Assessing five pilot carbon trading programs in China from a perspective of efficiency analysis

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Abstract. In order to overcome the challenge of growing carbon emissions in China, the pilot carbon emissions trading systems (ETSs) serve as precursors of the national carbon ETS. Five province-level pilot ETSs in Beijing, Tianjin, Shanghai, Guangdong and Hubei are assessed from the view of carbon emission efficiency analysis in this study. Firstly, both the environmental production technology and the Malmquist index are adopted to evaluate the carbon emission efficiency of 28 provinces in China. Then, the regression significance analysis of carbon emission efficiency and the operational information evaluation for pilot ETSs are combined to develop an integrated approach for assessing five considered pilot ETSs. The Efficiency analysis of carbon emissions indicate that the effect of ETS in Beijing is significant, the effect of ETS in Tianjin is weak significant, and those of the other three pilot ETSs are not significant. Based on the operational information for pilot ETSs, the evaluating results of pilot ETSs in Beijing and Hubei are better than those of other pilot ETSs. This study highlights two main findings. First, the pilot ETS in Beijing has better performance than the other considered pilot ETSs, and its operational experience should be promoted throughout the country to improve the construction of national carbon ETS. Second, the successful cooperation between the ETSs in Beijing and Tianjin implies that the regional cooperation among neighbouring ETSs should be encouraged and further implemented to enhance the overall performance of the regional ETSs.

1. Introduction

Due to the large energy consumption and coal-dominated energy consumption, China's carbon dioxide emissions are the largest one all over the world in 2016 according to the report of International Energy Agency (IEA). With growing resources and environmental constrains domestically and the need for meeting international commitment to GHGs abatement, China's National Development and Reform Commission (NDRC) launched a series of local carbon cap-and-trade pilots in seven provinces and cities including Shenzhen, Beijing, Tianjin, Shanghai, Chongqing, Guangdong, and Hubei, each of which has started its operation in 2013 or 2014. The development of carbon trading low-carbon economy and the establishment of ETSs to develop low-carbon economy has received more and more attention. The global carbon trading volume of 2006 - 2010 increased from 1.6 billion tons to 6.9 billion tons. As the largest carbon emitter in the world, China's ETSs in the global financial market occupies an important place. The development of carbon finance is of great significance to China's
economic development. Here, this study evaluates the performance of energy efficiency and carbon emissions, and analyzes the impact of ETSs.

The analysis of carbon trading policy attracted the attention of many researchers. Sorrell [1] aimed to improve the understanding of such interactions by examining the conditions under a cap-and-trade scheme. Their progress had been assessed in Hepburn [2], examined the problems that had emerged, and considered suggestions for future developments in climate policy including carbon trading strategy. Gilbertson [3] provided a devastating critique of both the theory and the practice of carbon trading, which lay at the heart of global climate policy. As for Chinese road of carbon reduction, many scholars studied the carbon trading policy as well. A computable general equilibrium model simulating a carbon tax policy was established in Liang [4] in China, and compared the macroeconomic effects of different carbon tax schemes as well as their impact on the energy- and trade-intensive sectors. Lo [5] showed that carbon trades in China simply served to demonstrate the compatibility of the market with the green house gas control regime, its legal infrastructure was not complete and regulatory uncertainties abound.

Several recent studies focused on the assessment of pilot ETSs in China from the views of economic and political context. Munnings [6] assessed the performance of the most developed pilot ETSs, in Guangdong, Shanghai, and Shenzhen, and made nine recommendations to improve the design and operation of the pilot programs and to inform the construction of the national CO2 ETS. On the basis of the effective market theory and fair game model, the reference Zhao [7] developed the unit root test and the run test to analyze the carbon emission market of four representative cities in China, and the results showed that the ETSs in China only achieved weak efficiency. Nai [8] showed that it is of vital importance for China to take a gradualist approach in establishing laws and institutions to guide and support the development of its emerging carbon market.

This paper aims to assess the performance of pilot ETSs reducing the carbon emissions from the perspective of efficiency analysis which was adopted by many studies about carbon emission analysis, e.g. [9], [10]. In this paper, the environmental production technology and the Malmquist index will be adopted to evaluate the impact of ETSs on the carbon dioxide emission performance. Section 2 of the paper introduces the methodology. Section 3 applies the methodology proposed in Section 2 to empirically study 28 provinces or province-level municipalities in China, analyzing their CO2 emission performance. Section 4 will analyze the impact of ETSs based on the results of CO2 emission performance analysis in Section 3. Finally, the conclusions and policy implications are proposed in Section 5.

2. Methodology

2.1. Environmental production technology

In the general economic system, both the expected output and the undesirable output can be brought out at the same time when the quantitative factors are put into production. Assume that there are \( n \) areas (i.e., \( n \) decision making units, DMUs), the corresponding input set is denoted by \( X = \{x_1, x_2, x_3, ..., x_n\} \), the set of expected output is denoted by \( E = \{e_1, e_2, e_3, ..., e_n\} \), and the set of undesirable output is denoted by \( U = \{u_1, u_2, u_3, ..., u_n\} \). This production process can be described as:

\[
P = \{X, E, U : X \text{ can produce } (E, U)\}.
\]

The output set has the following characteristics:

- Both the input and the expected output are strong disposal.
- The undesirable output is weak disposal, i.e., the reduction of undesirable output will be at the expense of the expected output, and will be reduced in the same proportion of the expected output.
- The expected output and non-expected output are null-jointness, i.e., if the undesirable output wants to be completely eliminated, the only choice is to stop production activities.
Concretely, the inputs in the actual production process are Capital stock \((K)\), labor force \((L)\) and energy \((E)\), and the generating desirable output and undesirable output are gross domestic product \((Y)\) and CO2 emissions \((C)\), respectively. This production process can be described as follows:

\[ P = \{(K, L, E, Y, C) : (K, L, E) \text{ can produce } (Y, C)\} \]  

(1)

Based on the assumption of constant returns to scale \((CRS)\), the environmental production technology can be expressed as follows:

\[ \sum_{i=1}^{n} l_i K_i \leq K; \sum_{i=1}^{n} l_i L_i \leq L; \sum_{i=1}^{n} l_i E_i \leq E; \sum_{i=1}^{n} l_i Y_i \geq Y; \sum_{i=1}^{n} l_i C_i = C; \]  

(2)

Where \((K_i, L_i, E_i, Y_i, C_i)\) is the input-output vector for the \(i = 1, 2, ..., n\). Among them, the inequality constraint of inputs and desirable outputs shows that inputs and desirable outputs satisfy the strong disposability. The constraint imposed on CO2 emissions is set as equality, making the technology satisfy weak disposability and null-jointness assumptions.

2.2. Malmquist CO2 emissions performance index

The Malmquist index is based on the distance function, which is the reciprocal of the C2R model and the BC2 model efficiency values in DEA theory.

By using the geometric average of two Malmquist productivity indices, the change in productivity from stage \(t\) to \(t+1\) is calculated by

\[ M(x', y', x'^{t+1}, y'^{t+1}) = \left( M^t \times M^{t+1} \right)^{\frac{1}{2}} = \left[ \frac{D_{C}^{t}(x'^{t+1}, y'^{t+1})}{D_{C}^{t}(x', y')} \right]^{\frac{1}{2}} \]  

(3)

In order to monitor and study the dynamic characteristics of CO2 emission, Zhou [11] integrated capital stock \((K)\), labor force \((L)\), energy \((E)\), gross domestic product \((Y)\), and CO2 emission \((C)\) into Malmquist productivity index, and constructed the Malmquist CO2 Emission Performance Index (MCPI) as follows

\[ MCPI_{C}(t,t+1) = \left[ \frac{D_{C}^{t}(K', L', E', Y', C')}{D_{C}^{t+1}(K'^{t+1}, L'^{t+1}, E'^{t+1}, Y'^{t+1}, C'^{t+1})} \right]^{\frac{1}{2}} \]  

(4)

MCPI can be respectively decomposed into two components, namely efficiency change \((EFFCH)\) and technological change \((TECHCH)\), given by formula five and formula six.

The EFFCH indicates the catch-up effect of the DMU from \(t\) to \(t+1\), representing the degree of changes in production technology. In production activities, this indicator reflects the extent of technological progress or innovation.

\[ EFFCH(t,t+1) = \frac{D_{C}^{t}(K', L', E', Y', C')}{D_{C}^{t+1}(K'^{t+1}, L'^{t+1}, E'^{t+1}, Y'^{t+1}, C'^{t+1})} \]  

(5)

The TECHCH indicates the frontier-shift effect of DMU from period \(t\) to period \(t + 1\).

\[ TECHCH(t,t+1) = \left[ \frac{D_{C}^{t+1}(K', L', E', Y', C') \cdot D_{C}^{t}(K'^{t+1}, L'^{t+1}, E'^{t+1}, Y'^{t+1}, C'^{t+1})}{D_{C}^{t+1}(K'^{t+1}, L'^{t+1}, E'^{t+1}, Y'^{t+1}, C'^{t+1})} \right]^{\frac{1}{2}} \]  

(6)

The four distance functions in formula six are calculated based on the techniques of different periods, and these distance functions can be completed by solving the linear programming problem corresponding to the region \(i\) in the framework of environmental production technology, as in formula seven, where \(p\) and \(q\) represent the periods, and
\[
\left[ D^p \left( K^g, L^p, E^g, Y^p, C^g \right) \right]^{-1} = \min \rho
\]

\[\text{s.t.} \sum_{i=1}^I \lambda_i K^p_i \leq L^p_i; \sum_{i=1}^I \lambda_i L^p_i \leq L^p_i; \sum_{i=1}^I \lambda_i E^p_i \leq E^p_i; \sum_{i=1}^I \lambda_i Y^p_i \geq Y^p_i; \sum_{i=1}^I \lambda_i C^p_i = \rho C^g \]  

(7)

3. Data collection and efficiency analysis

3.1. Data collection

This paper chooses the panel data of 28 provinces or province-level municipalities from 2007 to 2015. Considering the availability of data, Hainan and Tibet are not contained, while Sichuan and Chongqing are counted together. For the data of three input factors, the capital stock is used to depict the capital input, and its follow-up data is supplemented by the perpetual inventory method. This paper selects 1952 as the base period to do the data conversion. The input of labor force is mainly calculated by the annual mean value at the beginning and the end of a year by the China Statistical Yearbook. The energy input is mainly calculated by the energy standard coal coefficient to unify the energy consumption of all kinds of areas. In the process of obtaining data of desirable output and undesirable output, the desirable output GDP is mainly obtained by the China Statistical Yearbook. The undesirable output of CO₂ is mainly got through various areas of coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas and other energy. This paper estimates the CO₂ emissions, according to its emission factor of the product in Table 1.

| Table 1. Carbon emission coefficient of every type of energy (From: IPCC). |
|-----------------|
| **T** | **Coal** | **Coke** | **Crude** | **Gasoline** |
| Coefficient | 8.62006 | 0.85556 | 0.5857 | 0.5538 |

The descriptions of specific data sources in this study are proposed in Table 2.

| Table 2. Data sources. |
|------------------------|
| **Variable** | **Unit** | **Sources** |
| GDP | RMB trillion (1952) | China Statistical Yearbook (2016) |
| Carbon | Million tons (10,000 t) | Energy consumption and emission coefficient |
| Capital Stock | RMB trillion (1952) | Using the perpetual inventory method |
| Labour Force | Million workers | Statistical Yearbook of every province (2016) |
| Energy | equivalent (10,000 t) | China Energy Statistical Yearbook (2016) |

3.2. Efficiency analysis of CO₂ emissions

This paper adopts 2007 as the initial period, and mainly calculates its previous year's relative efficiency changes of each year. According to formula five, formula six and formula seven, this paper computes the MCPI for 28 provinces in China from 2007 to 2015.

| Table 3 shows the average value of MCPI and its two decomposition indicators |
|-------------------|
| **Variable** | **2008** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** |
| EFFCH | 0.9912 | 0.9943 | 1.0343 | 1.0021 | 1.0006 | 0.9967 | 1.0017 | 0.9975 |
| TECHCH | 1.1352 | 1.0427 | 1.4241 | 0.9 | 1.0738 | 1.0955 | 1.0571 | 1.0678 |
| MCPI | 1.1261 | 1.0363 | 1.4791 | 0.9053 | 1.0743 | 1.0921 | 1.0589 | 1.0686 |
During the period of 2009~2010, the MCPI reach the best. However, during the period of 2010~2011, the performance of carbon dioxide emission was reduced and the MCPI was lower than 1, which was mainly because of the degradation of TECHCH. Besides, it is also the only year where TECHCH has not played a positive role.

Table 4. The average and accumulate results of five considered pilot ETSs

|      | Average EFFCH | Average TECHCH | Average MCPI | Accumulative EFFCH | Accumulative TECHCH | Accumulative MCPI |
|------|---------------|----------------|--------------|--------------------|---------------------|-------------------|
| Beijing | 1             | 1.138125       | 1.138125     | 1                  | 3.180033            | 3.180033          |
| Shanghai | 0.99225       | 1.074625       | 1.0665       | 0.930731           | 1.872938            | 1.743159          |
| Tianjin  | 1             | 1.107125       | 1.107125     | 1                  | 2.451521            | 2.451521          |
| Hubei    | 1.03          | 1.08225        | 1.122        | 1.294023           | 1.83114             | 2.383474          |
| Guangdong | 0.99925       | 1.1305         | 1.129625     | 0.993255           | 2.200215            | 2.184129          |

In Table 4, the average and accumulate results for five considered pilot ETSs are proposed. Beijing has the biggest MCPI index and the biggest TECHCH index in the view of both average results and accumulate results. It shows that the performance of pilot ETSs in Beijing is outstanding among five considered pilot ETSs according to MCPI index and TECHCH index. For the EFFCH index, the result of pilot ETS in Hubei is bigger than those of other pilot ETSs.

4. Analysis of the impact of ETSs

4.1. Analysis of factors affecting CO2 Emissions

Based on the regress model in [11], the considered affecting factors including energy intensity (\(EI\)), economic development (\(ED\)), industrial structure (\(IS\)), opening to the outside world (\(OP\)) and ownership structure (\(OS\)) remained in this study. In addition, the carbon trading (\(CT\)) implementation is added as a dummy variable. The cumulative MCPI of each area is selected as a dependent variable. Then, the impact factor regression model used in this paper is proposed as follows:

\[
CMCPI_{i,t} = \eta_0 + \eta_1 EI_{i,t} + \eta_2 ED_{i,t} + \eta_3 IS_{i,t} + \eta_4 OP_{i,t} + \eta_5 OS_{i,t} + \eta_6 CT_{i,t} + \epsilon_{i,t} \tag{8}
\]

where \(\eta_0, \eta_1, \eta_2, \eta_3, \eta_4, \eta_5, \eta_6\) are parameters to be estimated, \(CT_{i,t}\) is a 0-1 variable such that \(CT_{i,t} = 1\) if the ETSs of area \(i\) is opened at time \(t\) otherwise \(CT_{i,t} = 0\), and \(\epsilon_{i,t}\) is a random disturbance term such that \(\epsilon \sim N(0, \sigma^2)\). Since Shenzhen is a city located in Guangdong, the data of pilot ETS in Shenzhen is added into Guangdong. This paper uses the generalized linear regression method to eliminate the deviation of regression, and the results of five considered provinces (i.e., Beijing, Shanghai, Tianjin, Hubei and Guangdong) are summarized in Table 5.

Table 5 shows the regression results of CO2 emission performance influencing factors. Firstly, from the view of the overall result of five considered areas, the energy intensity and the ownership structure reach the negative form efficiency, while the economic development and the industrial structure reach the positive form efficiency, and the implementation of ETSs is not significant. Secondly, from the view of ETSs, Beijing and Tianjin are significantly affected by the implementation of ETSs, while the other three areas (i.e., Shanghai, Guangdong and Hubei) and the overall result are not significantly affected. As shown in Table 5, the significance of Beijing is stronger than that of Tianjin from the view of the relationship between ETSs and CO2 emission performance.
Table 5. The regression results of CO₂ emission performance influencing factors

| Variable | Index | Beijing | Tianjin | Shanghai | Guangdong | Hubei | Overall |
|----------|-------|---------|---------|----------|-----------|-------|---------|
| EI       | Coefficient | 1.017977 | 0.301222 | -3.15549 | 3.267771 | -4.17132 | -0.88812 |
|          | Prob.     | 0.188   | 0.0654* | 0.0105** | 0.1996   | 0***   | 0***    |
| PC       | Coefficient | 0.031506 | 0.017905 | -0.00289 | 0.038776 | 0.006313 | 0.012239 |
|          | Prob.     | 0***    | 0***    | 0.741    | 0.027**  | 0.537   | 0***    |
| STR      | Coefficient | 0.031893 | -0.0133  | 0.000343 | 0.081993 | 8.238695 | 0.00084 |
|          | Prob.     | 0.5496  | 0.4587  | 0.4005   | 0.9427   | 0***    | 0.0464** |
| OP       | Coefficient | -0.08513 | -0.31432 | 0.219069 | -0.46931 | 2.671699 | -0.01991 |
|          | Prob.     | 0.3159  | 0.0685* | 0.0268** | 0.4232   | 0.165   | 0.8503  |
| SE       | Coefficient | -6.9799  | 1.609378 | 62.9837  | -29.0267 | 51.12638 | -4.73275 |
|          | Prob.     | 0.0641* | 0.2622  | 0.0177** | 0.3971   | 0.0003***| 0.003*** |
| CT       | Coefficient | 0.19759  | 0.187211 | -0.08868 | -0.25677 | -0.03555 | 0.065845 |
|          | Prob.     | 0.0015***| 0.0135**| 0.1729   | 0.3849   | 0.6495  | 0.1184  |

***The index is significantly different from unity at the 0.01 level.
**The index is significantly different from unity at the 0.05 level.
*The index is significantly different from unity at the 0.10 level.

4.2. Research on carbon trading policy

In this subsection, the information about the operational data of ETSs and the related regional agreements of carbon trading is collected and analyzed. Table 6 shows the trading volume, turnover and unit turnover of five pilot ETSs. When it comes to trading volume of ETSs, Hubei ranks the top one and Tianjin is the smallest one among the five ETSs in 2014 and 2015. Beijing, Guangdong and Hubei all have an increase on the trading volume, and it is special to denote that the trading volume of Guangdong in 2015 is 4 times of the volume in 2014. For the value of turnover, Hubei is the top one and Tianjin is the last one in 2014 and 2015. In these two years, Guangdong has little growth and Hubei increases to more than two times of 2014. Among them, Tianjin declines sharply about a third of 2014. Last, as for the unit turnover, Beijing is the top of five provinces. The minimum unit turnover of considered areas in 2014 is 18.495 CNY which belongs to Hubei. In 2015, the unit turnover of Tianjin (i.e. 13.984 CNY) ranks the last among 5 consider areas.

Table 6. The operational data of the carbon trading markets in pilot area in 2014-2015

|         | Beijing | Tianjin | Shanghai | Guangdong | Hubei |
|---------|---------|---------|----------|-----------|-------|
| 2014 Volume(10,000 t) | 105.62 | 98.99 | 171.08 | 105.55 | 898.14 |
| Turnover(10,000¥) | 6295.48 | 2008.69 | 6502.53 | 5623.21 | 16611.03 |
| Unit turnover(yuan/t) | 59.605 | 20.29185 | 38.00871 | 53.27532 | 18.49492 |
| 2015 Volume(10,000 t) | 125.87 | 52.67 | 168.95 | 465.63 | 1394.15 |
| Turnover(10,000¥) | 5872.57 | 736.53 | 4007.09 | 7652.81 | 34905.49 |
| Unit turnover(yuan/t) | 46.65584 | 13.98386 | 23.71761 | 6.43539 | 25.03711 |

In addition, many regional cooperation agreements among neighboring pilot ETSs were established in recent years, and the related information are collected in Table 6. As shown in Table 6, Beijing, Tianjin and Hebei proposed the earliest cross-regional cooperation on November 28, 2013, and managed to launch a pilot of cross-regional ETSs on December 18, 2014. Following the development of Beijing, Tianjin and Hebei, the areas of Yangtze River and the Pearl River Delta carried out their own regional cooperation agreements on April 2, 2014 and January 29, 2015, respectively. Combining the operational data of ETSs and the related regional agreements of carbon trading, the performance of Beijing is obviously better than those of any other considered pilot areas. This result is coincided with the significance analysis of Beijing. The trading volume and turnover price of the pilot
ETS in Tianjin is very low. This seems conflict with the significance analysis of Tianjin. The explanation of the confliction of Tianjin is that the regional cooperation agreement between Beijing and Tianjin, many companies located in Tianjin can go to Beijing to carry out their carbon emission trades. Contrary to Tianjin, Hubei has the high trading volume and the turnover price, but its significance test is not passed. The companies of neighbor provinces (i.e., Anhui, Jiangxi, Hunan and so on) can go to the ETS in Hubei to take part into their carbon emission trades, but the low unit turnover reduced its ETS’s impact on carbon emission.

5. Conclusions and policy implications

This paper firstly uses the environmental production technology and the Malmquist index to obtain the MCPIs evaluating the carbon dioxide emission performance of 28 provinces in China from 2007 to 2015. In the second, based on the obtained results of MCPIs, the generalized least squares regression and the significance analysis are used to analysis the correlation between the ETSs and the carbon dioxide emission performance (i.e., MCPI). Finally, the combined analysis of operational data and ETS cooperation agreement is proposed.

The analysis results indicate that ETS in Beijing has the best performance in the significance analysis and the operational situation of ETSs, and firstly launched its corresponding cross-regional cooperation about carbon trading. Although the trading volume and the turnover price of the ETSs in Tianjin ranks in the last position among five considered pilot ETSs, the significance analysis shows that the implementation of ETSs has the weak significant impact on the carbon emission performance of Tianjin. The result of significance analysis implies that the cooperation between the ETSs in Beijing and Tianjin is success. This implies the regional cooperation among neighboring ETSs is suggested to be encouraged and further implemented to enhance the overall performance of the regional ETSs. For the other three provinces with pilot ETS program (i.e., Shanghai, Guangdong and Hubei), the impact of the implementation of ETSs are not significant, and the corresponding performance on the operational data and the cooperation action of carbon trading in Shanghai, Guangdong and Hubei are overall in the middle reaches, which implies that the ETSs of in Shanghai, Guangdong and Hubei should be further enhanced referring to the successful experience of Beijing or developed areas abroad.

Despite the contribution of this work, there will have many new problems associated with the impact of ETSs in China to be solved in the future studies for the reason that the ETSs in China will fully open, which may lead to the new impact on the control of carbon emissions of China.

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