Efficiency of China's carbon trading schemes based on bootstrap-DEA: A tale of 7 pilot markets[1]

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Abstract:

China's carbon emission trading scheme (ETS) was launched in seven pilot regions in 2013. The purpose of this study is to evaluate the efficiency of China's seven pilots' ETS. Specifically, the overall, pure technical and scale efficiencies of the seven pilot ETS and their temporal dynamics in 2014-2018 are evaluated, and the determinant factors on the efficiency in different pilot carbon markets are systemically explored. An improved data envelopment analysis (DEA) model by integrating the bootstrap correction method (bootstrap-DEA) is used to solve the evaluation deviation of the traditional DEA model. Empirical results show the following. 1) The efficiency of China's carbon trading market maintains a prominent ascend trend year by year. The average overall efficiency of the seven pilot markets increased from 0.6119 in 2014 to 0.7184 in 2018, and the average pure technical efficiency increased from 0.8444 to 0.9211. 2) There are remarkable differences in efficiency and transaction price of the seven pilot carbon markets in China. The average overall efficiency is distributed in 0.5962–0.8444. 3) All seven pilot carbon markets have some shortages. The main constraint effect on the efficiency of the carbon markets is the small-scale market transaction. Such a constraint effect is manifested by the pilot carbon markets' average scale efficiency, which is only 0.7969. The innovation of this study is the introduction of the bootstrap-DEA model in the efficiency evaluation of ETS, which guarantees a more accurate efficiency estimation than the traditional DEA. This study provides quantifiable reference and concrete policy recommendations for policymakers to consummate the institutional designs to improve the ETS efficiency of China.

Keywords: Emission trading scheme (ETS); Efficiency evaluation; Bootstrap-DEA; Pure technical efficiency; Scale efficiency; China

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1. Introduction

Extreme climate events caused by global warming (Yüksel, 2008) have become challenging risks threatening the Earth's natural ecosystem (Sarkar et al., 2020), human survival (Calleja-Agius et al., 2020), and global political and economic stability (Kanlic, 2014). The main reason for global warming is the relentless growth of greenhouse gases, significantly the rapid increase of carbon emissions (Huisingh et al., 2015). The international community has formulated and adopted the United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol and Paris Agreement successively to cope with climate change. The emission trading system (ETS) is one of the milestone emission reduction policies proposed by the Kyoto Protocol and a supplementary provision of UNFCCC. Moreover, the parties of the Paris Agreement determine their emission targets as nationally determined contributions for coping with climate change, laying a foundation for promoting national carbon transactions (Fujimori et al., 2016).

ETS is a policy tool for reducing greenhouse gas emission by market-oriented means that has been adopted in the European Union, the United States, China, Canada, Japan, Korea, New Zealand, and other countries or districts (Li et al., 2019). Based on ETS, CO_2 emission is transformed into a scarce and tradable commodity, and its external cost is internalized. The independent emission of enterprises covered by carbon emission trading is promoted (Yang et al., 2016). Theoretically, carbon trading itself can maximize the profits of enterprises with different marginal emission-reduction costs and finally minimize the emission-reduction costs of the society (Yu et al., 2020). The ETS has the following advantages: 1) the system contributes to the potential GDP growth or the recovery of GDP losses (Zhao et al., 2016); 2) the government can promote energy saving, emission reduction, and the development of a low-carbon economy through the market mechanism (Zhao et al., 2016); 3) the ETS results in more cost savings than the command control policy and strengthens the economy and emission-reduction potential (Wang et al., 2016); 4) the ETS provides a capital bonus for sustainable development and stimulates environmental and

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ecological governance (Yan et al., 2020).

As the largest carbon emission country, China released a notice on carrying out carbon emission exemplary trading pilot work in October 2011 to achieve the goal of CO_2 emission reduction and announced the selection of Beijing, Tianjin, Shanghai, Guangdong, Shenzhen, Hubei, and Chongqing as pilot areas for the implementation of the carbon ETS (Xu et al., 2019). The cumulative quota trading volume of the seven pilot markets has reached 56.1504 million tons by the end of 2018 (Wind financial database). Fig. 1 shows the distribution and concentration of the average transaction prices of the seven pilot carbon markets in 2014-2018. If the color becomes redder, then the average transaction prices concentrate more on the surrounding of this price.

From the perspective of the distribution of a specific price in various carbon markets, the price span of the carbon market in Shenzhen is the largest, with the lowest price of 9.9 yuan and the highest price of 123 yuan, and the price mainly ranges from 21 to 44 yuan. The price span of the carbon market in Guangdong ranks second, with the lowest price of 1.3 yuan and the highest price of 77 yuan, and the price mainly ranges from 9 to 19 yuan. The price span of the carbon market in Beijing ranks third, with the lowest price of 30.3 yuan and the highest price of 77 yuan, and the price mainly ranges from 48 to 56 yuan. The price span of the carbon market in Shanghai ranks fourth, with the lowest price of 4.2 yuan and the highest price of 44.9 yuan, and the price mainly ranges from 28 to 40 yuan. The price span of the carbon market in Chongqing ranks fifth, with the lowest price of 1 yuan and the highest price of 39.6 yuan, and the price mainly ranges from 1 to 5 yuan. The price span of the carbon market in Tianjin is similar to that in Chongqing, with the lowest price of 7 yuan and the highest price of 42.4 yuan, and the price mainly ranges from 21 to 25 yuan. The Hubei carbon market, as one of the large-scale carbon markets in China, has the smallest price span of 9.4–32.6 yuan, and the prices mainly range from 12 to 18 yuan and from 21 to 27 yuan.

The average transaction price indicates different prices among different pilot carbon markets, and the desirable carbon price should be equal to the minimum marginal emission reduction cost for achieving the emission-reduction target.

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Therefore, the unreasonable carbon price caused by an imperfect quota system will affect the participation and commitment of enterprises in the ETS, thus affecting the market efficiency (Tang et al., 2020).

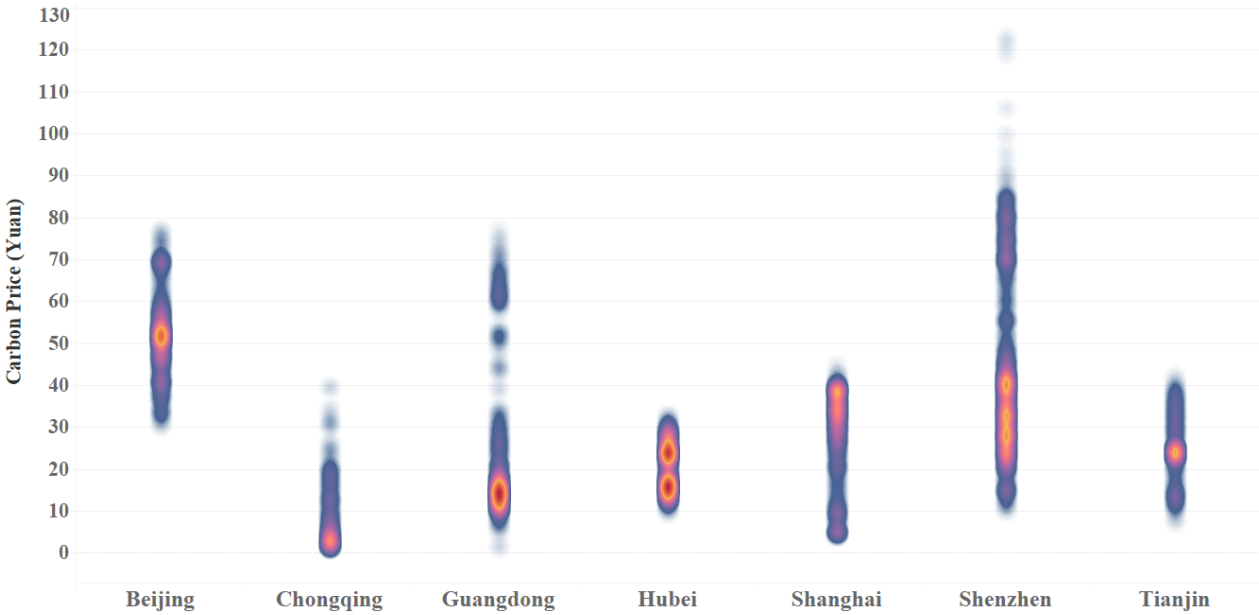

Fig. 1 Distribution of average transaction prices in China's seven pilot carbon markets in 2014–2018

Data sources: *Wind financial database*

This study aims to evaluate the efficiencies of the seven pilot ETS in China, i.e., Beijing, Tianjin, Shanghai, Guangdong, Shenzhen, Hubei, and Chongqing. Bootstrap-DEA, an improved DEA model by integrating the bootstrap correction method, evaluates the pilot ETS efficiencies during 2014-2018. The specific operating shortboards of ETS efficiency are identified by decomposing the overall efficiency into pure technical and scale efficiency. The research outcomes provide referential experience for the consummation of China's pilot ETS and establishing the national ETS.

The contributions of this study lie in the following two aspects. This paper performs comparative analysis on the overall efficiency of various carbon markets in China in terms of research contents. The overall efficiency is decomposed into pure technical efficiency and scale efficiency, which shed light on the key influencing factors on the overall efficiency of different pilot ETS. In terms of research method, Bootstrap-DEA, combining bootstrap sampling technique with DEA model, is an

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ideal solution to cope with the limitation of traditional DEA, such as sample sensitivity and overestimation of efficiency (Fall et al., 2018; Zhang, 2019).

The rest of this paper is organized as follows. A literature review is presented in the second section. Section 3 introduces the research method and data. Section 4 provides the empirical results. Section 5 concludes this study, and concrete policy suggestions are provided.

2. Literature review

A growing body of literature has focused on China's pilot ETS. Zhang et al. (2014) summarized the development status of China's seven pilot carbon markets and compared the mechanism characteristics of ETS in the coverage range, initial quota, monitoring, reporting and verification (MRV) and other aspects in all aspects of the pilot regions. Cui et al. (2014) pointed out that 23.67% of the total emission-reduction cost in the national carbon market could be reduced, and the carbon emission right trading scheme might have different cost-saving effects in other provinces. Meanwhile, some studies focused on disclosing problems in China's pilot ETS. Weng and Xu (2018) pointed out the lack of a perfect supervision system and a unified market regulatory organization in China's ETS. Yi et al. (2018) evaluated the maturity of the seven pilot markets of China through the fuzzy analytical hierarchy process (FAHP) and identified the constraint factors of a well-performing ETS. Liu et al. (2019) further verified that the overall maturity of China's carbon market is low by using the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method.

Some pieces of literature focused on a specific pilot ETS in China. Jiang et al. (2014) investigated the institutional background and the supervision framework of Shenzhen pilot ETS. Wu et al. (2014) qualitatively explored the flaws of Shanghai pilot ETS mechanism designs and proposed countermeasures for quota allocation, carbon information disclosure, risk management, etc. Qi et al. (2014) studied the pros and cons of Hubei's ETS design, including the following aspects, the upper limit, the

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quota, the transaction mechanism, the compliance, and the fine. Liao et al. (2015) simulated the initial allocation of Shanghai's carbon ETS based on the Shapley value to explore the fair quota allocation mechanism.

In summary, in terms of the research content of China's ETS, many studies investigated the development status and problems of China's overall carbon market or a pilot carbon trading market and the prospect forecast after implementing the carbon trading policy. A few studies have begun to pay attention to the efficiency of the carbon trading system. Zhang et al. (2020) evaluated the efficiency of China's carbon market in 2015-2017 by using the DEA method. Zhao et al. (2017) established the efficient market model of China's ETS based on the fair game model. They found that China's ETS had reached weak form efficiency but failed to reach semi-strong form efficiency and strong-form efficiency. Zhao et al. (2016) identified the reasons for the low efficiency of China's ETS by taking full consideration of four determinant factors such as carbon price, trading volume, market liquidity, and information transparency and proposed relevant suggestions. The root reasons may be the lack of supportive institution arrangement for ETS, insufficient market preparation, and obvious system design defects. Yi et al. (2020) studied the comprehensive service capability and market efficiency of seven pilot ETS markets by using the factor analysis method, the AHP (Analytical Hierarchy Process) and the DEA method and believe that great differences in comprehensive serviceability exists among the seven pilot ETS markets.

In terms of the research method, the methods of carbon market efficiency evaluation in the existing studies mainly include the variance ratio test (Montagnoli and de Vries, 2010), multifractal detrended analysis (Fan et al., 2018), the fair game model (Zhao et al., 2017), detrended fluctuation analysis (DFA) (Zhang et al., 2016) and the entropy weight–TOPSIS evaluation method (Yang et al., 2017). Montagnoli and de Vries (2010) used the variance ratio test to solve the problem of size distortion and low power consumption through the non-parametric test and joint inspection based on the concept that the variance in random walk process is linear in all sampling intervals, thereby exploring the effectiveness and efficiency of the EU ETS.

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Therefore, the EU ETS is inefficient in the first stage (i.e. the trial and learning stage) but shows signs of market efficiency recovery in the second stage. Fan et al. (2018) adopted multifractal detrended analysis. They found that China's ETS has low efficiency. The regression result further revealed that the low efficiency is positively correlated with the short-term market activity and negatively correlated with the long-term market activity. Zhao et al. (2017) tested the weak form efficiency by using the efficient market model for China's ETS established based on the fair game model. Zhang et al. (2016) studied the efficiency of the ETS by using the DFA method and found that, on the one hand, the efficiency of China's pilot ETS is generally low and thus difficult for the market to play a price discovery function; on the other hand, the time when investors are active in trading is often concentrated near the performance period.

Yang et al. (2017) analyzed and compared the operation efficiency of seven pilots ETS markets of China by using the entropy weight-TOPSIS evaluation method and found that the differences in transaction mechanism design among the various pilots of China cause a tremendous difference in operational efficiency. The carbon trading market is a complex multi-agent and multi-variable system. DEA performs better than game theory, regression analysis, and other analysis methods in evaluating a multi-dimensional input and output structure system. Zhang et al. (2020) evaluated the market efficiency using the DEA model and found that the average efficiency of China's seven pilot ETS markets increases year by year. Cheng and Mu (2017) evaluated the operation efficiency of the ETS by using the DEA model. Their result shows that the operation of the ETS markets in Shenzhen, Hubei and Tianjin is efficient, while the efficiency values of the ETS markets in Shanghai, Beijing, Guangdong and Chongqing are low. Furthermore, China's ETS has several common problems, such as excessive total quota and low participation of emission control enterprises.

To sum up, many studies on ETS have been conducted, but the following deficiencies remain:

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(1) In terms of research content, most of the literature investigates the overall emission reduction effect of the implementation of the ETS and the development status and existing problems of the ETS itself, but pay little attention to the operation efficiency of the carbon market.

(2) A few works studied the efficiency of the carbon market, but the research methods require further improvement. The ETS is subject to the characteristics of multi-agent and multi-variable. Practical analysis of the ETS cannot be achieved by some traditional methods such as game theory, regression analysis, etc. Some deviations exist in the empirical results. Some scholars measure the efficiency of the ETS by using the traditional DEA method. However, due to sample sensitivity, vulnerability to extreme values, and deviated estimation of the small size of samples (Fall et al., 2018), the estimated efficiency value can easily be higher than the true value in assessing the carbon market efficiency.

This work corrects the efficiency based on the traditional DEA method by using bootstrap for a more accurate and more authentic carbon market efficiency estimation.

3. Research methods and data

3.1 Research methods

3.1.1. DEA method

Charnes, Cooper, and Rhodes proposed DEA in 1978. DEA is an effective method for evaluating the multi-index input-output system. The technique aims to assess the relative efficiency of decision-making units (DMUs) with multi-input and multi-output by solving mathematical programming problems. DEA's most significant advantage is that it does not need to set the function form of the input and output variables in advance, avoiding the deviation of the function settings. For each DMU, the input-oriented, constant returns to scale (CCR) DEA model can be written as follows:

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$$\max \frac{\sum_{r=1}^{q} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}}$$

$$s.t. \frac{\sum_{r=1}^{q} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}} \leq 1$$

$$v \geq 0; u \geq 0$$

$$i = 1,2,\cdots,m; r = 1,2,\cdots q; j = 1,2,\cdots,n \qquad \text{Formula (1)}$$

where x_{ik} refers to the ith input variable of decision-making unit DMU_k, v_i refers to its input weight, y_{rk} refers to the rth output variable of decision-making unit DMU_k and u_r refers to its output weight. To calculate the efficiency value of the DMU, the mathematical programming problems must be solved, the appropriate v_i and u_r must be determined to maximize its efficiency, and the constraint conditions must be set to make the efficiency value of each DMU less than 1.

In the CCR model, the return to scale of production technology is assumed to remain unchanged or in the stage in which the return to scale is unchanged in the case of variable returns. However, many DMUs do not in the production state with the optimal scale. Thus, the technical efficiency obtained from the CCR model includes the scale efficiency component. Therefore, Banker et al. (1984) extended the CCR model to the BCC model by adding the constraint conditions for the variable return to scale, making the production scale in the projection point at the same level as the production scale of the DMU to be evaluated, excluding the influence of scale efficiency on technical efficiency under variable returns to scale. The specific model is as follows:

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$$
\begin{aligned}
&\min \theta \\
&\text{s.t.} \sum_{j=1}^{n} \lambda_j x_{ij} \le \theta x_{ik} \\
&\quad \sum_{j=1}^{n} \lambda_j \mathrm{y}_{rj} \ge y_{rk} \\
&\quad \sum_{j=1}^{n} \lambda_j = 1 \\
&\quad \lambda \ge 0 \\
&\quad i = 1,2,\cdots,m; r = 1,2,\cdots,q; j = 1,2,\cdots,n
\end{aligned}
\qquad \text{Formula (2)}
$$

where θ refers to the efficiency of the variable return to scale of the DMU.

3.1.2. Bootstrap-DEA method

Although DEA has some advantages that cannot be compared by the parameter estimation method, it leads to the deviation of efficiency evaluation in the case of a small sample size. It has some problems, such as sample sensitivity, vulnerability to extreme value, and estimation deviation for small-size samples (Fall et al., 2018). Therefore, Simar and Wilson (1998) introduced the bootstrap method in the DEA model. The bootstrap-DEA method is based on the DEA method. Thus, the combined approach does not need to set the function of the input and output variables in advance. The bootstrap-DEA method is suitable for evaluating the efficiency of a DMU with a multi-dimensional input-output structure. The bootstrap method is used to infer the empirical distribution of the DEA estimator by producing many simulated samples by repeated sampling.

Considering the sensitivity of the efficiency value to sample change, the confidence interval of the efficiency value is set, making the estimated value highly consistent with the actual value under a relatively loose condition. Therefore, the defects of the traditional DEA method are addressed. It provides the basis for judging the stability of the efficiency value (Zhang, 2019). This method can avoid the problems of small size samples, sample sensitivity, and outliers and compensate for the shortcomings of the traditional DEA method. The method's estimation process is as follows:

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（1） Assuming the original sample data in which each decision-making unit DMU_k input and output $(X_k,\ Y_k)$, $k = 1,\cdots,n,$ the DEA method is adopted to calculate the efficiency value ($\hat{\theta}_k$).

（2）Assuming the efficiency values of n decision-making units ($\hat{\theta}_k$), $k = 1,\cdots,n,$ the bootstrap method is adopted to obtain random efficiency values $\theta_{1b}^*,\cdots,\theta_{nb}^*$, where b refers to the number iterations using the bootstrap method.

（3）Calculate the simulated sample (X_{kb}^*,Y_k), $k = 1,\cdots,n,$ where, $X_{\mathrm{kb}}^* = \left(\frac{\hat{\theta}_k}{\theta_{nb}^*}\right) * X_k, k = 1,\cdots,n.$

（4） For each simulated sample, the DEA method is adopted to calculate efficiency value $\hat{\theta}_{kb}^*$, $k = 1,\cdots,n.$

（5） Repeat Steps (2)–(4) B times to produce a series of efficiency values $\left\{\hat{\theta}_{kb}^*, k = 1,2,\cdots,n; b = 1,2,\cdots,B\right\}.$

Given that the DEA method may cause estimation bias in the case of a few samples, a smooth bootstrap distribution can simulate the distribution of the original sample estimator to correct the estimation deviation of DEA.

$$Bias\left(\hat{\theta}_k\right) = E\left(\hat{\theta}_k\right) - \hat{\theta}_k,$$

$$\hat{Bias}\left(\hat{\theta}_k\right) = B^{-1}\sum_{b=1}^{B}(\hat{\theta}_{kb}^*) - \hat{\theta}_k.$$

Formula (3)

The efficiency value after modifying the bootstrap-DEA deviation is

$$\tilde{\theta}_{\mathrm{k}} = \hat{\theta}_k - \hat{Bias}(\hat{\theta}_k) = 2\hat{\theta}_k - B^{-1}\sum_{b=1}^{B}\hat{\theta}_{kb}^*$$

. Formula (4)

The confidence interval with α confidence level is calculated as follows:

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$$\Pr\left(-\hat{b}_{\alpha} \le \hat{\theta}^{*}_{kb} - \hat{\theta}_{k} \le -\hat{a}_{\alpha}\right) = 1-\alpha,$$

$$\Pr\left(-\hat{b}_{\alpha} \le \hat{\theta}_{k} - \theta_{k} \le -\hat{a}_{\alpha}\right) \approx 1-\alpha,$$

$$\hat{\theta}_{k} + \hat{a}_{\alpha} \le \theta_{k} \le \hat{\theta}_{k} + \hat{b}_{\alpha}.$$

Formula (5)

To sum up, the traditional DEA method has two basic models: the CCR model based on constant returns to scale and the BCC model based on variable returns to scale. Simar and Wilson showed that when the actual research problem is based on constant returns to scale, the estimators (i.e. $\hat{\theta}^{CCR}$ and $\hat{\theta}^{BBC}$) calculated by using the CCR and BCC models are consistent. However, if the actual research problem is based on variable returns to scale, $\hat{\theta}^{BBC}$ is consistent, while $\hat{\theta}^{CCR}$ is inconsistent. Therefore, to reduce the deviation of the calculation results caused by improper model selection, the efficiency is calculated based on the BCC model in this study. Meanwhile, the bootstrap method proposed by Simar and Wilson is adopted to correct the deviation of the efficiency score.

3.2 Index selection and data sources

Based on an extensive literature review, the input indicators of this study include the total quota of the pilot carbon trading market (x_1), the number of emission-control enterprises (x_2), and the number of third-party verification institutions (x_3). The output indicators include the total trading volume of the carbon market (y_1) and the stability of carbon price (y_2). See Table 1 for details.

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Table 1 Description of input-output indicators

Indicators		Definitions	Literature
Input indicators	Total quota	Annual carbon emission limit of all emission-control enterprises in the pilot area	Cheng and Mu (2017); Jin et al. (2020); Wu et al. (2016); Yu et al. (2018); Zhang et al. (2018)
	Number of emission-control enterprises	Number of enterprises keeping an agreement on carbon emission in the pilot area	Hu et al. (2017); Liu et al. (2019); Liu and Zhang (2019)
	Third-party verification institutions	Number of institutions for monitoring, verifying the carbon emission behavior of emission-control enterprises and providing relevant services	Liu and Zhang (2019); Ye et al. (2020); Zhang and Andrews-Speed (2020); Zhang et al. (2020)
Output indicators	Total trading volume	The annual cumulative trading volume of carbon emission quota	An (2018); Cong and Lo (2017); Ibikunle et al. (2016); Kalaitzoglou and Ibrahim (2013); Tan and Wang (2017); Yi et al. (2020)
	Stability of carbon price	For measuring the stability of carbon trading price near the weighted average price	Chang et al. (2018); Deng and Zhang (2019); Sun et al. (2020); Zhao et al. (2016)

（1）Total quota refers to the annual full carbon emission quota determined by the pilot provinces and cities according to the greenhouse gas emission control objectives and the national and provincial industrial policies. The total quota reflects the depth of the market and its coverage. If the coverage is wide, it is conducive to improving carbon price efficiency and limiting the environmental arbitrage space of high emission enterprises (Zhu, 2019). Therefore, the total quota is the basis of the supply-demand relationship in the carbon market, which determines the carbon price and trading volume to a certain extent. It is an essential input variable affecting the operation of the carbon market.

（2）The number of emission control enterprises refers to the number of units agreeing on carbon emission in the pilot carbon trading market. Zhu (2019) once

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mentioned that the number of emission-control enterprises incorporated into the carbon trading system reflects the breadth of the carbon financial market, ensuring that sufficient buyers and sellers in the carbon financial market can match each other and ensure the effectiveness of the carbon emission trading price. Therefore, if many enterprises are included in emission control, then the liquidity of high-quality low-carbon resources in various industries and the effectiveness of the carbon market are strong, and the emission-reduction potential of the carbon market is greater.

（3）The number of verification institutions refers to the institutions designated or entrusted by relevant governmental departments to monitor and verify the carbon emission information of carbon emission control enterprises and provide appropriate services. The number of third-party verification institutions is an essential prerequisite for the authority of carbon prices (Zhu, 2019) which ensures the efficiency of the carbon financial market and helps promote the discovery of the value of carbon emission trading rights and the transparency of market information disclosure.

（4）Total trading volume and trading scale are essential in market research because they represent the market activity. If the market activity is high, the trading scale is large. Otherwise, the trading scale is small. The trading scale in the market has two categories: the total trading volume and the trading amount. The total trading volume determines the market trend and direction, which are important indicators.

（5）The stability of carbon price is a vital monitoring indicator of ETS efficiency, and a relatively stable price factor is central for a large trading scale. The commonly used volatility indicators are calculated from many different transaction prices using statistical methods that can only compare different active markets horizontally. However, China’s ETS is partly active and inactive, while some markets have nearly no trading. Based on the price volatility as an indicator, the stability of the cold market is strong, while the stability of the active market is weak. The comparison between the two markets is not of great significance. Therefore, referring to the practice of An (2018), a price stability indicator based on the weighted average price is used as an alternative in this study.

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First, the weighted average price per year is calculated as follows: $P' = \frac{\sum P_{ij} Q_{ij}}{\sum Q_{ij}}$, where P_{ij} refers to the trading price on the Jth day of the ith year and Q_{ij} refers to the trading volume on the jth day of the ith year. Then, taking P' as the centre, [-10%,10%] as the price fluctuation diameter and the ratio of the trading volume in this interval to the total trading volume, price stability indicator $y_2 \in [0,1]$ is obtained. If y_2 is small, then the trading volume around the weighted average price is low, and the price is unstable; otherwise, the price is stable.

The research objects of this paper are the seven pilot ETS markets in China where carbon market trading was first developed, i.e., Beijing, Shenzhen, Shanghai, Tianjin, Guangdong, Hubei, and Chongqing. According to the requirements for data integrity, the selected sample interval is 2014-2018.

Among the data indicators, the specific data about the total trading volume and the trading price are sourced from the wind economic database. Total quota, the number of verification institutions, and the number of emission-control enterprises come from China's Carbon Market Report and open data published by China's carbon emission and trading network supplemented by multiple independent manual search and cross-verification to ensure the completeness of data sources. See Table 1 for details.

4. Analysis of empirical results

4.1 Data analysis on output indicators

Trading volume is an essential indicator for measuring the carbon market scale and affects market efficiency. According to longitudinal comparison, various pilot ETS trading volumes fluctuate slightly. Still, they show an overall upward trend, indicating that the development of China's ETS has been tortuous since its establishment, but the broad market scale is expanding. According to horizontal comparison, the trading volumes of various ETS markets vary greatly. The carbon market quota trading volumes in Guangdong and Hubei are relatively high, reaching 73.5990 and 53.7244 million tons in 2018, respectively. The trading volumes of

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carbon carbons in Tianjin and Chongqing are relatively low, i.e. only 5.4096 and 8.4430 million tons in 2018, respectively, mainly because the Tianjin and Chongqing trading volumes ETS markets at certain times are minimal. The trading activity is relatively low, except for some trading activities in the initial quota allocation and near the date when keeping an agreement.

Price stability is an essential indicator for measuring market stability and reflects the market risk. If the price stability is strong, the market is stable, and the market risk is low; otherwise, the market is unstable, and the market risk is high. Fig. 2 shows that in 2018, the price stability of the Shanghai ETS was the highest, reaching 80.19%, reflecting the emission-reduction cost of the emission-control enterprises in the Shanghai carbon ETS well. This result indicates that Shanghai's ETS operated well in 2018, and the market was stable and had a small risk. Meanwhile, the price stability of Chongqing's ETS was the lowest, i.e., only 9.93%. The price signal was seriously distorted, and the ability to reflect the emission-reduction cost through price was weak. Overall, the price stability of the pilot carton markets generally improved, reflecting the improvement of the effectiveness of China's ETS and the enhancement of the anti-risk capacity.

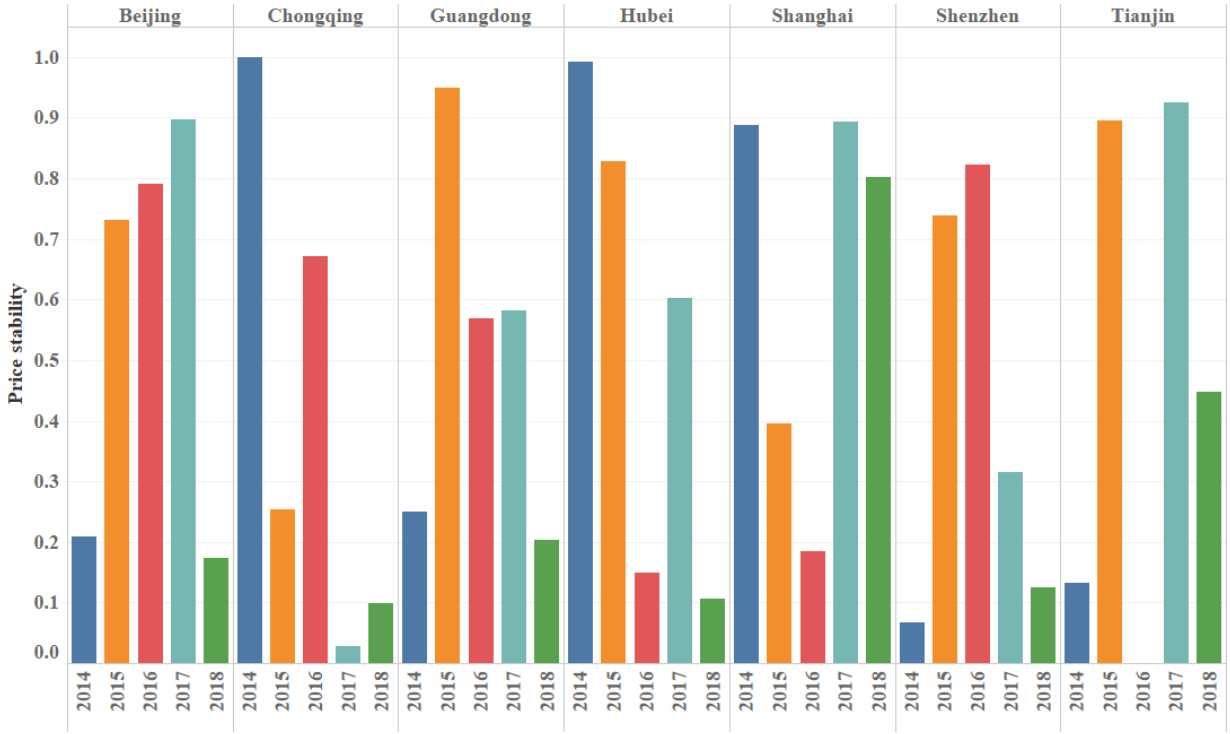

Fig. 2 Price stability of various pilot ETS markets in China

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4.2 Empirical results and discussion

According to the above input-output indicators, the traditional DEA efficiency of all the samples in 2014-2018 and the DEA efficiency value adjusted by the bootstrap method is calculated in this study. First, the overall efficiency is calculated by using the CCR model. Then, the pure technical efficiency is obtained by using the BCC model. Finally, the scale efficiency is obtained by dividing overall efficiency from pure technical efficiency.

4.2.1 Comparative analysis of efficiency between traditional DEA and bootstrap-DEA

Fig. 3 shows the technical efficiency using the CCR model (CCR_TE) from top to bottom, the technical efficiency modified by bootstrap (CCR_TE_Bootstrap), the technical efficiency by the BBC model (BBC_TE), and the technical efficiency modified by bootstrap (BBC_TE_Bootstrap). The horizontal axis represents the distribution of the average efficiency value of the seven pilots' ETS markets in China. The longitudinal axis represents the probability of the distribution of the efficiency values. Appendix Table 2 and Fig. 3 show that the average DEA efficiency values under the CCR and BCC model adjusted by bootstrap in the pilot area are smaller than those by the traditional DEA in 2014-2018, indicating that the DEA efficiency value modified by bootstrap decreases significantly. This phenomenon can be attributed to the ability of the sample distribution obtained by the bootstrap method to simulate the distribution of the original sample estimator and correct the deviation of the efficiency value. Therefore, the traditional DEA model tends to overestimate the efficiency of the pilot carbon trading market. In contrast, the DEA efficiency value modified by bootstrap is more consistent with the actual market efficiency than that by the traditional DEA model.

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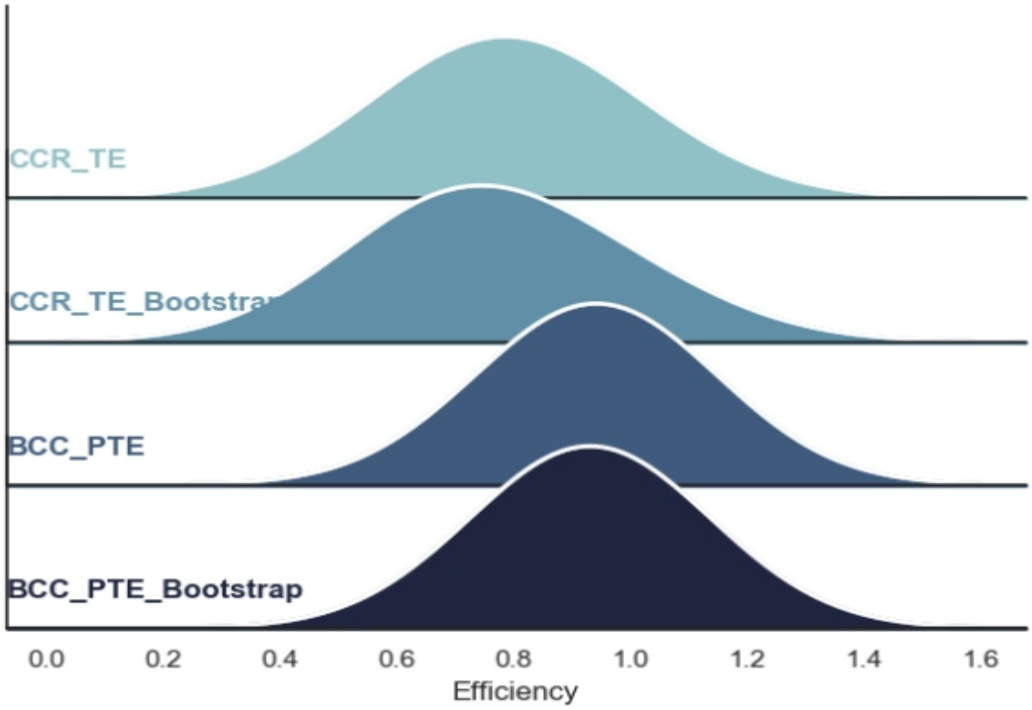

Fig. 3 Average technical efficiency (TE) and pure technical efficiency (PTE) of pilot ETS markets under the CCR and BCC models

4.2.2 Efficiency analysis of pilot ETS markets under the CCR and BCC models

The Appendix of Table 1 indicates the following:

① In 2014-2018, the overall efficiency of the pilot ETS was smaller than the pure technical efficiency. The overall efficiency was equal to the pure technical efficiency and the scale efficiency, indicating that the overall scale efficiency of China's pilot ETS is less than one during the entire sample period, as manifested in the state of scale inefficiency. The results further show that the operation mechanism of China's ETS is imperfect during the sample period, with insufficient effectiveness and a small market scale. The total quota of China's pilot ETS is up to 5.914 billion tons during the sample period, while the total trading volume is only 0.199 billion tons. This phenomenon can be caused by the government policies' lack of continuity, leading to the low emission reduction awareness of enterprises, a cold carbon trading market, low market liquidity, and the insufficient scale of the carbon market.

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② During the entire sample period, the overall scale and pure technical efficiency adjusted by bootstrap in the pilot ETS have increased year by year since 2014 and reached the peak values in 2017. Although the efficiency decreased in 2018, it is still higher than the efficiency value in 2014, indicating that the efficiency level of China's ETS shows an overall increasing trend. The operation mechanism of China's ETS has been improving year by year, and the awareness of enterprises to participate in the transaction has also been gradually improving. Thus, the market scale has been expanding and stable, and the price stability has been improving gradually. Therefore, the efficiency of the ETS has also been increasing year by year. Notably, the ETS's overall and pure technical efficiency in 2018 decreased by 27.15% and 7.76%, respectively. These results can be mainly attributed to the rapid decline of the price stability of most carbon markets in 2018. Except for the slight increase in price stability in Chongqing, the price stability of the remaining six pilot areas decreased greatly. The average price stability of the seven pilots ETS decreased from 60.59% in 2017 to 27.99% in 2018, reaching 53.81% on a month-on-month basis.

4.2.3 Comparative analysis on the efficiency of various pilot ETS markets

This study analyses the operating efficiency of various pilot ETS markets in this section. The Appendix of Table 1, as well as Figs. 4 and 5, show the following:

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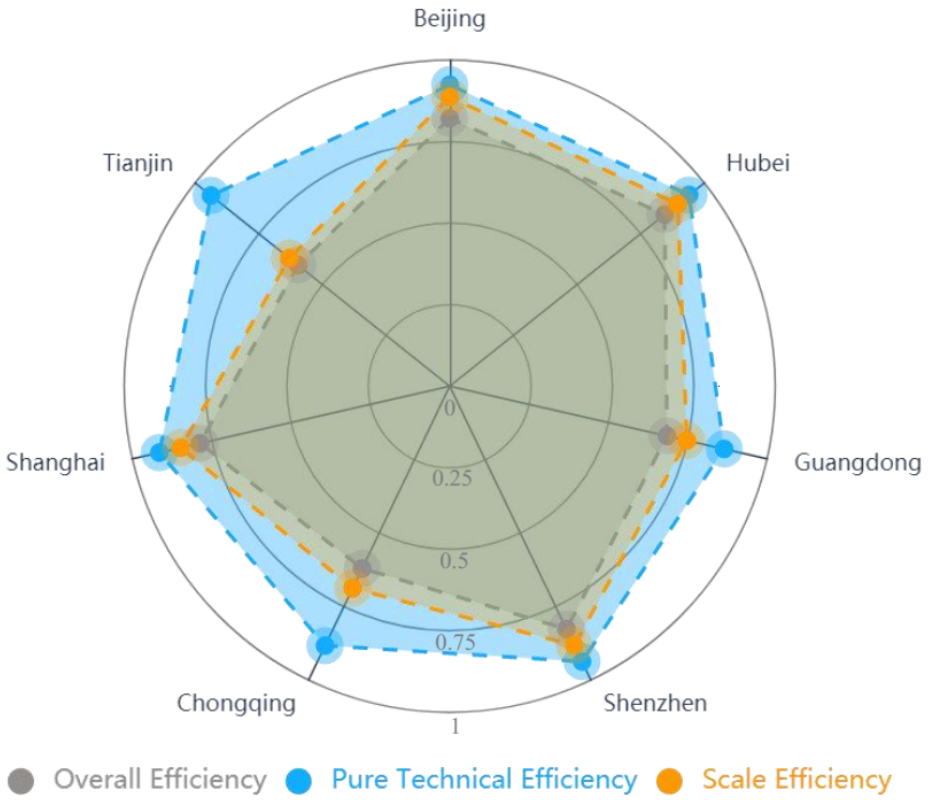

Fig. 4 The average efficiency of China's pilot ETS markets in 2014–2018

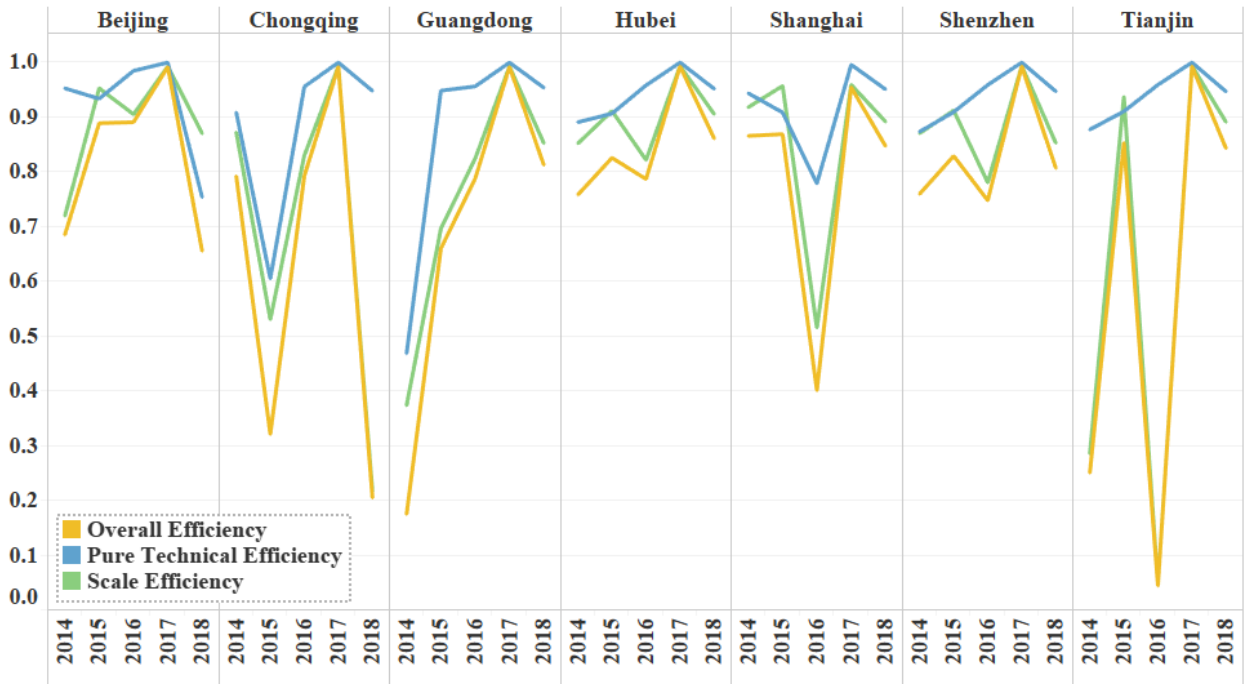

Fig. 5 Efficiencies of various ETS markets adjusted by bootstrap

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（1）The Hubei ETS was always outstanding during the sample period, with an average overall efficiency of 0.8444, ranking first among the seven pilot markets. The overall efficiency of the Hubei ETS fluctuated strongly during the sample period and remained at a high level. The pure technical and scale efficiencies were high, i.e., 0.9408 and 0.8926, respectively. The pure technical efficiency increased year by year in 2014–2017 and decreased by 4.81% in 2018; the scale efficiency was unstable like the overall efficiency in changing trend, indicating that the efficiency of the Hubei ETS was greatly affected by the market size.

（2）The average overall efficiency of the Shenzhen ETS was 0.8268, ranking second among the pilot markets. Generally, the overall efficiency of the Shenzhen ETS during the sample period was unstable, showing a rising-declining-rising-declining trend. The fluctuation range in 2016 was extensive but still at a high level. The Shenzhen ETS market's average pure technical and scale efficiencies were still high, i.e., 0.9371 and 0.8820, respectively. The pure technical efficiency increased year by year in the first four years and decreased slightly by 4.51% in 2018. The changing trend of scale efficiency was the same as that of overall efficiency, fluctuating wildly and decreasing by 14.5% in 2016, indicating that the overall efficiency of the Shenzhen ETS was mainly affected by scale efficiency.

（3）The average overall efficiency of the Beijing ETS was 0.8219, ranking third among the pilot markets. Generally, the average overall efficiency of the Beijing ETS increased slightly in the first four years during the sample period and decreased by only 33.88% in 2018. The Beijing ETS's average pure technical and scale efficiencies were also high, i.e., 0.9243 and 0.8731, respectively. The pure technical efficiency was roughly the same as the overall efficiency in changing trend, decreasing by 24.59% in 2018. The scale efficiency was unstable, showing a rising-declining-rising-declining trend but did not fluctuate considerably. The scale efficiency remained high, indicating that the Beijing ETS's operation mechanism and scale setting were reasonable. Overall, the operating efficiency of the Beijing ETS was greatly affected by pure technical efficiency.

（4）The average overall efficiency of the Shanghai ETS was 0.7869, ranking

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fourth among the seven markets. The overall efficiency of the Shanghai ETS fluctuated greatly in 2014–2018, was stable in 2014-2015, decreased significantly in 2016 by 53.86%, from 0.8683 to 0.4006, and then increased significantly again to 0.9538 in 2017. Finally, it decreased slightly to 0.8467 in 2018. The pure technical efficiency of the Shanghai ETS was 0.9149, and the scale efficiency was 0.8509. The pure technical efficiency fluctuated during the sample period but remained high. The pure technical efficiency fluctuated more greatly in 2016 and decreased by 14.29%, and the efficiency values in the other years exceeded 0.9. The scale efficiency was also unstable and decreased greatly by 46.17% in 2016. The overall efficiency of the Shanghai ETS was greatly affected by the scale efficiency.

（5）The average overall efficiency of the Guangdong ETS was low, i.e., 0.6849, ranking fifth among the seven pilot markets. The overall efficiency of the Guangdong ETS increased greatly year by year in 2014-2017. The overall efficiency primarily increased in 2015 by 277.56% from that in 2014, and however, it decreased slightly by 18.06% in 2018. In addition to the overall efficiency, the Guangdong ETS's average pure technical and scale efficiencies were low, i.e., 0.8647 and 0.7748, respectively. The changing trend of the purely technical and scale efficiencies was the same as that of overall efficiency during the sample period, increasing year by year in 2014–2017 and decreasing slightly in 2018 by 4.59% and 14.12%, respectively. Overall, the efficiency of the Guangdong ETS was greatly affected by scale efficiency.

（6）The performance of the Chongqing ETS was inferior, and its average overall efficiency was only 0.6202, ranking sixth among the markets. The overall efficiency of the Chongqing ETS showed significant volatility during the sample period. In 2015, the overall efficiency decreased greatly by 59.49%, increased to the original level in the next year, and decreased again by 79.33% in 2018. The pure technical efficiency was high, i.e., 0.8829, while the scale efficiency was low, i.e., only 0.7516, in the stage of scale increase. The changing trend of the pure technical efficiency was the same as that of the overall efficiency of the Chongqing ETS during the sample period, greatly decreasing by 33.39% in 2015 and slightly decreasing by

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5.17% in 2018. The scale and overall efficiencies have the same changing trend, i.e., decreasing by 39.17% in 2015 and significantly decreasing by 78.21% in 2018. Thus, the efficiency of the Chongqing ETS was greatly affected by the scale efficiency.

（7）The performance of the Tianjin ETS was the worst, with an average overall efficiency of only 0.5962. The overall efficiency of the Tianjin ETS fluctuated considerably during the pilot period. The overall efficiency in 2014 was only 0.2501 and increased by 340.78% in 2015 to 0.8523. Then, the overall efficiency decreased by 94.83% in 2016 to 0.0441 in 2017 and significantly increased again by 2149.66% to 0.9921 in 2018, showing a slight decrease of only 15.09%. However, the average pure technical efficiency of the Tianjin ETS is up to 0.9371, and the average scale efficiency is only 0.7672. The pure technical efficiency of the Tianjin ETS increased year by year in the first four years during the sample period and decreased slightly by 5.17% in 2018. The scale efficiency fluctuated in 2014-2018, and the fluctuation and changing, Therefore, the efficiency of the Tianjin ETS was greatly affected by the scale efficiency.

5. Conclusions and policy recommendations

This study uses the bootstrap-DEA method to evaluate the operational efficiency of China's seven pilot ETS markets in 2014-2018. A multi-input and output indicator evaluation system is proposed by selecting the total quota, the number of emission-control enterprises and the number of third-party verification institutions as input indicators, the annual total trading volume, and the carbon price stability as output indicators. This study further explores the root reasons for the low efficiency of various pilot ETS markets. This study has three main findings:

（1）From the temporal dynamic perspective, the overall efficiency of China's seven pilot ETS markets increased year by year in 2014-2017, but the purely technical and scale efficiencies fluctuated frequently. Thus, the carbon price of China's ETS fluctuated wildly. Furthermore, a clear market price signal cannot be provided for enterprises, which is not conducive to promoting enterprises' long-term emission

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reduction investment and the sustainable and healthy development of the ETS. In 2018, the scarcity of quota was enhanced due to promoting the unified national ETS. The price stability of most ETS markets decreased rapidly, and the carbon price fluctuated greatly, resulting in the increase of trading risk and the decrease of market activity. Thus, the efficiency of various ETS markets declined slightly. With the establishment of the unified national ETS, the requirement for the operation mechanism of the ETS increased. On this basis, each pilot ETS should establish and perfect a unified trading mechanism to ensure the stable and sustainable development of the carbon market and strive to integrate with the national carbon trading market.

（2） From the horizontal comparison perspective, some differences can be observed in developing the seven pilot ETS markets. Furthermore, the average overall efficiency was distributed in the range of 0.5962-0.8444. The average trading prices of the ETS markets also varied greatly. The average price in Beijing was mainly in the range of 40-80 yuan/ton, while that in Chongqing was in the range of only 0-20 yuan/ton, possible because of the different economic development levels and industrial structures of emission-control enterprises in various regions. The apparent price differences are also related to the inconsistent policies and ETS mechanisms in different regions. The local governments where the pilot ETS markets are located should strengthen legal supervision and reasonably allocate carbon resources according to the local economic development and industrial structure. Meanwhile, the local governments should support the publicity of carbon trading policy and invest workforce and material resources to maintain the operation of the carbon market to improve the emission-reduction awareness and trading enthusiasm of enterprises.

（3） Regarding the reasons for influencing the ETS efficiency, except the Beijing ETS, low scale efficiency is the main reason for the low overall efficiency. However, the efficiency of the Beijing ETS can still be improved, i.e., the insufficient scale is a common problem faced by China’s ETS markets. The insufficient scale of ETS is mainly manifested in the low trading volume and amount and leads to the cold market transaction and low market activity. Consequently, the ETS cannot exert its emission reduction effect. In China’s ETS, the insufficient market scale has two

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leading causes. One is excessive total quota which affects the enthusiasm of enterprises, thus affecting the operational efficiency of the market.

（4）According to statistics, enterprises' initial annual carbon emission quotas are approved based on the historical emission level in the seven pilot markets of China. However, the historical emission method is relatively primitive, and the emission data obtained is rather rough. Therefore, the quota allocated cannot match the real industry level. The total trading volume of the pilot ETS markets in China, except for Shenzhen, failed to reach 5% of the full quota. The total trading volume in the Tianjin ETS is only 0.63%. The other one is the ETS policy's insufficient continuity, which leads to the unclear market expectation of trading enterprises. The operation mechanism and trading rules in various pilot ETS markets are adjusted frequently, resulting in insufficient awareness of emission reduction and a lack of market trading power. Centralized transaction only occurs near the performance period, while the trading volume is low on normal trading days. Thus, the liquidity of the ETS is extremely low, and the market trading is cold. To address the low market scale, various pilot ETS markets should further consider and determine the total volume and allocation method, appropriately reduce the quota amount and promote the growth of the total trading volume and amount to promote the expansion of the market scale and improve the operation efficiency of the market. Meanwhile, attention should be given to the continuity and unity of policies for a clear market expectation for enterprises.

Based on the research findings, the following policy recommendations are proposed to improve the efficiency of China's ETS market. First, we should improve the relevant laws and regulations on the carbon trading market, strengthen the legal supervision and ensure the policy stability for the market to form a stable policy expectation. Second, we should scientifically allocate carbon emission rights and refine the total volume determination and allocation method to promote the expansion of the trading volume and amount. Third, we should ensure the adequacy and transparency of the supervision and information disclosure systems and the stringency and fairness of the reward and punishment system. Fourth, we should accelerate the

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establishment of a unified market mechanism and promote the construction of the national carbon trading market for the market to play a leading role in carbon transactions.

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Appendix:

Table 1 The efficiencies of various pilot ETS adjusted by bootstrapping

(a) Overall efficiency

Year	Pilot ETS						
	Beijing	Guangdong	Hubei	Shanghai	Shenzhen	Tianjin	Chongqing
2014	0.6847	0.1747	0.7579	0.8652	0.7593	0.2501	0.7916
2015	0.8884	0.6596	0.8251	0.8683	0.8285	0.8523	0.3207
2016	0.8901	0.7873	0.7863	0.4006	0.7474	0.0441	0.7922
2017	0.9911	0.9911	0.9920	0.9538	0.9921	0.9921	0.9915
2018	0.6553	0.8121	0.8607	0.8467	0.8065	0.8424	0.2049
均值	0.8219	0.6849	0.8444	0.7869	0.8268	0.5962	0.6202

(b) Pure technology efficiency

Year	Pilot ETS						
	Beijing	Guangdong	Hubei	Shanghai	Shenzhen	Tianjin	Chongqing
2014	0.9520	0.4681	0.8902	0.9431	0.8728	0.8767	0.9080
2015	0.9330	0.9477	0.9059	0.9079	0.9087	0.9099	0.6048
2016	0.9840	0.9555	0.9576	0.7782	0.9582	0.9585	0.9551
2017	0.9991	0.9991	0.9992	0.9951	0.9992	0.9992	0.9991
2018	0.7534	0.9532	0.9511	0.9502	0.9464	0.9461	0.9474
均值	0.9243	0.8647	0.9408	0.9149	0.9371	0.9381	0.8829

(c) Scale efficiency

Year	Pilot ETS						
	Beijing	Guangdong	Hubei	Shanghai	Shenzhen	Tianjin	Chongqing
2014	0.7192	0.3732	0.8514	0.9174	0.8700	0.2853	0.8717
2015	0.9522	0.6960	0.9108	0.9564	0.9117	0.9367	0.5302
2016	0.9045	0.8239	0.8212	0.5149	0.7800	0.0460	0.8294
2017	0.9920	0.9920	0.9928	0.9585	0.9929	0.9930	0.9924
2018	0.8697	0.8520	0.9050	0.8912	0.8522	0.8904	0.2162
均值	0.8875	0.7474	0.8962	0.8477	0.8814	0.6303	0.6880

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Table 2 Technical efficiency (TE) and pure technical efficiency (PTE) of pilot ETS markets under the CCR and BCC models in 2014-2018

Model	Year	Traditional DEA	Bootstrap-DEA
CCR-TE	2014	0.7485	0.6119
	2015	0.7988	0.7490
	2016	0.7485	0.6354
	2017	0.9938	0.9862
	2018	0.8491	0.7184
	Average	0.8278	0.7402
BCC-PTE	2014	0.9261	0.8444
	2015	0.9403	0.8740
	2016	0.9697	0.9353
	2017	0.9994	0.9986
	2018	0.9666	0.9211
	Average	0.9604	0.9147

Table 3 Weighted carbon prices of China's pilot ETS markets in 2014–2018 (Unit: RMB/ton)

Pilot ETS	2014	2015	2016	2017	2018
Beijing	59.50	46.63	48.77	50.06	57.95
Tianjin	20.23	14.30	11.33	8.90	12.12
Shanghai	34.87	25.41	8.41	34.87	36.54
Guangdong	53.27	16.37	12.45	13.57	12.45
Shenzhen	62.55	38.15	26.45	27.91	23.46
Hubei	23.79	24.99	17.67	14.63	22.91
Chongqing	30.74	17.74	7.96	2.25	4.36

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