Measurement and Evaluation of the Efficiency of Carbon Emission Trading Markets in China

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Abstract: This paper constructed an input-output indicator system for carbon emissions trading market from both primary and secondary markets, adopted DEA model to measure the national carbon market's and seven local carbon markets' efficiency, then classified them by hierarchical cluster method, and further analyzed scale returns and improvement space. The results show that the national carbon market and local carbon markets in Beijing, Shenzhen, Hubei and Shanghai are leading, while the local carbon market in Guangdong is in the middle, and the carbon markets in Chongqing and Tianjin are left behind. Further analysis of scale returns and room for improvement reveals that the national carbon market and the carbon markets in Beijing, and Shenzhen have consistently maintained constant scale returns and there is no room for improvement. The carbon markets in Shanghai and Hubei have relatively little room for improvement. There is significant room for improvement in the carbon markets of Guangdong, Chongqing, and Tianjin. Finally, suggestions about pure technology and scale for each carbon market are put forward.

Keywords: Carbon Market; Efficiency Measurement; DEA Model; Hierarchical Cluster

1. Introduction

The carbon emissions trading market is a crucial arena for tackling climate change[1], and its market efficiency has garnered the interest of numerous scholars[2-3]. China is the biggest emitter in the world and has one national carbon market and seven local carbon markets. Variations in market access and trade regulations substantially impact the operational impacts of these carbon markets. To attain carbon neutrality and peak carbon emissions, it is essential to analyze and evaluate the effectiveness of all carbon markets and to use this information as a benchmark for the development of the carbon market.

Similar to the capital market, the efficiency of the carbon market can be assessed through the efficacy of prices[4-6]. Given the preliminary stages of the carbon market and the limited effectiveness of prices in the secondary market [7-8], concurrent consideration is also given to factors in the primary market[9-10]. However, these researches ignore scale differences in different markets, and less consideration is given to whether the scale of the carbon market is reasonable and whether the operational efficiency has reached its optimal level, excluding scale factors. Furthermore, due to its late establishment time, there has been a lack of research on the national carbon market. Building upon these observations, this paper takes the national carbon market and seven local carbon markets as research objects, not only compares their comprehensive efficiency, but also compares pure technical efficiency and scale efficiency, thus providing a more comprehensive measurement.

2. Methodology

2.1 DEA Model

DEA is a linear programming approach that can evaluate the comparative efficiency of decision-making units with multiple inputs and outputs[11]. Given that it generates comprehensive data on efficiency, explains the reasons behind the inefficiency of a unit and delineates ways to improve, it has been implemented extensively in evaluations of environmental efficiency[12]. The specific solution of the DEA model is as follows:

For P regions, each region is a decision-making unit $DMU_i(1 \le i \le p)$, and each decision-making unit is composed of m input elements X and n various expected outputs Y, thus forming a possible set P of production:

$$P = \{(X,Y), X > 0, Y > 0; X \in E_m, Y \in E_n\} \quad (1)$$

Here the input and output vectors of the $i(i = 1,2,3,..., p)$ decision-making units are:

$$X_i = (x_{1i}, x_{2i}, ..., x_{mi})^T \quad (2)$$

$$Y_i = (y_{1i}, y_{2i}, ..., y_{ni})^T \quad (3)$$

Where x_{mi} denotes the m input variable in the decision-making unit i and y_{ni} is the n output variable in the decision-making unit. Then the dual equation is introduced to solve the optimal solution, that is,

$$\min\{\theta_k - \varepsilon \cdot (e1^T S^- + e2^T S^+)\}$$

$$\begin{cases} \sum_{i=1}^{p} \lambda_i \cdot X_i + S^- = \theta_k \cdot X_k \\ \sum_{i=1}^{p} \lambda_i \cdot Y_i - S^+ = Y_k \\ \sum_{i=1}^{p} \lambda_i = 1, \lambda_i \ge 0 \\ S^+ \ge 0, S^- \ge 0 \end{cases} \quad (4)$$

Here $e1^T = (1,1,...,1) \in E_m$, $e2^T = (1,1,...,1) \in E_n$, and S^- and S^+ are the slack variables of input and output respectively. When $\theta \ne 1$, DEA was invalid; When $\theta = 1$ and the optimal solution $e1^T S^{0-} + e2^T S^{0+} \ne 0$, it means that DEA is weakly efficient; When $\theta = 1$ and the optimal solution $e1^T S^{0-} + e2^T S^{0+} = 0$, DEA is efficient.

2.2 Indicator System

In order to completely assess the efficiency of the carbon market, this study uses indicators derived from the input-output perspective, utilizing the DEA model. The specific indicator system is shown in **Table 1.**:

Table 1.Market Efficiency Indicator System

	Indicator	Calculation
Input	Average carbon emission quota I_1	$\frac{A}{U}$, where A refers to the total quota, and U refers to the number of companies trading in the market
	The proportion of CCERs offset I_2	$\frac{C}{A}$, where C indicates the total amount of CCERs that can be offset by companies
	Greenhouse gas coverage proportion I_3	Obtained from the market
	Industry coverage quantity I_4	Obtained from the market
Output	Turnover rate O_1	$\frac{Q}{A}$, where Q indicates the total turnover volume
	Transaction dispersion O_2	$\frac{Q}{Q_{20\%}}$,where $Q_{20\%}$ represents the total transaction volume in the first 20% trading days after ranking
	Decline rate of energy consumption relative to GDP O_3	$1-\frac{1+E}{1+G}$, where E refers to the growth rate of total energy consumption; G refers to the GDP growth rate

The input of the carbon market is measured by four indicators. The first is the average carbon emission quota, I_1. The total carbon emission quota directly impacts carbon pricing and market efficiency[13]. For comparison between different markets, this article uses the average quota as a measure of carbon market input. The carbon market in China consists of two components: a quota trading market and a voluntary emission reduction trading market. CCERs, Chinese Certified Emission Reductions, assert that a portion of real emissions can be offset by voluntary emission reductions that have been certified by the appropriate agencies; thus, such reductions can also be exchanged on the market. Together with carbon emission quota, I_2 represents the supply of carbon market, and the greater its value, the more supply[14]. The fraction of greenhouse gases covered by each carbon market is denoted by I_3. The participation structure of the carbon market can be shown in I_4. Zhang (2021) pointed out that it is necessary to further expand the industry participation to activate the carbon market[15].

The output is measured by three indicators. An essential metric of market liquidity is the turnover rate, and an increase in liquidity fosters an environment that is conducive to enhancing market efficiency[16]. This paper uses the total carbon trading volume ratio to total quota to represent the turnover rate. Nevertheless, assessing market efficiency solely through turnover rate becomes ambiguous when trading activity is limited to specific periods while remaining minimal during others. To account for this, we propose the transaction dispersion O_2: rank the trading days according to transaction volume, and compute the ratio between the annual transaction volume and that of the initial 20% of trading days. The market is more efficient and transactions are more dispersed as the value increases. In addition, Hu(2023) emphasized the need for the carbon emission trading mechanism to consider the incentive impact associated with reducing emissions[17]. In light of the data availability and the correlation between energy consumption and carbon dioxide emissions, this study used the decrease rate of energy consumption concerning GDP (O_3) as an indicator of the carbon market's impact on carbon emission control.The larger the value, the more significant the effect of carbon emission reduction.

3. Efficiency Measurement

3.1 Data Description

Local carbon markets in China, like those in Shenzhen and Beijing, commenced their operations in around 2014, although the national carbon market launched operations in July 2021. Considering convenient comparison and data availability, the year 2018-2021 was set as the sample interval, and a preliminary description was presented. Their efficiency was then measured by year. The data are garnered from national and provincial statistical yearbooks, and carbon emission trading centers.

The average value of each input indicator for the sample period is computed after acquiring the annual input indicators of the carbon markets spanning the years 2018 to 2021. The resulting values are displayed in **Table 2.** The national carbon market only covers 2021, while seven local carbon markets cover all the sample intervals from 2018 to 2021.

Table 2. Average Input Description

Carbon market	Average carbon emission quota I_1(ten thousand tons)	Proportion of CCERs offset I_2(%)	Greenhouse gas coverage proportion I_3(%)	Industry coverage quantity I_4
National	208.14	5	17	1
Beijing	5.59	5	40	8
Shanghai	39.78	3	57	17
Guangdong	203.17	10	70	6
Shenzhen	3.66	10	40	6
Hubei	61.46	10	42	15
Chongqing	93.85	8	62	7
Tianjin	52.27	10	55	9

The national carbon market grants each corporation an average quota of 2,081,400 tons, which is greater than any local carbon market. The distribution of CCERs offset proportions spans from 3% to 10%. The Guangdong carbon market accounts for an average of 70% of greenhouse gas emissions, but the national carbon market accounts for only about 17%. The carbon markets in Shanghai and Hubei have the highest industry coverage quantity, with 17 and 15, respectively. In contrast, the national carbon market is limited to covering a single industry.

The average output indicators of all carbon markets for 2018 to 2021 are subsequently computed and presented in **Table 3.** The turnover rate of China’s carbon markets varies from 0.3% to 7.8%. Comparatively, the turnover rate of the EU carbon market is approximately 500%, indicating that China's carbon market remains less liquid. The average turnover rate of the carbon market in Chongqing is a mere 0.3%, which places it at the bottom of the industry. Transaction dispersion of all carbon markets fluctuates around 120%, indicating that transaction occurs mainly in two or three months during the year, but seldom in other months. Evidently, the average rate of drop in energy consumption relative to GDP in the carbon markets of Beijing and Shanghai is more than in other carbon markets, demonstrating the remarkable impact of carbon emission reduction in these two regions.

Table 3. Average Output Description

Carbon market	Turnover rate O_1(%)	Transaction dispersion O_2(%)	Decline rate of energy consumption per unit of GDP in the region O_3(%)
National	2.0	116.0	2.700
Beijing	4.5	120.8	5.160
Shanghai	1.4	111.3	4.978
Guangdong	3.7	130.5	2.785
Shenzhen	7.8	102.3	3.320
Hubei	3.2	140.0	2.450
Chongqing	0.3	104.5	2.743
Tianjin	1.6	106.3	2.260

3.2 Efficiency Measurement

This study uses the DEA method and the VRS (variable returns to scale) model to assess the market efficiency of China's carbon markets across three dimensions: comprehensive efficiency, pure technical efficiency, and scale efficiency. The findings are presented in **Table 4.**

TE of the national, Beijing and Shenzhen carbon markets during the sample period are always equal to 1, so the operating mechanism and scale design of the three markets are reasonable.

Table 4. Market Efficiency Measurement

Carbon market	2018			2019		
	TE	PTE	SE	TE	PTE	SE
National	-	-	-	-	-	-
Beijing	1.00	1.00	1.00	1.00	1.00	1.00
Shanghai	1.00	1.00	1.00	1.00	1.00	1.00
Guangdong	1.00	1.00	1.00	0.60	1.00	0.60
Shenzhen	1.00	1.00	1.00	1.00	1.00	1.00
Hubei	1.00	1.00	1.00	0.87	0.95	0.92
Chongqing	0.85	0.98	0.87	0.51	0.65	0.78
Tianjin	0.71	0.77	0.92	0.56	0.73	0.78
Carbon market	2020			2021		
	TE	PTE	SE	TE	PTE	SE
National	-	-	-	1.00	1.00	1.00
Beijing	1.00	1.00	1.00	1.00	1.00	1.00
Shanghai	0.74	0.80	0.94	1.00	1.00	1.00
Guangdong	1.00	1.00	1.00	0.71	1.00	0.71
Shenzhen	1.00	1.00	1.00	1.00	1.00	1.00
Hubei	1.00	1.00	1.00	1.00	1.00	1.00
Chongqing	0.96	1.00	0.96	0.73	0.73	0.99
Tianjin	0.78	0.78	0.99	0.80	0.81	0.99

Note: TE represents comprehensive efficiency; PTE represents pure technical efficiency; SE represents scale efficiency. TE=PTE × SE.

The carbon markets in Shanghai and Hubei failed to reach the optimal comprehensive efficiency in one year. In particular, the Shanghai carbon market had the lowest TE of any carbon market in 2020, at a mere 0.74. The primary reason, as seen in Table 4, is that both the PTE and SE are suboptimal. Specifically, the SE is 0.94, which is extremely near to 1.00 and indicates little opportunity for improvement; hence, the Shanghai carbon market should concentrate on technical efficiency in order to increase productivity. TE of Hubei carbon market is 0.87 in 2019, after only Beijing and Shenzhen carbon markets. Both PTE (0.95) and SE (0.92), which are both around 1, suggest that the Hubei carbon market is capable of attaining ideal results with minimal effort.

From 2018 to 2021, the TE of the Guangdong carbon market had significant changes, and its PTE has been consistently high at 1.00, indicating that the market's operation mechanism is reasonable; nevertheless, the scale must be adjusted. The TE of the carbon markets in Chongqing and Tianjin has consistently remained at a lower level from 2018 to 2021. Their extremely low PTE and SE render them less efficient than alternative carbon markets.

4. Efficiency Evaluation

4.1 Market Classification

To analyze all carbon markets, this paper classifies them according to their TE using the hierarchical cluster method; the findings of this classification are presented in **Table 5.** The initial level comprises the national, Beijing, Shenzhen, Hubei, and Shanghai markets, with a mean TE of 0.98 during the course of the sample. The TE of the national, Beijing, and Shenzhen carbon markets reached 1.00 every year, and that of the Hubei and Shanghai carbon markets was only slightly lower than 1.00 in 2019. With a TE of 0.83, the Guangdong market is positioned in the second level. The average TE for Chongqing and Tianjin markets, comprising the third level, is a mere 0.74.

Table 5. Clustering Results

	Level 1	Level 2	Level 3
Market	The national, Beijing, Shenzhen, Hubei and Shanghai market	Guangdong market	Chongqing and Tianjin market
Average TE	0.98	0.83	0.74

4.2 Improvement Potential Analysis

PTE, as defined by DEA, pertains to the utmost efficiency achieved using the existing technology, excluding any changes in scale. Subsequently, the improvement potential of the current scale can be assessed by comparing PTE and TE[10]; the findings are presented in **Table 6.**

The national, Beijing and Shenzhen carbon markets had no potential for efficiency enhancement; Hubei and Shanghai carbon markets had moderate room for efficiency improvement in 2020 and 2019, respectively. In contrast, the Guangdong, Chongqing, and Tianjin carbon markets had substantial room for efficiency improvement. Consequently, to improve market efficiency, it is imperative to further fortify the construction of these three carbon markets.

Table 6. Improvement Potential Analysis

Carbon market	2018	2019	2020	2021
National	-	-	-	0.00
Beijing	0.00	0.00	0.00	0.00
Shanghai	0.00	0.00	0.06	0.00
Guangdong	0.00	0.40	0.00	0.19
Shenzhen	0.00	0.00	0.00	0.00
Hubei	0.00	0.08	0.00	0.00
Chongqing	0.13	0.14	0.04	0.00
Tianjin	0.06	0.17	0.00	0.01

4.3 Return to Scale Analysis

The change in output resulting from an equal proportional increase or decrease in input elements under the present technological conditions is referred to as "return to scale." It is stated that production circumstances are optimal when the return to scale is constant and the increased ratio of output factors is equivalent to that of input factors; otherwise, there is room for scale adjustment.

Table 7. Return to Scale

Carbon market	2018	2019	2020	2021
National	-	-	-	constant
Beijing	constant	constant	constant	constant
Shanghai	constant	constant	increasing	constant
Guangdong	constant	decreasing	constant	decreasing
Shenzhen	constant	constant	constant	constant
Hubei	constant	increasing	constant	constant
Chongqing	increasing	increasing	increasing	constant
Tianjin	increasing	increasing	constant	decreasing

The national, Beijing, and Shenzhen carbon markets maintained constant returns to scale from 2018 to 2021, as shown in **Table 7.** This indicates that these carbon markets have attained maximum efficiency. Shanghai and Hubei carbon markets have only an increasing return to scale in 2020 and 2019 respectively. However, the carbon market in Chongqing has been in a return-to-scale increase phase from 2018 to 2020, indicating that it is capable of increasing input factors to improve performance. As the return to scale for the Guangdong carbon market decreased between 2019 and 2021, the market will be required to cut its input variables. With the exception of a consistent return to scale in 2020, the return to scale for the Tianjin carbon market increased throughout the first two years but decreased in the final year; therefore, the ratio of output to input components must be optimized further.

5. Conclusions

This study uses the DEA approach to measure the efficiency of the national and seven local carbon markets in China. Then it classifies them according to their comprehensive efficiency from 2018 to 2021 using the hierarchical cluster method. The national, Beijing, Shenzhen, Hubei and Shanghai markets are leading; Guangdong market is in the middle, while the markets of Chongqing and Tianjin are lagging behind. The national, Beijing and Shenzhen markets have maintained constant returns to scale and there is no improvement potential; Shanghai and Hubei carbon markets have had an increasing return to scale in one year, and there is little room for improvement; the Guangdong carbon market experienced decreasing return to scale in two consecutive years, and should reduce its carbon emission quota; Chongqing carbon market is always in a stage of increasing return to scale, while Tianjin carbon market has both increasing and decreasing return to scale, and there is much room for improvement in these two carbon markets. They should learn from the successful practical experience of other carbon markets, improve market liquidity and play the resource allocation function. Further research can be conducted on the influencing factors of market efficiency, then more feasible suggestions can be proposed for each carbon market.

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References

[1] Yu Z, Cao Y, Liu M, et al. Does carbon emission trading policy affect bank loans of firms? Evidence from China. Applied economics letters, 2022.

[2] Ibikunle G, Gregoriou A, Hoepner A, et al. Liquidity and market efficiency in the world's largest carbon market. The British Accounting Review, 2016, 48(4): 431-447.

[3] Tang B J, Gong P Q, Shen C. Factors of carbon price volatility in a comparative analysis of the EUA and sCER. Annals of operations research, 2017, 255(1): 157-168.

[4] Wang Y, Wang Z, Tang N. Comparative Study on Efficiency of China's Pilot Carbon Trading Market Based on Sharpe Ratio. Scientific and Technological Management of Land and Resources, 2022, 39(1): 9-19.

[5] Zhang N. Analysis on the Operation Status and Efficiency of China's Carbon Emission Trading Market—Based on the Calculation of Carbon Trading Police. Journal of Industrial Technological Economics, 2023, 42(04): 100-107.

[6] Ren, X, Li, Y, Duan, K and Mishra, T, 2023. Evaluation of European Union

carbon and energy networks: Evidence from market efficiency. Energy & Environment, 2023: 1-24.
[7] Zhao X G, Jiang G W, Nie D, et al. How to improve the market efficiency of carbon trading: a perspective of China. Renewable & Sustainable Energy Reviews, 2016, 59(6): 1229-1245.
[8] Ren, X, Li, Y, Qi, Y and Duan, K, 2022. Asymmetric effects of decomposed oil-price shocks on the EU carbon market dynamics. Energy, 2022, 254: 124172.
[9] Cheng Y W, Mu D. Study on the Operation Efficiency Evaluation of Pilot Carbon Trading Markets in China. Science and Technology Management Research, 2017, 37(4): 96-100.
[10]Zhou R. Efficiency Analysis of Carbon Emission Trading Market in Hubei Province. Huazhong University of Science & Technology, 2019.
[11]Norabajra A, Timothy J. Gronberg, et al. Introducing a new DEA methodology for environmental inputs. Applied Economics Letters, 2013, 20(17): 1592-1595.
[12]Wang C, Wang X. Carbon Emission Efficiency of the Yangtze River Economic Belt: Measurement and Analysis. Statistics & Decision, 2022, 38(17): 82-85.
[13]Wu W, Zhu Y, Gu G. Determinants of the effectiveness of China’s pilot carbon market. Resources Science, 2021, 43(10): 2119-2129.
[14]Zhang X, Zhang D and Yu R. Theory and Practice of China's National Carbon Emissions Trading System. Journal of Management World, 2021, 37(08): 80-95.
[15]Chung D Y, Hrazdil K L and Market E: Analysis of NASDAQ Firms. Global Finance Journal, 2010, 21(3).
[16]Hu J, Fang Q and Long W. Carbon Emission Regulation, Corporate Emission Reduction Incentive and Total Factor Productivity: A Natural Experiment Based on China’s Carbon Emission Trading System. Economical Research Journal, 2023, 58(04): 77-94.
[17]Yan Z, Yu Z, Gu X. Research on Conduction Mechanism between Carbon Price and Coal Future Price in China. On Economic Problems, 2022, 514(06): 67-74.