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Comparative study on different initial allocation methods of carbon emission rights from the perspective of efficiency: historical method, benchmark method, and ZSG-DEA method

Yu Wang*, Xiaoxuan Zhang, Pengwei Cong

State Grid Energy Research Institute Co., Ltd, Beijing 102209, China

Abstract: The research focuses on the initial allocation of carbon emission rights, aiming to analyze the advantages, disadvantages, and applicable scenarios of historical methods, benchmark methods, and ZSG-DEA methods from an efficiency perspective, and provide reference for policy-making. The study focused on 31 provinces in China in 2020, collected multidimensional data, and used three methods to calculate quota allocation schemes. The empirical results showed that the ZSG-DEA method performed the best, with an average efficiency improvement of 17.8% and an increase of 5 efficient provinces, which can balance carbon reduction and regional development equity; Although the historical method has good political acceptability, it is difficult to stimulate technological progress, and the benchmark method considers differences in carbon intensity but does not take into account multidimensional development capabilities. Based on this, the study suggests that policy makers choose allocation methods based on national conditions and industry characteristics, improve regulatory oversight and data systems, and guide enterprises to incorporate emission reduction into their strategies to achieve a win-win situation for both the economy and the environment.

1. Introduction

As a scarce environmental resource, the reasonable allocation of carbon emission rights plays a crucial role in achieving carbon reduction targets and promoting sustainable economic development. Different initial allocation methods of carbon emission rights will have a significant impact on the production and operation, market competition pattern, and carbon reduction effect of enterprises. Studying the initial allocation of carbon emission rights from an efficiency perspective can provide theoretical support for formulating more scientific and reasonable allocation policies, help improve resource allocation efficiency, promote economic transformation towards low-carbon, and achieve a win-win situation between economic development and environmental protection.

This study aims to conduct an in-depth analysis of three common initial allocation methods for carbon emission rights: historical method, benchmark method, and ZSG-DEA method, and compare their advantages, disadvantages, and applicable scenarios from an efficiency perspective, providing a reference for the formulation and optimization of carbon emission rights allocation policies.

2. Theoretical basis for initial allocation of carbon emission rights

2.1. Historical method

The historical method, also known as the grandfather method, is a method of allocating future carbon emission quotas based on a company's past carbon emission history data. The core idea is to believe that a company's past emissions can to some extent reflect its future emission needs and capabilities, and therefore allocate carbon emission rights based on a certain proportion of the company's historical emissions.

The advantages of this allocation method are quite obvious. On the one hand, its allocation process is relatively simple and easy to implement, without the need for complex calculations and data collection. It is also easy for enterprises to understand and accept because it is based on the existing emission situation of enterprises, reducing the resistance to the implementation of new policies and enabling enterprises to smoothly transition to the carbon emission trading system[1]; On the other hand, the historical method considers the historical development and operating conditions of enterprises. For those enterprises that have long-term stable operation and relatively stable emissions, it can ensure the continuity of their production and operation, avoid excessive impact on the enterprise due to sudden and significant reduction of carbon emission quotas, and to a certain extent safeguard the interests of the enterprise.

However, historical law also has many shortcomings. From an efficiency perspective, it lacks incentives for companies to reduce emissions efforts and potential. Due

*wangyu1@sgeri.sgcc.com.cn

to the fact that the quotas obtained by enterprises mainly depend on their past emissions, high emission enterprises can still obtain more quotas even without taking any emission reduction measures. However, enterprises that actively reduce emissions may receive fewer quotas due to their low historical emissions, and may not be able to obtain sufficient economic returns from the emission reduction results, thereby suppressing their enthusiasm for technological innovation and energy conservation and emission reduction, which is not conducive to the efficient achievement of the overall carbon reduction target[2]; From a fairness perspective, historical laws have not taken into account the needs of new entrants. New enterprises often find themselves at a disadvantage in quota allocation due to the lack of historical emission data, which may hinder their development and affect fair competition and innovation vitality in the market.

2.2. Benchmark method

The benchmark method is to set a carbon emission benchmark value for each enterprise based on the average production technology level and emission performance within the industry, and then determine its carbon emission quota based on the actual output or output of the enterprise. The principle is to set a unified industry benchmark to encourage enterprises to approach the advanced level of the industry, motivate them to improve production technology, enhance energy utilization efficiency, and reduce carbon emissions per unit of output.

The benchmark method has multiple advantages. Firstly, it can motivate enterprises to improve production efficiency and reduce carbon emission intensity[3]. Because enterprises can only obtain sufficient carbon emission quotas by reaching or exceeding industry benchmark levels, otherwise they need to purchase additional quotas. This encourages enterprises to actively adopt advanced production technology and management experience, reduce carbon emissions per unit product, and promote technological progress and energy conservation and emission reduction in the entire industry; Secondly, the benchmark method is relatively fair. It treats all enterprises equally and allocates quotas based on unified industry standards, avoiding the unfairness caused by differences in historical emissions of enterprises in historical laws. It provides a relatively fair competitive environment for new entrants and is conducive to fair competition in the market and rational allocation of resources.

But the benchmark method also has some shortcomings. In practical applications, accurately determining a reasonable industry benchmark value is not an easy task. There are significant differences in production processes, equipment levels, and management capabilities among different enterprises. It is very difficult to develop a benchmark value that can cover all enterprise situations, which may lead to unreasonable quota allocation for some enterprises; Moreover, updating industry benchmark values requires a significant amount of data collection and analysis work, and needs to consider various factors such as industry development and technological progress. If not updated in a timely manner, it may not reflect the latest situation in the industry, affecting the effectiveness and scientificity of quota allocation.

2.3. ZSG-DEA method

The ZSG-DEA (Data Envelopment Analysis) method is a multi input multi output analysis method based on efficiency evaluation, which is applied to the initial allocation of carbon emission rights. The aim is to achieve fair and efficient allocation of carbon emission rights by evaluating the input-output efficiency of various decision-making units (such as enterprises, regions, etc.). The basic principle is to construct a DEA model based on various factors such as energy input, capital input, labor input, output products, and carbon emissions generated by each decision-making unit in the production process, under the premise of total quantity control. The efficiency value of each decision-making unit is calculated, and then carbon emission rights are allocated based on the efficiency value, so that the decision-making unit with high efficiency obtains relatively more carbon emission rights, while the one with low efficiency obtains less carbon emission rights[4].

The advantages of the ZSG-DEA method are significant. It can comprehensively consider multiple input-output factors and objectively evaluate the carbon emission efficiency of each decision-making unit, thereby achieving effective allocation of carbon emission rights and improving resource allocation efficiency; At the same time, this method emphasizes the combination of fairness and efficiency, allocating based on efficiency values, incentivizing decision-making units to improve their own carbon emission efficiency, promoting overall energy conservation, emission reduction, and sustainable development.

However, the ZSG-DEA method also has certain limitations. It has high requirements for data and requires a large amount of accurate and detailed input-output data to construct the model. If there are missing or inaccurate data, it will affect the accuracy of the model and the reliability of the results; Moreover, the DEA model itself has certain assumptions and limitations, such as the assumption that the return to scale remains unchanged, which may not fully hold in practice, which may affect the applicability of the model and the rationality of the results[5].

3. Data and models

3.1. Data source

This study takes 31 provinces (autonomous regions, municipalities directly under the central government) in China in 2020 as the research object, comprehensively considering multidimensional variables such as economic development level, population size, energy consumption, research and development investment, environmental governance investment, etc. The purpose is to calculate the optimal carbon emission quota allocation plan for each province based on the zero sum game data envelopment analysis (ZSG-DEA) method.

Data preprocessing and indicator calculation: Unit conversion and standardization of raw data are performed to calculate derived indicators including carbon intensity, per capita GDP, per capita emissions, etc., providing basic data support for subsequent analysis.

3.2. Historical method and benchmark method

The historical method is based on the historical emission data of each province from 2017 to 2019, calculates the historical average emissions, and allocates the overall emission reduction target proportionally as the benchmark allocation scheme.

The benchmark method adopts the carbon intensity benchmark method, setting carbon intensity benchmark values (default is the carbon intensity level of the top 10% provinces), adjusting quota allocation based on the relative carbon intensity differences of each province's benchmark, and reflecting a reward and punishment mechanism for excellence.

3.3. ZSG-DEA method

- Objective function

$$\min \sum_{k=1}^{n} \theta_k \tag{1}$$

θ_k :Technical efficiency score of province k（$0<\theta_k \le 1$）;

Goal: Maximize overall efficiency in all provinces.

- Carbon emission input constraint (zero sum)

$$\sum_{j}^{n} \lambda_j x_{1j} \times \left[1 + \frac{x_{1k}(1-\theta_k)}{\sum_{j=1, j\neq k}^{n} x_{1j}} \right] \le \theta_k x_{1k} \tag{2}$$

$x_{1k} \times (1-\theta_k)$:The reduced emissions of province k;

$\sum_{j=1, j\neq k}^{n} x_{1j}$:Total emissions of all provinces except for province k;

$\frac{x_{1k}(1-\theta_k)}{\sum_{j=1, j\neq k}^{n} x_{1j}}$:The average proportion of emissions reduction in k province among other provinces;

$\theta_k \times C_k$:Optimized emissions of province k.

- Constraints on total energy input

$$\sum_{j=1}^{n} \lambda_j x_{2j} \le x_{2k} \tag{3}$$

- R&D investment constraints

$$\sum_{j=1}^{n} \lambda_j x_{3j} \le x_{3k} \tag{4}$$

- Environmental governance investment constraints

$$\sum_{j=1}^{n} \lambda_j x_{4j} \le x_{4k} \tag{5}$$

- GDP constraint

$$\sum_{j=1}^{n} \lambda_j \times y_{1j} \ge y_{1k} \tag{6}$$

Meaning: While reducing emissions, economic output cannot be reduced and must reach at least the GDP level of province k.

- Population constraints

$$\sum_{j=1}^{n} \lambda_j \times y_{2j} \ge y_{2k} \tag{7}$$

Meaning: While reducing emissions, population output cannot be reduced and must reach at least the population level of province k.

- Total quantity constraint

$$\sum_{k=1}^{n} X_k = T_X \tag{8}$$

Meaning: The total emissions after redistribution in all provinces are equal to the total target value.

- Weighted constraint

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{9}$$

- Non negative constraints

$$\begin{aligned} \lambda_j &\ge 0 \\ \theta_k &\ge 0 \end{aligned} \tag{10}$$

4. Empirical result analysis

Table 1 shows the comparison of the effects of three methods. The ZSG-DEA method performs the best in two key indicators, with an average efficiency improvement of 17.8% (from 0.749 to 0.882) and an increase in the number of efficient provinces by 5, proving the effectiveness of the ZSG-DEA algorithm.

Table 1. Comparison of Three Allocation Methods.

Allocation method	Average efficiency	Efficient provinces	Number of emission reduction provinces	Number of emission increase provinces
Historical method	0.749	19	27	3
Benchmark method	0.817	22	20	10
ZSG-DEA	0.882	24	6	24

Figure 1 shows a comparison of efficiency scores among provinces. It is evident from the figure that the ZSG-DEA optimized allocation scheme has a higher efficiency score, indicating a more reasonable allocation scheme.

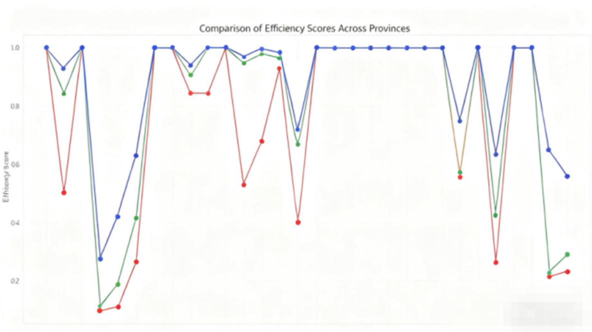

Figure 1. Efficiency levels under three allocation methods.

According to the calculation results, it can be concluded that under the given carbon emission reduction constraints, the ZSG-DEA optimization allocation method has the most systematic efficiency, achieving efficiency improvements of 17.8% and 8.0% compared to the historical method and benchmark method, respectively. At the same time, the number of efficient provinces has been increased from 19 to 24, effectively balancing carbon emission reduction targets with regional development equity requirements. The numerical verification shows that the ZSG-DEA method successfully identified and rewarded provinces with high technical efficiency such as Jiangsu and Guangdong by constructing an efficiency optimization mechanism under zero sum game constraints. At the same time, it implemented reasonable quota constraints on provinces with high carbon intensity such as Shanxi and Inner Mongolia, reflecting the distribution concept of "efficiency oriented and fair".

In addition, by comparing the three allocation methods, it can be found that although the traditional historical method maintains good political acceptability, it has significant shortcomings in incentivizing technological progress and structural optimization; The benchmark method to some extent reflects the differences in carbon intensity, but fails to fully consider the multidimensional development capabilities of each province; The ZSG-DEA method constructs a more scientific and reasonable efficiency evaluation system by comprehensively considering multidimensional factors such as GDP output, population size, energy consumption, and R&D investment, providing an important policy tool reference for achieving the national 2030 carbon peak target and regional coordinated development. The successful application of this method has demonstrated the effectiveness and practicality of the multi input multi output DEA model in the design of carbon quota allocation policies.

In theory, the efficiency oriented allocation method of ZSG can effectively promote provinces to pay more attention to environmental protection and rational utilization of resources while pursuing economic development, achieving coordinated development between regions and maximizing overall benefits. However, the challenges it faces in the implementation process, such as data availability, regulatory capabilities, and adaptability, should not be underestimated. The availability of data, as the cornerstone of this method, seriously affects the accuracy and reliability of the model; The shortcomings in regulatory capacity make it difficult for policies to receive effective supervision and protection during the implementation process; The differences in economic structure and the issue of stakeholder acceptance have increased the complexity and resistance of policy implementation. It is necessary to establish a unified data platform, strengthen regulatory capacity building, and develop differentiated adaptation strategies. In future policy-making, the ZSG-DEA method is expected to play a greater role in resource allocation, environmental protection, and other fields. With the continuous advancement of technology and the increasingly perfect system, data acquisition and processing will be more efficient and accurate, regulatory capabilities will be significantly improved, and the interests and demands of various regions will be more fully considered in the policy-making process.

5. Conclusion and suggestion

Based on the above research conclusions, the following suggestions are proposed for policy makers: when choosing the initial allocation method of carbon emission rights, China's national conditions, industry characteristics, and emission reduction targets should be fully considered. For some traditional industries with relatively stable production technology and complete carbon emission data, the historical method can be appropriately adopted in the early stage of establishing the carbon emission trading system to ensure a smooth transition for enterprises. However, a reasonable adjustment mechanism should be set up to gradually guide enterprises to transform towards low-carbon development.

For most industries, especially those with high energy consumption, high emissions, and rapid technological updates, priority should be given to using benchmark methods or ZSG-DEA methods, or a combination of both. When adopting the benchmark method, it is necessary to strengthen the research and development of industry benchmark emission rates, ensure that the benchmark emission rates can accurately reflect the actual situation of the industry, and update and adjust them in a timely manner according to technological progress and market changes. When using the ZSG-DEA method, it is necessary to increase investment in data collection and management, improve data quality, and strengthen training for relevant technical personnel to enhance the operability and application effectiveness of the method.

The government should improve relevant policies and regulations, strengthen supervision of the carbon emission trading market, and ensure fairness, impartiality, and openness in the allocation process. Establish and improve a monitoring, reporting, and verification system for carbon emissions data, crack down on illegal activities such as data fraud, and provide reliable data support for the initial allocation of carbon emission rights. In addition, tax policies, subsidy policies, and other means can be used to guide enterprises to actively participate in emission reduction actions and improve carbon emission efficiency.

For enterprises, regardless of the allocation method used, they should actively respond to the challenges brought by carbon emissions trading and incorporate emissions reduction into their strategic planning. Increase investment in the research and application of energy-saving and emission reduction technologies, improve production processes and management models, enhance energy utilization efficiency, and reduce carbon emission intensity. At the same time, enterprises should closely monitor the dynamics of the carbon emission trading market, arrange production and business activities reasonably, fully utilize market mechanisms to reduce emission reduction costs, and achieve a win-win situation of economic and environmental benefits.

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