pollution model based on game theory and studied the cost-effectiveness of emission reduction for three cities in Hunan Province, China. Huang (2018) considered the spatial dependence of SO_2 emissions and used the Spatial Durbin model to study the impact of governmental expenditure for environmental protection on SO_2 emissions. On the other hand, the allocation of initial emission rights for specific pollutants is determined by establishing an index system, which involves the determination of influencing factors and the weight of each factor. For instance, Mackenzie (2009) proposed a new initial allocation mechanism, i.e., the ranking of companies by assessing their external behaviors or characteristics independent of the emission trading market, to obtain the initial allocation. Chen et al. (2019) used a cost-benefit analysis method to compare the economic costs and social benefits of desulfurization and emission reduction between China and the United States.

With regard to the choice of research objects, with the increasing rise of carbon emissions trading, most scholars currently study the initial allocation of CO_2 emissions (Duan et al. 2018; Han et al. 2018; Li et al. 2018). In addition, because of the serious haze phenomenon, the initial allocation of particulate matter emission rights has recently become the focus of scholars (Wu et al. 2015). The existing literature has mainly focused on the initial allocation of SO_2 emission rights in a specific region or province, between industries, or enterprises within an industry. Mostly, the distribution of SO_2 was considered from the perspective of regional integration, i.e., the total SO_2 emissions of a province as a whole, allocated to each city, or the total SO_2 emissions of a specific city, allocated to each region (Guo et al. 2012; He et al. 2016). Only a few studies investigated the initial allocation of SO_2 emission rights from the perspective of an industry or region. However, enterprises represent the main body of pollutant discharge, and thermal power enterprises are an important source of SO_2 emissions. Hence, it would be more effective to study the emission reduction of SO_2 from the perspective of thermal power plants. Pollutant emission rights affect the allocation of enterprise resources to a certain extent, which is key to affect enterprise benefits (Ji et al. 2017; Wong et al. 2020). Therefore, it is necessary to study the initial allocation of SO_2 emission rights to improve the environment. To fill this research gap, the present paper studies the initial allocation of emission rights of eight major thermal power enterprises in Dalian. Based on establishing an indicator system and empirical verification, suggestions for the government, industry, and enterprises are presented to effectively reduce SO_2 emissions.

3. Methodology

3.1 Standardization of Indexes

An indicator system usually contains different dimensions and orders of magnitude among indexes based on their meanings and properties. When the order of magnitude of indicators varies strongly, and if the original index value is directly analyzed, an index with larger value will play a stronger role for calculations, while an index with smaller value will appear to have less effect. Therefore, to weaken the impact of different dimensions on the evaluation results, while ensuring reliability, it is necessary to standardize the data of the original indexes under each criterion level. The calculation equation is as follows (Zhao et al. 2018):

$$Y_{ij} = \frac{X_{ij} - \min\limits_{1 \le i \le m}(X_{ij})}{\max\limits_{1 \le i \le m}(X_{ij}) - \min\limits_{1 \le i \le m}(X_{ij})} \tag{1}$$

Where Y_{ij} represents the normalized value of data; X_{ij} represents the value of index j of the enterprise i ; m represents the number of evaluated enterprises; n represents the number of indexes in the evaluation system; $i = 1,2,\ldots,m$; $j = 1,2,\ldots,n$.

3.2 Index Weight Calculation

In the existing research, the integration of subjective and objective weighting methods is almost adopted (Feng et al. 2018; Han et al. 2018; Li et al. 2018). This paper combines two subjective and two objective weighting methods, which can minimize the information display and yield more scientific index weights (Guo 2002). The principle underlying this method is simple, its operability is strong, and the results of comprehensive evaluation are comparable. Compared with the single subjective or objective weighting method, the combined one is more scientific and its results are more reliable.

3.2.1 G1 Method

The G1 method is a subjective method without consistency test, which was proposed by

Guo (Guo 2002). Compared with Analytic hierarchy process (AHP), the G1 method does not need to construct a judgment matrix, which clearly reduces the computational complexity (Qian et al. 2014). It is simple, intuitive, and does not restrict the number of elements in the same level:

a) Determining the order relation among evaluation indexes.

b) Ratio r_j of the importance of adjacent evaluation indexes Y_{j-1} and Y_j is given by experts.

c) The weight of the index k (k = 1, 2,… , n) is calculated as follows:

$$\omega_k = \left(1 + \sum_{j=2}^{k} \prod r_j\right)^{-1} \tag{2}$$

d) With the weight ω_k , the values of other indexes can be obtained.

$$\omega_{j-1} = r_j \omega_j \ , \ j = k, k-1, \ldots, 3, 2 \tag{3}$$

3.2.2 G2 Method

The G2 method is an interval mapping weighting method for practical application, which can directly express the subjective views and risk awareness of experts, and offers the advantages of less calculation and easy promotion (Zhao et al. 2018):

a) Experts identify the least important indicator Y_k .

b) Determine the ratio r_j of the importance of other indicators to Y_k .

c) Calculate the weight of the index j to the criterion layer.

$$\omega_j = \frac{r_j}{\sum_{j=1}^{n} r_j} \tag{4}$$

3.2.3 Entropy Method

The entropy method is a widely used method for objectively calculating weights, suitable for continuous variables and its calculation process is clear. It considers that the information entropy value is a measure of information uncertainty (Zhang et al. 2019). The smaller the value, the larger the influence of the index on the decision result, and the greater the weight that should be assigned; the larger the information entropy value, the smaller the difference between the indicators, and the smaller the weight that should be assigned. The size of the information entropy value represents the degree of differences between different indicators, and objective weights are calculated according to the size of the value. The main steps are as follows:

a) The equation for calculating the index proportion f_{ij} is as follows.

$$f_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{5}$$

Where x_{ij} represents the initial value of the index j in enterprise i ; i = 1, 2, …, m ; j = 1, 2, …, n .

b) Calculate the entropy of indexes.

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} f_{ij}\ln(f_{ij}) \tag{6}$$

Where e_j represents the entropy of the index j; suppose that when $f_{ij} = 0$, $f_{ij}\ln(f_{ij}) = 0$.

c) ω_j is set as the weight of the index j, and its calculation equation is shown below:

$$\omega_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \tag{7}$$

3.2.4 Maximum Deviation Method

The maximum deviation method assumes that if the index is more discrete, the impact of the index on the evaluation results will be larger, and consequently, the weight of the index should be higher. This method can automatically determine the weighted coefficients among the evaluation indexes. The obtained ranking results are accurate and reliable, and have no subjective randomness (Qian and Luan 2017; Yi et al. 2019).

a) Suppose that t_{ij} is the normalized value of index j in enterprise i; ω_j is the weight of the index j. For index j, the equation to calculate the deviation $F_{ij}(\omega)$ between enterprise i and other enterprises is (k = 1, 2, …, m):

$$F_{ij}(\omega) = \sum_{j=1}^{n}\left|t_{ij}\omega_j - t_{ik}\omega_j\right| \tag{8}$$

b) For index j, the total deviation F between all enterprises and other enterprises is:

$$F_j(\omega) = \sum_{i=1}^{m} F_{ij}(\omega) = \sum_{i=1}^{m}\sum_{k=1}^{m}\left|t_{ij} - t_{ik}\right|\omega_j \tag{9}$$

c) According to the principle of maximum deviation, the following optimization model is constructed:

$$\max H(\omega) = \sum_{j=1}^{n}\sum_{i=1}^{m}\sum_{k=1}^{m}\left|t_{ij} - t_{ik}\right|\omega_j$$

$$s.t.\begin{cases} \omega_j \geq 0 \\ \sum_{j=1}^{n} \omega_j^{\,2} = 1 \end{cases} \tag{10}$$

d) The optimization model is solved and normalized to obtain the index weight.

$$\omega_j = \frac{\sum_{i=1}^{m}\sum_{k=1}^{m}\left|t_{ij} - t_{ik}\right|}{\sum_{j=1}^{n}\sum_{i=1}^{m}\sum_{k=1}^{m}\left|t_{ij} - t_{ik}\right|} \tag{11}$$

In Eq. (11), $\sum_{i=1}^{m}\sum_{k=1}^{m}\left|t_{ij} - t_{ik}\right|$ represents the deviation obtained after the normalization of index j of enterprises by subtracting two by two. Then, the absolute value is taken and summed up;

$\sum_{j=1}^{n}\sum_{i=1}^{m}\sum_{k=1}^{m}|t_{ij}-t_{ik}|$ represents the sum of the deviations of all indexes.

3.2.5 Combination Weighting Method

The weight obtained by the G1 method, the G2 method, the entropy method, and the deviation method is calculated respectively, and then, the combination weight c is:

$$\omega_j = \sum_{c=1}^{4} \alpha_c \omega_c \tag{12}$$

In Eq. (12), α_c represents the combination coefficient; and $\sum_{c=1}^{4} \alpha_c = 1$, $c = 1, 2, 3, 4$.

With regard to the combination coefficient, the following two factors should be considered.

a) The minimum generalized distance between the weighted score of each evaluation object and the ideal point should be guaranteed.

$$\min \sum_{i=1}^{m} d_i = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{c=1}^{4} \alpha_c \omega_j^c (1 - Y_{ij}) \tag{13}$$

In Eq. (13), d_i represents the generalized distance between weighted score and the ideal point of each evaluation object; ω_j^c represents the weight of index j under the method c; Y_{ij} represents the normalized value of index j in enterprise i.

b) The Jaynes maximum entropy principle is introduced to reflect the consistency of the weight allocation results for each index. The following objective functions are established based on minimizing the difference of the weight allocation results.

$$\max Z = -\sum_{c=1}^{4} \alpha_c \ln \alpha_c \tag{14}$$

Objective function:

$$\begin{aligned} &\min \theta \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{c=1}^{4} \alpha_c \omega_j^c (1 - x_{ij}) + (1-\theta)\sum_{c=1}^{4} \alpha_c \ln \alpha_c \\ &s.t. \sum_{c=1}^{4} \alpha_c = 1, x_c \geq 0 \end{aligned} \tag{15}$$

Where θ ($0 \leq \theta \leq 1$) represents the equilibrium coefficient (generally $\theta = 0.5$).

c) The Lagrange function is constructed to solve the combined weight coefficient A.

$$\alpha_c = \frac{\exp\left\{-\left[1 + \theta \sum_{i=1}^{m}\sum_{j=1}^{n} \omega_j^c (1 - x_{ij}) / (1-\theta)\right]\right\}}{\sum_{c=1}^{4} \exp\left\{-\left[1 + \theta \sum_{i=1}^{m}\sum_{j=1}^{n} \omega_j^c (1 - x_{ij}) / (1-\theta)\right]\right\}} \tag{16}$$

Compared with other methods, the coefficient obtained by Eq. (16) minimizes the generalized distance between the weighted score of each evaluation object and the ideal point; furthermore, it can better reflect the consistency of the weighting results (Zhao et al. 2018).

4. Empirical analysis

4.1 Construction of index system

The initial allocation of emission permits needs to comprehensively consider factors in the decision-making process. Chen et al. (2013) studied the initial allocation of CO_2 emissions by establishing an index system, which incorporates economy, technology, policy, carbon emissions, and energy efficiency. He et al. (2016) explored the influencing factors of regional SO_2 emission. The results showed that the scale is the main factor causing the increase of SO_2 emission, while the progress of technology and the treatment improvement are the main ones for its reduction. On establishing the index system of emission right allocation (Guo et al. 2012; Feng et al. 2018; Hang et al. 2019), scholars mainly focused on the economic development of regions, industries or enterprises, and seldom took into account the social contribution of enterprises.

Therefore, this paper sets up three criteria layers that affect the initial allocation of emission right: enterprise size, pollutant discharge and social contributions, pollution control capacity. It reflects the overall strength and development of enterprises through size, and examines the effects of the behavior of enterprises through the pollutant discharge and social contributions. Furthermore, it reflects the scientific and technological capabilities and developmental prospects of enterprises through their emission reduction and pollution control capability. In summary, this paper not only focuses on the pollutant emissions of enterprises, but also pays attention to their social contributions and performances, making the allocation more equitable. Under criterion layers, 10 tertiary indicators are set up. The constructed indicator system is shown in Table 1.

Table 1: Index system for SO_2 emission allocation

Target layer	Criterion layer	Index layer	Number	Meaning
SO_2 emission right of Dalian thermal power plants	Enterprise size(X1)	Registered capital	X11	The total amount of capital registered by an enterprise in the registration authority.
		Installation supply	X12	The sum of rated power of all turbo-generators or hydro-generators in thermal power plants.
		Boiler tonnage	X13	The sum of the rated evaporation of the boiler.
		Staff number	X14	Number of employees in an enterprise.
	Pollutant discharge and social contributions(X2)	SO_2 emission	X21	The amount of SO_2 discharged into the atmosphere in the process of production.
		Coal consumption	X22	Coal consumption by enterprises in one year.
		Generation supply	X23	Electricity produced by enterprises in one year.
		Heating supply	X24	The heat produced by enterprises in one year.
	Pollution control	SO_2 removal	X31	The ratio of SO_2 removal to SO_2 production.

capacity(X3)	rate		
	Desulfurization equipment quantity	X32	Equipment used to reduce SO_2 emission.

4.2 Data source and processing

Thermal power generation is the main source of SO_2 in China (Liu and Wen 2012; Bai et al. 2018). This study selects 8 thermal power enterprises of Dalian as the research sample, and the indicator data were provided by Dalian Eco-Environmental Affairs Services Centre due to the difficulty of obtaining the relevant data directly. For data confidentiality and convenient analysis, these enterprises are listed as Enterprise 1-8, and the value of each indicator are brought into Eq. (1) for standardized calculation according to their attributes.

4.3 Determination of the combination weights

The process of determining index weight by the G1 method is as follows.

Firstly, the importance of the criterion layer is ranked based on the experts' opinions: X3 > X2 > X1.

Secondly, the relative importance ratio of adjacent indexes is determined: r2 = X3 / X2 = 1.6, r3 = X2 / X1 = 1.2. Then, by substituting r2 and r3 into Eqs. (2) and (3), the weights of the criteria layers are 0.2427, 0.2913 and 0.4660, respectively. Similarly, the weight of each index can be obtained, as shown in the third column of Table 2.

The process of determining index weight by the G2 method is as follows.

Firstly, the least important index X1 is given by experts.

Secondly, the importance ratios of other indicators to X1 are determined: r1 = X2 / X1 = 1.2; r2 = X3 / X1 = 1.6. By introducing r1 and r2 into Eq. (4), the weights of the criteria layers are 0.4211, 0.3158 and 0.2632, respectively. Similarly, the weight of each index can be calculated, as presented in the fourth column of Table 2.

Next, the normalized data are brought into Eqs. (5) and (6), and the entropy value of each index is obtained. Then, the weight of the entropy value of each index is calculated according to Eq. (7), as shown in the fifth column of Table 2.

Then, the normalized data are brought into Eq. (11) to get the weight of each index under the maximum deviation method, as shown in the sixth column of Table 2.

Finally, the standardized data and the index weights from each method are substituted into Eq. (16), The weight coefficients of methods are got: α_1 = 0.2605, α_2 = 0.20825, α_3 = 0.1567, α_4 = 0.3003. Then, the index weights under the optimal combination are obtained from Eq. (12), as shown in the seventh column of Table 2.

Table 2: Weight calculation results of the evaluation index

Criteria layer	Index layer	G1	G2	Entropy	Maximum deviation	Comprehensive weight	Order

Enterprise size	Registered capital	0.0597	0.1095	0.0420	0.1194	0.0889	7
	Installation supply	0.0543	0.1011	0.0838	0.1045	0.0872	8
	Boiler tonnage	0.0836	0.1263	0.0426	0.0973	0.0934	6
	Staff number	0.0452	0.0842	0.0065	0.1181	0.0720	10
Pollutant discharge and social contributions	SO_2 emission	0.0981	0.0947	0.0444	0.0816	0.0838	9
	Coal consumption	0.0817	0.0884	0.2806	0.0642	0.1095	4
	Generation supply	0.0584	0.0695	0.1869	0.1082	0.0966	5
	Heating supply	0.0531	0.0632	0.2834	0.1145	0.1105	3
Pollution control capacity	SO_2 removal rate	0.2718	0.1487	0.0020	0.1134	0.1472	1
	Desulfurization equipment quantity	0.1942	0.1144	0.0279	0.0788	0.1109	2

4.4 Calculation of initial allocation ratio of enterprises

When calculating the initial allocation ratio of each enterprise, the original data is normalized firstly, and then multiplied with the comprehensive weight to obtain the initial allocation ratio of each enterprise. The results are shown in Table 3 and Fig. 1.

Table 3: Results of data normalization

Index \ Enterprise number	1	2	3	4	5	6	7	8
Registered capital	0.22	0.01	0.10	0.07	0.25	0.19	0.00	0.16
Installation supply	0.03	0.01	0.06	0.01	0.15	0.43	0.01	0.29
Boiler tonnage	0.08	0.04	0.05	0.11	0.34	0.20	0.01	0.18
Staff number	0.11	0.18	0.10	0.08	0.12	0.18	0.08	0.14
SO_2 emission	0.15	0.04	0.12	0.06	0.40	0.11	0.02	0.11
Coal consumption	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Generation supply	0.51	0.00	0.49	0.00	0.00	0.00	0.00	0.00
Heating supply	0.42	0.09	0.00	0.09	0.00	0.39	0.00	0.01
SO_2 removal rate	0.11	0.16	0.10	0.11	0.12	0.15	0.10	0.14
Desulfurization equipment quantity	0.06	0.12	0.35	0.12	0.12	0.12	0.06	0.06

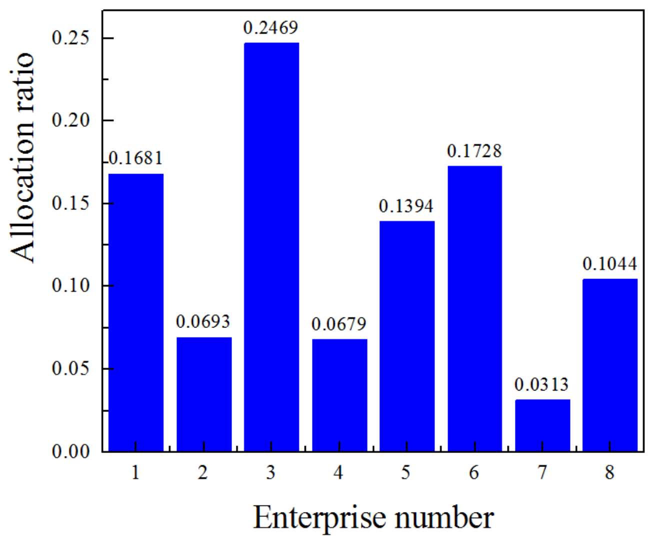

Fig. 1. Initial allocation ratio of enterprises

5. Results and discussion

5.1 Analysis of the initial allocation results

As seen in Fig. 1, the initial allocation proportion of emission right obtained by Enterprise 3 is the largest, accounting for 24.69% of the total. According to Table 3, the desulfurization equipment quantity of Enterprise 3 is the largest, and its SO_2 emission is also at a high level. Therefore, it is reasonable for Enterprise 3 to get the largest proportion of emission rights. And Enterprise 6 and Enterprise 1 is only next to Enterprise 3, which is 17.28% and 16.81% respectively. The heating supply of these two enterprises is obviously higher than that of others, so the allocation proportions of these are larger. Enterprise 6 is the only coal-fired power plant in the Dalian Development Zone, which mainly focuses on heating and cogeneration. Its social contribution is particularly significant.

Enterprise 7, Enterprise 4 and Enterprise 2 have the least allocation of emission rights, accounting for 3.13%, 6.79% and 6.93%, respectively. Their scales are comparatively small, which is an important factor that affects the allocation of emission rights. Based on the optimal combination of weights, the initial allocation model of SO_2 emission right considers all characteristics of thermal power enterprises. Subjective and objective methods are combined, thus making the results more scientific.

5.2 Analysis of the difference between the actual and theoretical SO_2 emission

In 2017, the industrial SO_2 emission of Dalian was 50628.2 tons. According to the statistical data of recent years, the SO_2 emission of the thermal power industry accounts for about 16% of the total emission of Dalian. The theoretical SO_2 emissions of these 8 enterprises calculated via the above allocation model are shown in Fig. 2, while the actual SO_2 emissions of enterprises are shown in Fig. 2.

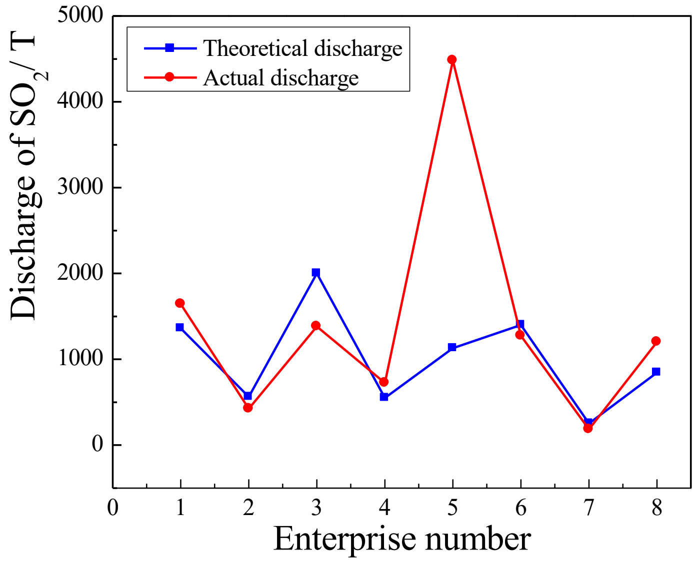

Fig. 2. Comparison between theoretical and actual SO_2 emissions

As can be seen, the actual SO_2 emissions of Enterprise 1, Enterprise 4, Enterprise 5 and Enterprise 8 all exceed the theoretical value, while the emission value of Enterprise 3 is the far lower than the theoretical value. In Table 2 and Table 3, the number of desulfurization equipment in Enterprise 3 is large, which indicates that the technology level or the ability to control pollutants are strong, so the Enterprise 3 can reduce the emission of SO_2 through treatment equipment and means. During the 12th Five Year Plan period, Enterprise 3 reformed the electrostatic bag dust removal system, optimized the original sulfur removal system, and greatly improved the effect of pollutant treatment. This material and the results of this study have achieved mutual confirmation. Also, this enterprise is of medium scale; however, the power generation is at a high level, the production efficiency is high, and the contribution to society is high. Such enterprises should be encouraged and supported. The common characteristic of enterprises whose actual emissions exceed the theoretical ones is that although the scale of the enterprise is large, the quantity of desulfurization equipment is small. This leads to low removal rate, thus causing more severe environmental pollution. Such enterprises should increase their investment in environmental protection equipment and should improve the applied treatment technology. Moreover, the government should strengthen the monitoring and control of these enterprises.

A significant difference exists between the actual and theoretical SO_2 emission values for each enterprise. This indicates that the government's current regulation on the pollutant emissions of enterprises is not scientific enough. In this case, strict initial allocation of SO_2 emission rights plays an important role for reducing the generation of pollutants and regulating production behavior. For enterprises with high generation supply, heating supply, and SO_2 removal rate (e.g., Enterprise 3), the government should grant more initial SO_2 emission rights to encourage enterprises to expand production scale and create more value for the society. In contrast, for large-scale enterprises with low SO_2 removal rates (e.g., Enterprise 2), these should receive less initial emission rights. In this way, if enterprises want to discharge more pollutants, they need to buy additional emission rights on the market, which will increase production costs of these enterprises. To a certain extent, enterprises therefore have to increase their environmental investment, improve their technology level, and reduce their SO_2 emissions.

5.3. Analysis of the Main Influencing Factors

According to the above research, the importance of the three criterion layers can be ranked as follows (from large to small): pollutant discharge and social contribution, enterprise scale, and pollution control capability. The weights of the first two are both 0.7419, which indicates that the relevant management departments should pay more attention to these two criteria layers during the initial allocation of SO_2 emission rights. However, with regard to specific indicators, the top three are SO_2 removal rate, desulfurization equipment quantity, and heating supply. It can be seen that in the initial allocation process of SO_2 emission rights, the larger the scale of enterprises, the more emission rights they will obtain. The scale of an enterprise typically reflects its economy and development, and to a certain extent, also reflects its economic contribution to society. This embodies the principle of efficiency. In general, the larger the scale of an enterprise, the greater the proportion of its social contribution, and the easier more emission permits can be obtained.

Besides, SO_2 removal rate and desulfurization equipment quantity have the largest weight, indicating that under the condition of a certain total amount of allocation rights (although the economic contribution of enterprises needs to be considered), the level of sewage treatment of enterprises also occupies a certain proportion. This means that the importance of the pollution control level of enterprises has been affirmed, which induces the enthusiasm of enterprises to conduct pollution control from their side and embody certain fairness. Independent of which kind of policies the government formulates, these need to improve the efficiency and enthusiasm of enterprises toward pollution control. The result affirms that enterprises with high level of discharge treatment provide an incentive for other enterprises.

Moreover, the weight of staff number is the smallest since modern enterprises gradually adopt intelligent production and detection; therefore, the number of employees does not reflect the size of an enterprise anymore. Although the number of employees in specific enterprises is small, which may be because of their high level of modernization and intelligence, their production level and pollution control capacity may be stronger. The second smallest weight is the weight of SO_2 emissions. More SO_2 emissions do not represent the economic or social contribution of enterprises, which is possibly due to the use of outdated equipment or the high sulfur content of raw materials. If more emission rights are obtained because of its large emissions, this will lower the enthusiasm of enterprises to conduct pollution control and reduce emissions. This is not conducive to environmental protection and violates the original purpose of the allocation of emission rights.

6. Conclusions and implications

By focusing on the initial SO_2 emission right allocation in thermal power industry, this paper establishes the index system including enterprise scale, environmental pollution, social contribution, and emission reduction capacity, and develops an initial allocation model by combining the two subjective weighting methods of G1 and G2 with the two objective ones of entropy method and maximum deviation method. Then an empirical analysis is conducted to evaluate the initial right of SO_2 emission through taking 8 thermal power plants in Dalian as research objects. The findings of this study are as followed.

Firstly, SO_2 emission rights of 8 thermal power plants in Dalian are redistributed. The results show that the enterprises with more desulfurization equipment or large heating supply are allocated more emission rights.

Secondly, based on the evaluation results, there are four thermal power enterprises of Dalian in 2017 whose actual emission values exceeded the theoretical allocation ones. These enterprises are generally smaller and have weaker ability to control pollutants.

Thirdly, according to the weight calculation results, the main influencing factors including SO_2 removal rate, desulfurization equipment quantity and heating supply are identified. The first two factors indicate the enthusiasm of enterprises in pollution control and emission reduction, and heating supply reflects the social contribution of enterprises.

The findings of this paper are conducive to the initial allocation of emission permits being more equitable while providing some references for government departments to make decisions on thermal power plants. Some suggestions are put forward for the government, industry, and enterprises.

For government departments, first of all, it is urgent to improve the legal system of SO_2 emissions trading. By promulgating regulations and trading rules related to SO_2 emissions trading, the responsibilities and rights of the main pollutant discharging body and the distribution body are clearly defined. This provides strong legal support for SO_2 emissions trading. Moreover, the government should start from the sources of pollution, strengthen the control over the source discharge, strictly verify the data reported by enterprises, and establish a real-time monitoring management and supervision system. These measures will ensure the smooth progress of emissions trading.

For the thermal power industry, as the focus of the development of the power industry, 70% of the total annual electricity consumption in China is a contribution of the thermal power industry. The thermal power industry needs to sum up the experience and lessons learnt of their extensive development in the past. Moreover, they should constantly improve and innovate, and vigorously promote energy saving and emission reduction. These measures can realize the coordination of high-speed economic development and the protection of the ecological environment. At the same time, the industry should also improve the index system of the initial SO_2 emission rights allocation to ensure the efficiency and fairness of the initial allocation results.

For enterprises, it is time to improve production and management modes, and promote energy saving and emission reduction to the strategic level of enterprises. Also, the market will inevitably be dominated by green high-tech industries; therefore, enterprises are facing serious pressures and challenges, and consequently, they must increase investment in scientific research, engage in technological innovation, and decrease costs while protecting the ecological environment. This can not only meet the requirements of environmental protection policies, but also reduce energy consumption and enhance the competitiveness of enterprises.

The limitations of this paper are as follows: On the one hand, this paper uses eight thermal power plants in Dalian as the research object, and therefore, the results may mainly be applicable to Dalian, but not to other areas. In the future, more cities should be selected and regional research should be conducted to thus improve the applicability and universality of the index system. On the other hand, while the key factors that affect the initial allocation of SO_2 emission rights in thermal power plants were identified, the impact path of these key factors on the results of the allocation of emission rights is also valuable and should be deeply studied to provide a theoretical reference for the decision-making of relevant governmental departments at a deeper level.

Declarations

- Ethics approval and consent to participate

Not applicable.

- Consent for publication

Not applicable.

- Availability of data and materials

The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

- Competing interests

The authors have declared that no competing interests exist.

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- Authors' contributions

Ying Qu contributed to the conception of the study;

Yingmin Yuan performed the data analysis and wrote the manuscript;

Lingling Guo helped perform the analysis with constructive discussion;

Yusha Li helped collect the data.

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- Authors' information (optional)

All the authors are from School of Economics and Management, Dalian University of Technology, No.2 Ling Gong Road, Dalian City 116024, China.

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Figures

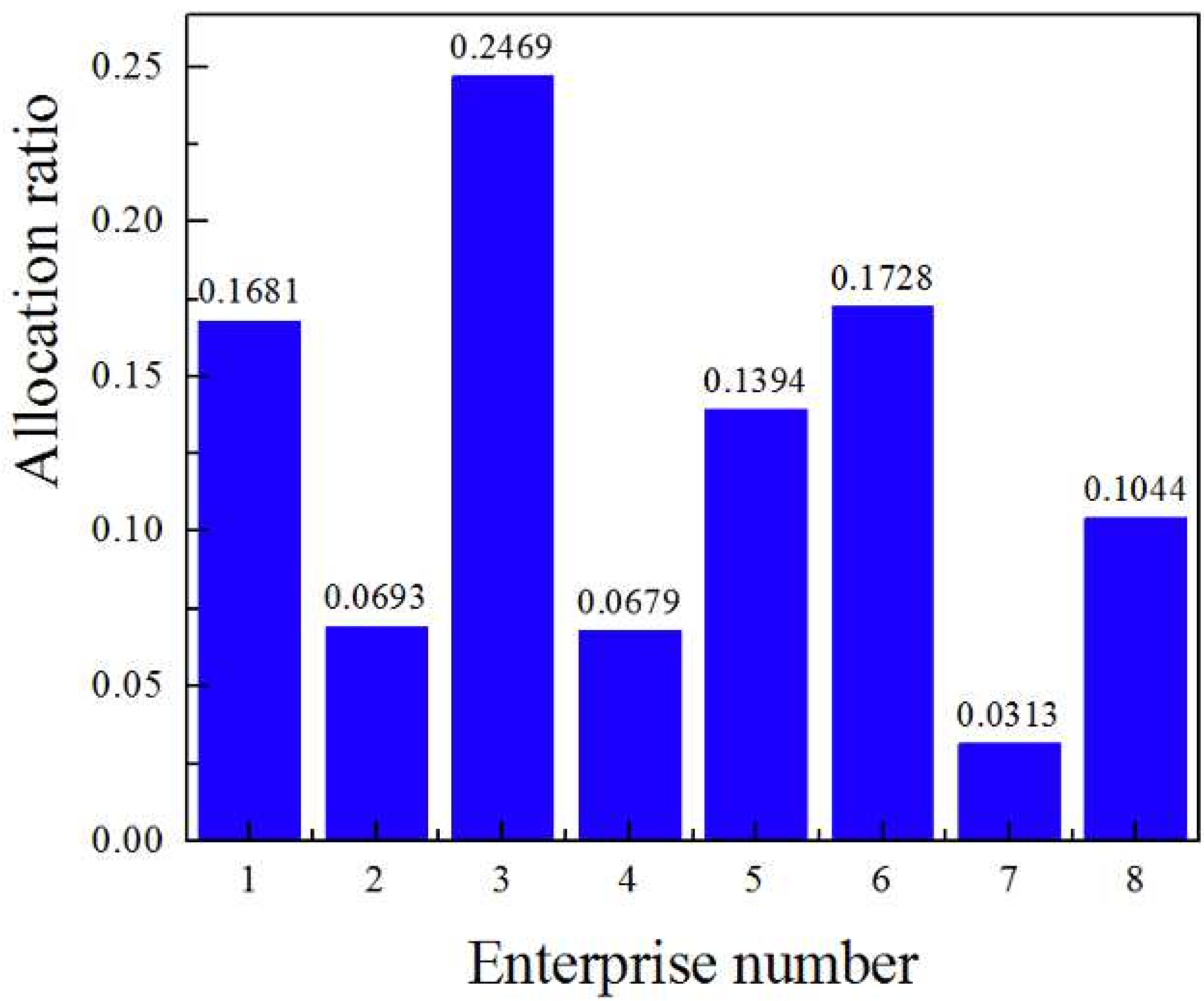

Figure 1

Initial allocation ratio of enterprises

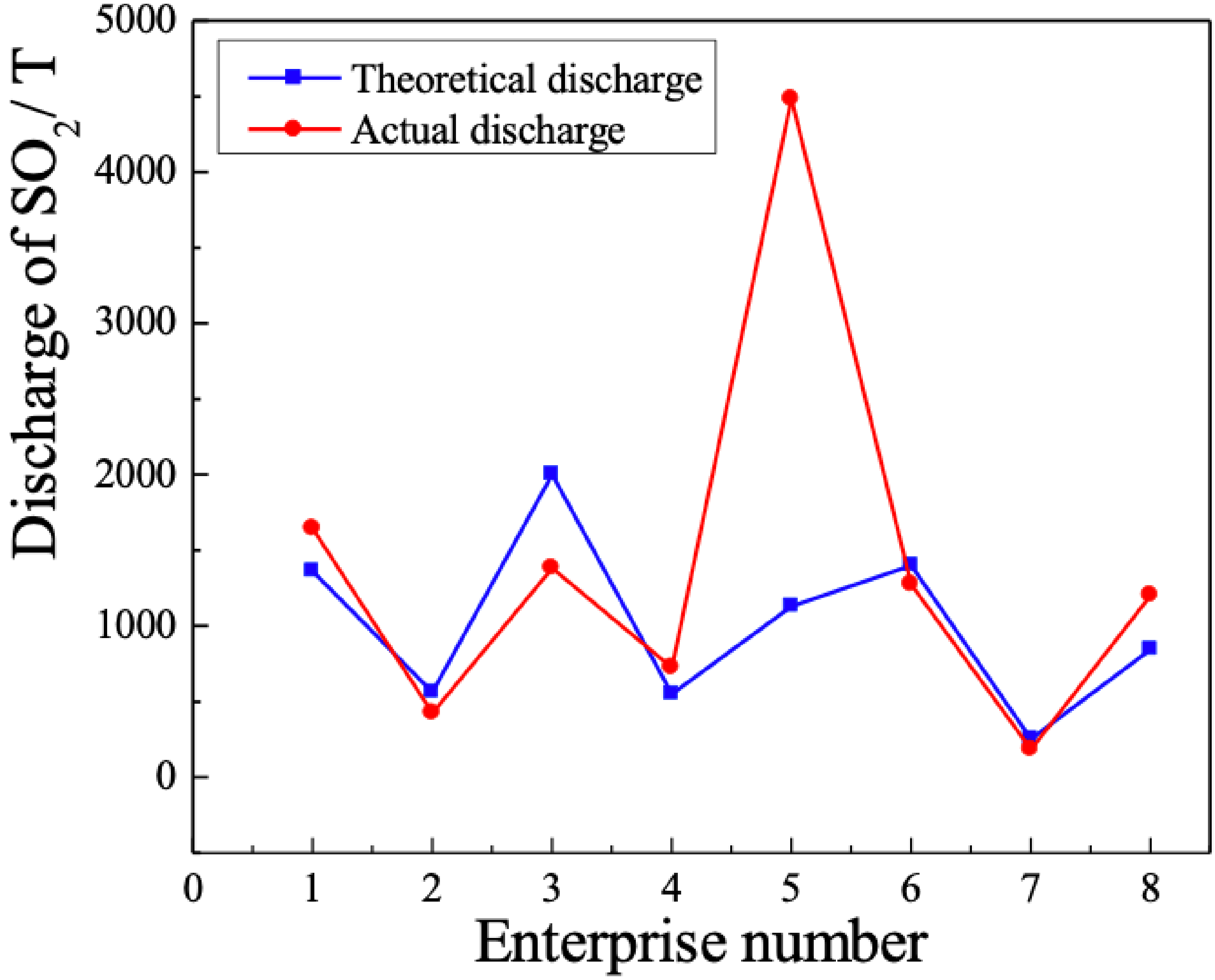

Figure 2

Comparison between theoretical and actual SO2 emissions