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Comparative Evaluation of Carbon Emission Efficiency in the Beijing-Tianjin-Hebei Region

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ABSTRACT

In order to promote the achievement of the "dual carbon (carbon peaking and carbon neutrality)" goal, a comparative evaluation of carbon emission efficiency in the Beijing-Tianjin-Hebei region is conducted to address the issues of energy consumption intensity and insufficient research on carbon emission efficiency. Based on the input-output perspective, this study constructs an evaluation system consisting of three dimensions and six indicators: carbon emission input, expected output, and unexpected output. The super-efficiency SBM model is used to measure the carbon emission efficiency of the Beijing-Tianjin-Hebei region from 2012 to 2022. Research shows that the overall average annual growth rate of carbon emission efficiency in the Beijing-Tianjin-Hebei region is 4.07%, but there is significant spatial differentiation; Beijing is a high-level high-speed growth model and will reach an effective state in 2022, while Tianjin and Hebei have lower efficiency (both not exceeding 0.35), which hinders overall improvement; The efficiency improvement is mainly affected by the redundancy of capital and energy investment, as well as the lagging effectiveness of emission reduction policies. Finally, the study proposes suggestions such as establishing a green science and technology innovation transformation platform, promoting industrial structure upgrading, and improving energy consumption monitoring mechanisms to provide support for the green and high-quality development of the Beijing-Tianjin-Hebei region.

Keywords: *Carbon emission efficiency, Evaluation system, Super-efficiency SBM model, Beijing-Tianjin-Hebei region.*

1. INTRODUCTION

In recent years, greenhouse gas emissions have been continuously increasing, and climate issues have become a major global challenge. “The United Nations Framework Convention on Climate Change”, “Kyoto Protocol”, and other agreements have been signed and implemented successively, and countries around the world have actively responded and strived to achieve "net zero emissions" and the temperature control goals of the “Paris Agreement”. As an active participant and supporter of global climate governance, China solemnly proposed at the 75th United Nations General Assembly in September 2020 that China aims to peak its carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. In September 2021, the Central Committee of the Communist Party of China and the State Council issued the "Opinions on Fully, Accurately, and Comprehensively Implementing the New Development Concept and Doing a Good Job in Carbon Peak and Carbon Neutrality", proposing the overall requirements of "incorporating carbon peak and carbon neutrality into the overall economic and social development, taking the comprehensive green transformation of economic and social development as the guide, taking energy green and low-carbon development as the key, accelerating the formation of an industrial structure, production mode, lifestyle, and spatial pattern that saves resources and protects the environment, firmly adhering to the high-quality development path of ecological priority, green and low-carbon, and ensuring the timely realization of carbon peak and carbon neutrality". The 20th National Congress of the Communist Party of China further emphasized that promoting green and low-carbon development is an important measure to achieve high-quality development, and proposed active and prudent strategies such as "based on China's energy and resource endowment, adhering to the principle of first establishing and then breaking through, and implementing carbon peak action in a planned and step-by-step manner", which has pointed out the direction for promoting carbon peak and carbon neutrality work. The Beijing-Tianjin-Hebei region is an important engine and hinterland for promoting high-quality economic development in China. However, as an energy intensive area, it urgently needs to improve carbon emission efficiency to provide important support for promoting carbon peak and carbon neutrality in the Beijing-Tianjin-Hebei region and building a demonstration zone for ecological civilization "coordinated construction". Therefore, conducting research on the evaluation of carbon emission efficiency in the Beijing-Tianjin-Hebei region is of great significance for improving the region's ability to reduce emissions and fix carbon, and achieving the "dual carbon" goals as scheduled.

The academic community has focused on conducting research on measuring and evaluating carbon emission efficiency from multiple levels, including national, regional, and corporate levels. On the one hand, Qiao Lei et al.[1-2] used qualitative research methods to evaluate the carbon emission efficiency of China's construction and logistics industries. On the other hand, early scholars used quantitative analysis methods based on differences in knowledge backgrounds, mainly using single factor evaluation indicators such as carbon emission intensity[3], carbonization index[4], and the ratio of total carbon dioxide emissions to a certain factor[5] to evaluate carbon emission efficiency. However, carbon emission efficiency is the result of the comprehensive effects of multiple factors such as economic industry development and industrial energy consumption, and has the characteristics of all factors. To this end, scholars have successively applied production theory to construct carbon emission efficiency measurement indicators, and adopted data envelopment models[6], super-efficiency SBM models[7-8], asymptotic double difference models[9], stochastic frontier analysis models[10], and scale direction distance functions[11] to evaluate carbon emission efficiency.

According to literature review, scholars have conducted extensive qualitative research and quantitative measurements to explore carbon emission efficiency in practice, but there are still some shortcomings in existing research. From the construction of the carbon emission efficiency evaluation model, it can be seen that in the case where the optimal value of carbon emission efficiency is 1, it is impossible to further achieve spatiotemporal comparability between different periods and regions, resulting in incomplete calculation results of the impact of technological innovation level on carbon emission efficiency. From the perspective of research areas, few scholars have measured the carbon emission efficiency of the Beijing-Tianjin-Hebei region, resulting in a lack of consensus on the evaluation of carbon emission efficiency in the region. Therefore, it is urgent to improve the indicator design of carbon emission efficiency, construct a more spatially and temporally comparable carbon emission efficiency evaluation model, and conduct in-depth analysis of the carbon emission efficiency level in the Beijing-Tianjin-Hebei region. The contribution of this article is mainly reflected in the systematic design of indicators for carbon emission efficiency in the Beijing-Tianjin-Hebei region based on theoretical foundations, literature achievements, and research practices. The super-efficiency SBM model is used to achieve spatiotemporal comparability of carbon emission efficiency in different periods and regions, and countermeasures and suggestions are proposed to promote the improvement of carbon emission efficiency in the Beijing-Tianjin-Hebei region.

2. RESEARCH METHODS

2.1 Evaluation System Construction

According to the references [7-8,11], based on the input-output perspective, the researchers design carbon emission efficiency indicators for the Beijing-Tianjin-Hebei region from three dimensions: carbon emission input (C_1), desirable output (C_2), and undesirable output (C_3). First, the C_1 dimension mainly involves three aspects: capital input, labor input, and energy input. Capital investment refers to the capital stock in the Beijing-Tianjin-Hebei region, calculated using the perpetual inventory method developed by Zhang Jun et al.[12] with the year 2000 as the base year. The researchers use the number of employed people and energy consumption in the Beijing-Tianjin-Hebei region as labor input and energy input, respectively; Second, the C_2 dimension takes the GDP of the Beijing-Tianjin-Hebei region as the desirable output; Third, the C_3 dimension takes carbon emissions as the undesirable output. According to the “IPCC National Greenhouse Gas Emission Inventory Guidelines 2006”, the carbon emissions of the

Beijing-Tianjin-Hebei region are calculated based on the consumption of eight fossil fuels, including coal, natural gas, and coke.[13] Finally, by integrating three dimensional indicators, the carbon emission efficiency of the Beijing-Tianjin-Hebei region was evaluated, represented by C as the numerical value of the dependent variable. The selection of indicators is shown in "Table 1".

Table 1. Selection of carbon emission efficiency evaluation indicators

Variable	Indicators	First-level indicators	Second-level indicators
			Capital stock
		Carbon emission input (C_1)	Employment
C	Carbon emission efficiency		Energy consumption
		Desirable output (C_2)	GDP
		Undesirable output (C_3)	Carbon emissions

a Note: The data mainly comes from the "Beijing Statistical Yearbook", "Tianjin Statistical Yearbook", "Hebei Statistical Yearbook", "China Energy Statistical Yearbook", and the official website of the National Bureau of Statistics.

2.2 Evaluation Model Construction

The evaluation of carbon emission efficiency in the Beijing-Tianjin-Hebei region must simultaneously consider both expected and unexpected outputs. Scholar Tone[14] proposed that the SBM model is a non-radial DEA model that considers the role of unexpected output and is in line with the demand for carbon emission efficiency evaluation. However, the SBM model may result in multiple regions having carbon emission efficiency values of 1. The super-efficiency SBM model overcomes this limitation and facilitates comparative analysis of carbon emission efficiency values of 1 between different regions. Therefore, the super-efficiency SBM model is adopted to evaluate the carbon emission efficiency of the Beijing-Tianjin-Hebei region. Assuming that each region of the Beijing-Tianjin-Hebei region is taken as a decision-making unit, with a total of k regions containing m input factors, r_1 desirable output, and r_2 undesirable output, the carbon emission efficiency evaluation model for the Beijing-Tianjin-Hebei region can be expressed as:

$$\rho_{kt} = \min \rho[1-\frac{1}{m}\sum_{i=1}^{m}(\overline{w_i}/w_{ij})]/[1+\frac{1}{r_1+r_2}\cdot\left(\sum_{s=1}^{r_1} w_s^d / y_{sk}^d + \sum_{q=1}^{r_2} w_q^u / y_{qk}^u\right)]$$

$$s.t.\begin{cases} x_{ij} = \sum_{k=1}^{n} x_{ik}\lambda_k + \overline{w_i} \\ y_{qj}^u = \sum_{k=1}^{n} y_{qk}^u \lambda_k + w_q^u \end{cases} \quad (1)$$

In equation (2), ρ_{kt} represents the carbon emission efficiency value of the Beijing-Tianjin-Hebei k region in the t year. $\overline{w_i}$, w_s^d and w_q^u are relaxation variables, and both are greater than or equal to 0. $x_{ik}, y_{sk}^d, y_{qk}^u, \lambda_k$ represents the linear combination coefficients of the i input, s desirable output, q undesirable output, and k region in the Beijing-Tianjin-Hebei k region. $i=1,2,3$, $s=1$ and $q=1$, $\lambda_k \geq 0$. When ρ_{kt} reaches 1, the SBM is valid for the k region. The super efficiency SBM model for evaluating carbon emission efficiency in the Beijing-Tianjin-Hebei region can be expressed as:

$$\varphi_{kt} = \min \varphi = \frac{1}{m}\sum_{i=1}^{m}(\bar{x}/x_{ik})/[\frac{1}{r_1+r_2}\cdot(\sum_{s=1}^{r_1}\bar{y}^d/y_{sk}^d+\sum_{q=1}^{r_2}\bar{y}^u/y_{qk}^u)]$$

$$s.t.\begin{cases} \bar{x} \geq \sum_{k=1,j\neq k}^{n} x_{ik}\lambda_k \\ \bar{y}^d \leq \sum_{k=1,j\neq k}^{n} y_{sk}^d\lambda_k \\ \bar{y}^u \geq \sum_{k=1,j\neq k}^{n} y_{qk}^u\lambda_k \\ \sum_{k=1,j\neq k}^{n} \lambda_k = 1 \end{cases} \quad (2)$$

In equation (3), $\bar{x} \geq x_{ik}, \bar{y}^d \leq y_{sk}^d, \bar{y}^u \geq y_{qk}^u, \lambda_k \geq 0$.

3. EVALUATION OF CARBON EMISSION EFFICIENCY IN THE BEIJING-TIANJIN-HEBEI REGION

According to equation (1)(2), the super-efficiency SBM model is adopted to evaluate the carbon emission efficiency of the Beijing-Tianjin-Hebei region from 2012 to 2022. (See "Figure 1")

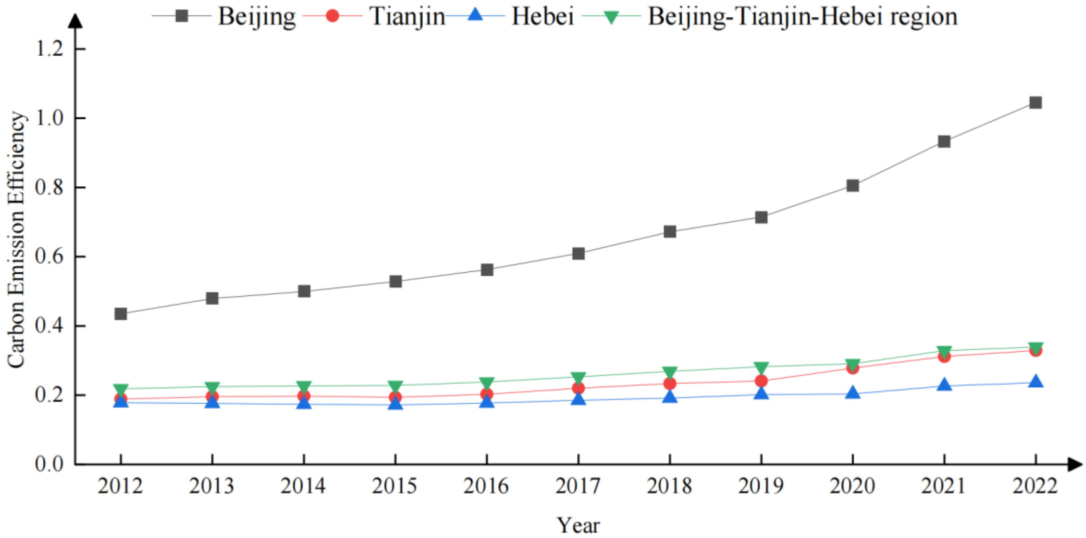

Figure 1 Changes in carbon emission efficiency in the Beijing-Tianjin-Hebei Region from 2012 to 2022.

As shown in "Figure 1", the carbon emission efficiency of the Beijing-Tianjin-Hebei region showed an overall increasing trend from 2012 to 2022, but the spatial differentiation characteristics were obvious. Among them, firstly, in terms of efficiency value changes, Beijing is significantly higher than Tianjin and Hebei, and the gap between Beijing and the Tianjin-Hebei region is gradually widening, while Tianjin is slightly higher than Hebei. As of 2022, Beijing's carbon emission efficiency has reached the forefront of carbon emission production, with an efficiency value greater than 1, indicating that Beijing's carbon emissions have reached an effective state. However, the carbon emission efficiency of Tianjin and Hebei did not exceed 0.35, indicating that the carbon emission input in the Tianjin-Hebei region has not been fully utilized, and the unexpected output or carbon emissions have not significantly decreased. Secondly, from the comparison of efficiency value growth, the average annual growth rates of Beijing, Tianjin, and Hebei are 8.29%, 5.19%, and 2.58%, respectively. Beijing belongs to the high-level high-speed growth type, significantly higher than Tianjin and Hebei. Tianjin and Hebei as a whole show a "slow first, then fast" growth trend. From 2020 to

2022, there has been a significant improvement in carbon emission efficiency in Tianjin and Hebei. The reason for this is that Tianjin's investment in scientific and technological personnel has significantly decreased, while Hebei's capital investment and carbon emissions have decreased.

Overall, the carbon emission efficiency of the Beijing-Tianjin-Hebei region has shown a steady growth trend with an average annual growth rate of 4.07%. Although Beijing's carbon emission efficiency has reached a state of super efficiency, due to the relatively low level of carbon emission efficiency in the Tianjin-Hebei region, Beijing's driving effect on the overall carbon emission efficiency improvement of the Beijing-Tianjin-Hebei region is limited. As of 2022, the overall carbon emission efficiency of the Beijing-Tianjin-Hebei region is only 0.34, which is still far from reaching an effective state.

Research has shown that from the relaxation value results of carbon emission efficiency evaluation indicators in the Beijing-Tianjin-Hebei region, the improvement of carbon emission efficiency in the region is mainly constrained by prominent input redundancy, especially capital and energy inputs, which maintain undesirable output or carbon emissions at a high level, affecting the improvement of carbon emission efficiency. First, from a development perspective, the Beijing-Tianjin-Hebei region, as the capital economic circle of China, is also the largest and most active economic development area in the northern region. Continuously promoting the construction of an open economic system, with a large influx of population, increasingly frequent production activities, and continuous increase in economic production value in the region, inevitably increases carbon emissions. When a large amount of investment fails to timely and effectively exchange for higher expected benefits, the improvement of carbon emission efficiency is constrained. Second, from the perspective of environmental regulation, in response to China's "dual carbon" strategic goals, the Beijing-Tianjin-Hebei region has introduced a series of energy-saving and emission reduction policies, and invested a large amount of resources to promote green and low-carbon development. However, there is a certain lag in reducing carbon emissions, and a large amount of resource investment cannot immediately show results, which to some extent affects the improvement of carbon emission efficiency in the Beijing-Tianjin-Hebei region.

4. CONCLUSION

Taking into account the impact of desirable and undesirable outputs, the researchers selected capital stock, employment, energy consumption, GDP and carbon emissions. A systematic evaluation system for carbon emission efficiency in the Beijing-Tianjin-Hebei region was designed based on six indicators of carbon emissions. The super efficiency SBM model was used to comprehensively evaluate the carbon emission efficiency of the Beijing-Tianjin-Hebei region from 2012 to 2022. The research results indicate that from 2012 to 2022, the Beijing-Tianjin-Hebei region has shown a steady upward trend in development, and Beijing's carbon emission efficiency belongs to a high-level high-speed growth type, which has reached an effective state. The carbon emission efficiency of Tianjin and Hebei shows a trend of slow to fast development, but still at a relatively low level, which restricts the overall improvement of carbon emission efficiency in the Beijing-Tianjin-Hebei region. From the perspective of development and environmental regulation, the phenomenon of investment redundancy, especially excessive investment in capital and energy, has a certain negative impact on carbon emission efficiency. This inefficient input mode leads to an increase in unexpected output, namely the sustained high operation of carbon emissions, which in turn limits the improvement of carbon emission efficiency.

To accelerate the green and high-quality development of the Beijing-Tianjin-Hebei region, it is urgent to promote the improvement of carbon emission efficiency by enhancing the level of regional scientific and technological innovation and upgrading the industrial structure. On the one hand, the efficient transformation of overall green technology innovation achievements in the Beijing-Tianjin-Hebei region can help improve regional carbon emission efficiency. The Beijing-Tianjin-Hebei region must rely on regional technological resources, promote collaborative innovation and resource sharing, and promote carbon emission efficiency improvement with a high level of technological innovation. On the other hand, the changes in carbon emission efficiency in the Beijing-Tianjin-Hebei region are mainly influenced by labor input and energy consumption. The Beijing-Tianjin-Hebei region must effectively control the input of resources in the production process, transfer more manpower and material resources to industries with lower energy consumption, promote industrial structure upgrading according to local conditions, and improve the overall carbon emission efficiency of the Beijing-Tianjin-Hebei region. Specifically, it includes:

Firstly, it is to establish a platform for the transformation of green technology innovation achievements, and guide Beijing high-tech enterprises to assist in the research and development of low-carbon technologies in Tianjin and Hebei, jointly developing and promoting low-carbon technologies. By gathering scientific and technological innovation resources in the Beijing-Tianjin-Hebei region through the platform, exchanging technology, exploring cooperation, it can form a closer industrial chain and value chain, jointly promoting the transformation and application of green scientific and technological innovation achievements, accelerating the development of green innovation industries, and promoting emission reduction and pollution reduction in the Beijing-Tianjin-Hebei region.

Secondly, for Beijing, which has a high level of technological innovation and advanced industrial structure, the researchers encourage it to continue to vigorously develop low-carbon technologies, focus on high-tech emerging industries for future development, and drive the transformation and development of industries in Tianjin and Hebei. At the same time, the government management departments of Tianjin and Hebei are promoting the transformation of their industrial structure towards green and low-carbon direction through policy guidance and market mechanisms, such as phasing out outdated production capacity and introducing efficient environmental protection technologies, in order to control and reduce the overall carbon emissions in the Beijing-Tianjin-Hebei region.

Thirdly, by establishing a sound long-term energy consumption monitoring mechanism in the Beijing-Tianjin-Hebei region, such as building a comprehensive visual monitoring system for energy consumption in the region, and regularly evaluating the input and use of energy resources, it is necessary to establish a feedback mechanism to avoid redundant resource investment and control and reduce the overall carbon emissions in the Beijing-Tianjin-Hebei region. At the same time, the researchers will strengthen environmental protection publicity and education in the Beijing-Tianjin-Hebei region, raise public awareness of environmental protection, and create a good atmosphere for the whole society to participate in emissions reduction.

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