Original Research

An International Comparison of Carbon Dioxide Emission Performance Using the Nonparametric Metafrontier Approach

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Abstract

Cross-country assessment of carbon dioxide (CO_2) emission performance provides quantitative information for determining the responsibility of various countries in reducing global CO_2 emissions. This paper proposes a nonparametric metafrontier approach to evaluating the CO_2 emission performance of 49 major emitting countries. It has been found that the CO_2 emission performance of different countries shows a large discrepancy and the performance level of the group frontier is higher than that of the metafrontier. These countries can be divided into three categories based on their performance levels of group frontier and metafrontier. American's CO_2 emission performance is closest to the best practice of world countries. Although Asia is still further from the efficient frontier and its CO_2 reduction potential is the highest, the gap has narrowed over time. The technology gap of the sample countries in CO_2 emission performance has experienced two stages of decrease and increase.

Keywords: carbon dioxide, emission performance, metafrontier function, DEA

Introduction

Global carbon dioxide (CO_2) emission reduction has become one of the key policy issues for most countries. Although the Copenhagen Climate Conference did not reach a legally binding agreement on responsibility for greenhouse emissions reduction in the post-Kyoto era, it highlighted the significance of "*common but differentiated responsibilities*" in future global emissions reduction. Due to the huge discrepancies in economic development, degree of industrialization, industrial structure, resource endowments, and other aspects in different countries, the initiation of various emission reduction activities and the implementation of policy measures at a global level should be built upon an accurate assessment of historical and current status of CO_2 emissions. It is therefore meaningful to conduct an international comparison of CO_2 emission performance, which may provide partial but valuable information for determining the responsibility of different countries in global emissions reductions.

Previous studies on CO_2 emission performance mainly focused on CO_2 emission intensity, total CO_2 emissions, and their affecting factors, in which decomposition analysis methodology (including index decomposition analysis and structure decomposition analysis) and econometric analysis are widely employed. Ang and Zhang [1] analyzed the

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causes of CO_2 emissions in different regions in OECD countries by using the log-mean divisia index (LMDI) decomposition method and pointed out that the economyic level, industrial structure, energy intensity, and industrial energy consumption patterns had different driving roles for the increase of CO_2 emissions of different countries. Also, Ang and Choi [2], Greening [3], and Kwon [4] found some differences in the research of the driving factors of carbon intensity changes in the household department, transport department, and power department in the OECD countries. Wang et al.[5] and Fan et al. [6] analyzed the changes of CO_2 intensity in China and concluded that China's achievements in carbon emission reduction was mainly attributed to the improvements in energy efficiency. Lise [7] and Hatzigeorgiou et al. [8] found that the economic factor was the most important one to drive carbon emissions in the cases of Turkey and Greece.

On the other hand, Coondoo and Dinda [9] found that the differences of income among countries had great significance on the differences of carbon emissions by using econometric models, which was also reflected on the different testing results of Kuznets curve of carbon emission in the literature [10, 11]. Based on a similar idea, Lee et al. [12] analyzed the main factors leading to the differences of carbon emissions in IEA member countries earlier. Feng et al. [13] conducted a study of China and analyzed the influential factors of carbon emissions in five regions of China and the differences.

Although a number of studies have examined carbon intensity and its driving force and influential factors, it is still meaningful to further look into them from a different point of view. Firstly, previous CO_2 emission performance indicators, e.g. carbon intensity, are mainly single-factor indicators that neglect the impact of economic development, energy structure, and alternative elements on CO_2 emission performance [14]. Secondly, although the total-factor CO_2 emission performance (TFCP) index has recently attracted great attention, e.g. Zhou et al. [15], Wang et al. [16], and Zhang et al. [17], the assumption that CO_2 is produced in the same technical condition does not match with the actual situation. Thirdly, it lacks contrast based on different reference objects to understand the differences in emission performance and the sufficient quantitative characterization of CO_2 emissions in different countries and regions.

Motivated by these issues, in this paper we extend the TFCP by Zhou et al. [15] to the case of metafrontier function by considering group heterogeneity, and use it to analyze the CO_2 emission performance of the world's major emitting countries.

Methodology

Metafrontier Function

Metafrontier function was first proposed by Hayami [18] and Hayami and Ruttan [19]. The basic idea is that there are differences of production technology in different production units and the differences are often reflected in the intrinsic properties like region, type, size, etc. Assume that there are I regions which are separated into K ($K\geq1$) different groups based on the proximity of the production technology. The number of regions in group k is I_k (k=1,2...K) and $\sum_{k=1}^{K} I_k = I$ [20, 21]. To describe the practical production process, we further assume that $x = (x_1,x_2,...x_n)\in R_N^+$, $y = (y_1,y_2,...y_m)\in R_M^+$, and CO_2 emissions (c) are respectively inputs, desirable outputs, and undesirable output [17, 22]. Then the production process of group k can be described as $P^k(x)=\{(y,c):(x,y,c)\in T^k\}$, in which T^k represents the technology set in the specific production process of group k. Its production frontier can be defined as group frontier (GF) or region frontier.

Based on Shephard distance function, a CO_2-oriented distance function is defined as follows [15, 23]:

$$D^k\left(x,y,c\right)=\sup\left\{\lambda:\left(x,y,c/\lambda\right)\in P^k\left(x\right)\right\} \quad (1)$$

Equation (1) calculates the maximum contraction ratio of CO_2 emissions by determining the value of λ so as to judge the total factor CO_2 performance of the evaluated region[1]. Their relationship is shown in Equation (2). When the distance function D^k (x,y,c)=1, it indicates that the region is on the group frontier and its emission performance is the best in the region.

$$TFCP^k\left(x,y,c\right)=1/D^k\left(x,y,c\right) \quad (2)$$

Following O'Donnell et al. [21, 25] and Oh [22], T^* is defined as the technology set of the over-arching metafrontier function. Metafrontier function is formed by the envelopment of the production frontier in all regions, i.e. $T^* = \{T^1\cup T^2..T^k\}$. Similarly, $P^*(x)$ is set to be the output set of metafrontier function. Then the corresponding distance function and CO_2 emission performance index can be defined as:

$$D^*\left(x,y,c\right)=\sup\left\{\lambda:\left(x,y,c/\lambda\right)\in P^*\left(x\right)\right\} \quad (3)$$

$$TFCP^*\left(x,y,c\right)=1/D^*\left(x,y,c\right) \quad (4)$$

Fig. 1 is an example in which the same inputs are used to produce single desirable output and CO_2 emissions. The envelopment of three group frontiers forms a metafrontier.

[1] To model CO_2 emission performance, the measurement of Zhou et al. [15], with CO_2-oriented shepherd distance function, to reduce CO_2 emissions by focusing on one aspect; the approach of Zhang et al. [24], with directional distance function (DDF), to reduce CO_2 emissions and increase GDP simultaneously. Though the idea of Zhang et al. [24] has attracted much attention in recent literature the performance defined by DDF is the comprehensive efficiency of economic development and CO_2 reduction, not the pure CO_{2n} emission performance. Therefore, we define the performance using shepherd distance function according to Zhou et al. [15].

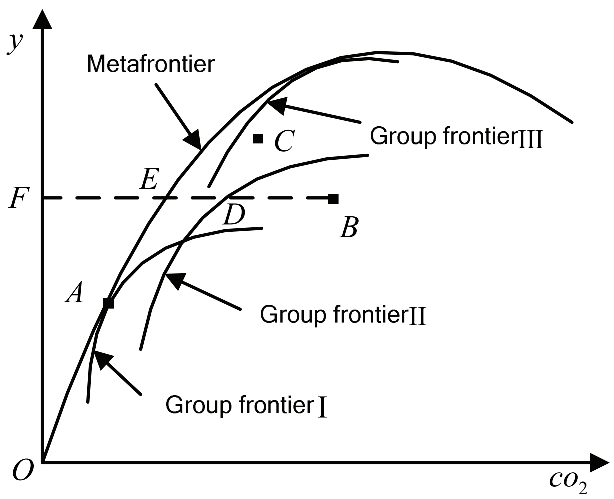

Fig. 1 Metafrontier function.

Points A, B, and C represent regions in group frontiers I, II, and III, respectively. Different references provide possibilities for the differences of CO_2 emission performance in the comparing region.

Technology Gap Ratio

As T^k is the subset of T^*, it can be shown that $D^k(x,y,c) \leq D^*(x,y,c)$. If a certain region is on the group frontier and the metafrontier (e.g. the case of A in Fig. 1), the equality will hold. For region B, taking the technology set of group frontier II as a reference, its distance function is $D_B^k(x,y,c)=\frac{BF}{DF}$. If the technology set T^* of the metafrontier is taken as a reference, its distance function is $D_B^*(x,y,c)=\frac{BF}{EF}$. Because $DF \geq EF$, we have $\frac{BF}{DF} \leq \frac{BF}{EF}$. Then the technology gap ratio (*TGR*) of CO_2 emission performance can be defined as Equation (5).

$$TGR^k(x,y,c)=\frac{D^k(x,y,c)}{D^*(x,y,c)}=\frac{TFCP^*(x,y,c)}{TFCP^k(x,y,c)} \quad (5)$$

The range of values of $TGR^k(x,y,c)$ is (0, 1], which characterizes the ratio of the potential minimum emissions in the metafrontier to the potential minimum emissions in the group frontier. It measures the closeness between the group frontier and the metafrontier. A smaller $TGR^k(x, y, c)$ represents a longer distance from the group frontier to the metafrontier.

Calculation of Distance Function

The non-parametric data envelopment analysis (DEA) proposed by Charnes et al. [26] is one popular method for calculating the distance function [21, 27, 28]. Compared to the parametric method, such as stochastic frontier analysis (SFA), DEA has the advantages of not setting the specific functional form, not requiring price information, and easy calculation [29]. It is used to study efficiency and productivity in a number of areas [30-33]. Assume that there are I regions and the vector of inputs, desirable outputs, and CO_2 emissions in region i is (x_i, y_i, c_i), then the distance function can be derived by solving the following DEA model.

$$\begin{aligned} &\left[D^d(x_i,y_i,c_i)\right]^{-1}=\min \quad \rho^d \\ &s.t. \quad \sum_{i=1}^{I}\lambda_i x_i \leq x_i \\ &\qquad \sum_{i=1}^{I}\lambda_i y_i \geq y_i \\ &\qquad \sum_{i=1}^{I}\lambda_i c_i = \rho c_i \\ &\qquad \lambda_i \geq 0, i=1,2,\cdots I \end{aligned} \quad (6)$$

In Equation (6), the superscript d in $D^d(\bullet)$ represents two different types of distance functions. When $d=*$, it indicates that the distance function is calculated in the metafrontier. When $d=k\,(1,2...K)$, it means that it is the distance function in the group frontier. λ_i refers to the intensity variables by which the production frontier is formed and I is determined according to the actual region number forming the group frontier or metafrontier. The non-negative restriction of intensity variables represents the production technology exhibits constant return to scale (CRS). If returns to scale are regarded as alterable, the constraint of $\sum_{i=1}^{I}\lambda_i=1$ should be added to make the metafrontier smooth [21]. However, the scale of production technology cannot be changed in a short time for countries. Therefore, CRS assumption is used here. Inequality constraints indicate the strong disposability of the inputs and desirable outputs. The equality constraints integrated with the undesirable outputs illustrate the null-jointness of the weak disposability of CO_2 and two types of outputs. The detailed explanation of Equation (6) can be found in the description of the environmental production technology by Tyteca et al. [23], Chung et al. [34], and Färe et al. [35].

Empirical Application

Data

The methodology described in Section 2 is applied to forty-nine major emitting countries in the world from 2001 to 2007. In 2007, the total CO_2 emissions of the whole sample accounted for 78% of the total emissions in the world (Fig. 2). Based on the geographical proximity principle, it is divided into three groups, namely Asia (18), Europe (17), and America (14). It is generally believed that geographically close regions have similar production technology. Therefore, geographical proximity principle is often regarded as a natural principle when the countries are divided into different groups [22, 36]. The specific list and group information is provided in Table 1. Due to its relatively small volume of CO_2 emissions and the lack of data, the African region is not included in our study.

Table 1. Countries/regions for the empirical application.

Code	Group	Country/Region	Code	Group	Country/Region
1	1	Australia	26	2	Italy
2	1	Bangladesh	27	2	Netherlands
3	1	China	28	2	Norway
4	1	Hong Kong	29	2	Portugal
5	1	India	30	2	Romania
6	1	Indonesia	31	2	Spain
7	1	Iran	32	2	Sweden
8	1	Israel	33	2	Switzerland
9	1	Japan	34	2	Turkey
10	1	Korea	35	2	United Kingdom
11	1	Malaysia	36	3	Argentina
12	1	New Zealand	37	3	Brizal
13	1	Pakistan	38	3	Canada
14	1	Philippines	39	3	Chile
15	1	Singapore	40	3	Colombia
16	1	Syria	41	3	Dominican
17	1	Taiwan	42	3	Ecuador
18	1	Thailand	43	3	Mexico
19	2	Austria	44	3	Panama
20	2	Belgium	45	3	Peru
21	2	Denmark	46	3	Puerto Rico
22	2	Finland	47	3	Trinidad and Tobago
23	2	France	48	3	United States
24	2	Greece	49	3	Venezuela
25	2	Ireland			

Groups are: 1 Asia, 2 Europe, 3 America. Australia and New Zealand in Oceania are included in Asia.

CO_2 has been selected as the typical undesirable output as our focus is to assess CO_2 emission performance. Regarding input and output variables, we follow Wei et al. [37], Oh [22], and Wang et al. [16] to choose labor, capital stock, and energy as inputs, and gross domestic product (GDP) as a single desirable output. The data on energy and CO_2 are obtained from statistics published by the U.S. Energy Information Administration (EIA) in 2009. The capital stock is calculated from the relevant data in Penne World Table Version 6.3 (PWT6.3) with the perpetual inventory method. The data on labor and GDP are collected according to PWT6.3. To eliminate the impact of price fluctuations, the data on capital stock and GDP are adjusted with the approach of purchasing power parity (PPP) and converted to 2005 constant prices. Table 2 shows the summary statistics of the data collected and compiled.

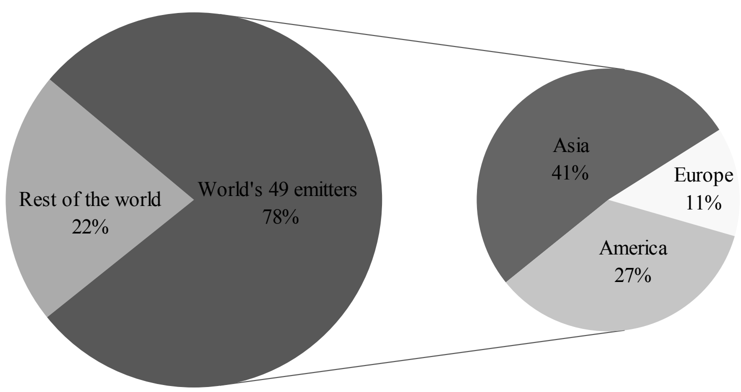

Fig. 2. Distribution of CO_2 emissions for the 49 emitting countries in 2007.

Table 2. Summary statistics of inputs and outputs in 2001-07.

	GDP (bil.USD)		CO_2 (mil.tons)		Labor (mil.)		Energy (mil.toe)		Capital (bil.USD)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Asia	1208.9	1,984.7	556.5	1,116.8	91.6	189.8	275.2	491.9	2,777.1	4,540.1
Europe	576.5	586.3	182.3	167.4	10.7	9.8	122.0	111.9	1,632.2	1,635.4
America	1,372.7	2,349.9	555.4	1,199.4	91.2	180.4	281.9	526.4	2,776.3	4,664.1
Total	1,003.4	2,065.2	427.5	1,065.0	45.2	122.4	242.6	565.1	2,429.5	5,001.2

Table 3. Statistical description of CO_2 emission performance for select countries.

	CO_2 emission performance with respect to the group frontiers ($TFCP^k$)				CO_2 emission performance with respect to the metafrontiers ($TFCP^*$)			
	Mean	S.D.	Max	Min	Mean	S.D.	Max	Min
Total	0.736	0.251	1.000	0.152	0.664	0.276	1.000	0.129
Asia	0.722	0.241	1.000	0.313	0.604	0.278	1.000	0.233
Europe	0.736	0.234	1.000	0.260	0.694	0.239	1.000	0.237
America	0.753	0.282	1.000	0.152	0.704	0.305	1.000	0.129
Argentina	0.886	0.101	1.000	0.775	0.869	0.115	1.000	0.751
China	0.342	0.014	0.356	0.316	0.279	0.023	0.305	0.240
Greece	0.563	0.026	0.591	0.521	0.527	0.035	0.564	0.474
India	0.585	0.036	0.624	0.517	0.509	0.013	0.525	0.489
Japan	0.855	0.055	0.924	0.766	0.515	0.020	0.543	0.479
Norway	1.000	0.000	1.000	1.000	1.000	0.000	1.000	1.000
Thailand	0.575	0.034	0.619	0.515	0.397	0.020	0.435	0.375
Turkey	0.722	0.172	1.000	0.526	0.405	0.024	0.431	0.356
UK	0.998	0.007	1.000	0.983	0.861	0.058	0.914	0.744
USA	0.996	0.012	1.000	0.969	0.976	0.047	1.000	0.877
Venezuela	0.392	0.034	0.445	0.356	0.332	0.027	0.366	0.294

Results and Discussion

We take the frontier formed in the input and output process in the countries of Asia, Europe, and the Americas as the group frontier and frontier of the sample countries as the metefrontier. In using DEA to calculate distance functions, it could be difficult to construct the approximate smooth frontier due to the small sample size in the group. To avoid this issue, this paper follows Nghiem and Collie [38] to use the two-year window approach to constructing production frontier. That is to say, the reference technology for one year is determined by the data on input and output variables for the current and previous year. The 2000 data also are included in the reference technology in 2001.

We then calculate the distance functions of the group frontier and metafrontier, respectively, with Equation (6) and derive the TFCP scores of various countries. Table 3 shows the descriptive statistics of CO_2 emissions in three continents and several countries in 2001-07.

Table 3 shows that compared with the group frontier, the CO_2 emission performance score for Japan during the sample period is between 0.766 and 0.924, with an average of 0.855. This implies that by taking Asian countries as a reference, the annual CO_2 emissions in Japan may be reduced by 14.5% on average through efficiency improvement without increasing inputs or reducing GDP. However, based on the metafrontier, its maximum performance score is only 0.543, with an average improvement rate of 48.5%, which is much higher than the potential improvement rate of 14.5% in the group frontier. This result shows that with two different reference technologies, the relative performance of Japan has a significant change.

Unlike Japan, Norway and the United States have shown better performance under two frontiers and appeared

Table 4. The focus and target of CO_2 reduction measures.

	Focus and target	Representative
Category one (high-high)	These countries should continue to promote technology and management innovation, and push the technical progress and institutional arrangements related to carbon emission reduction. In addition, technical assistance and diffusion to other countries should be strengthened (especially the countries in category three) while maintaining high performance of carbon emission reduction.	Norway United States
Category two (low-high)	These countries need to gradually catch up the advanced production and technology related to carbon emission reduction by some measures of updating, introducing, and absorbing, etc. In a word, the countries in category one are the target to pursue.	Japan Turkey
Category three (low-low)	These countries should pay attention to the basic work of carbon emission reduction and improve related technical and management levels. Furthermore, they should seek technical support and assistance from other countries (especially the countries in category one) to make a significant improvement in carbon emission reduction performance. For these countries, the countries in category two are the short-term target.	China Venezuela

on the frontier during the sample period, indicating that these countries are the leaders of regional CO_2 emission performance. Norway has never been out of the two frontiers and should be treated as the leading country in CO_2 emission performance, both Europe and worldwide. Compared with other countries, its location is similar to point A in Fig. 1. On the other hand, developing countries like China, Thailand and Venezuela showed relatively poor emission performance both in the group frontier and the metafrontier. Meanwhile, it has been found that the performance of some countries (like Argentina and Greece) has little change with respect to two frontiers.

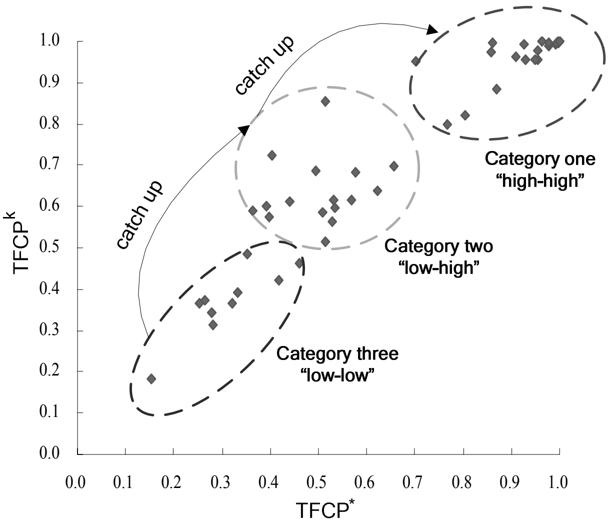

Fig. 3. Categories of CO_2 emission performance.

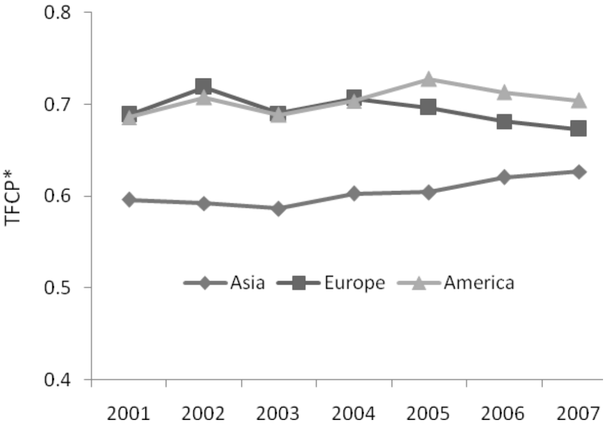

Fig. 4. Trend of CO_2 emission performance in three continents.

Through analysis of CO_2 emission performance in several typical countries above, we can divide all countries into three categories as shown in Fig. 3. The first category is the high-high combination. Those countries show high performance respect to two frontiers, so they are the representatives of high CO_2 emission performance worldwide. The second category is the low-high combination. Although these countries have low performance in the world, they show a high-performance level in the local area, so they are the regional leaders in CO_2 emission performance. The third category is the low-low combination. Countries in this category show low performance with respect to two frontiers and they are the relatively backward regions in CO_2 emission performance in the world. Since after including more samples the performance score of a country with respect to the metafrontier is always less than that with respect to the group frontier, there is no high-low combination.

Table 4 shows the possible emission reduction policy choices for countries in the three categories.

From the point of view of three continents, the average CO_2 emission performance in Asia, Europe, and the Americas are 0.604, 0.694, and 0.704 with respect to the metafrontier, while the values are 0.722, 0.736, and 0.753, respectively according to the group frontier, also reflecting the phenomenon that CO_2 emission performance respect to the group frontier is higher than that of the metafrontier (Table 3). Fig. 4 shows the trend of CO_2 emission performance in three continents in respect to the metafrontier. It is found that the performance of Europe and America is roughly equal during 2001-04, while America's performance has been better than Europe's since 2005. Although the CO_2 emission performance of Asia is always in the backward, an upward trend is most obvious there.

Fig. 5 shows the TGR changes in three continents during 2001 and 2007. Except for 2001, TGR in the Americas is always the highest, around 0.95. This indicates that, compared to the group frontier formed by the American countries with the metafrontier formed by all the sample countries, the American countries are the closest to the best global CO_2 emission performance. The European TGR is slightly less than that of America, remaining about 0.91, indicating that Europe has realized 91% of the potential minimum CO_2 emissions. The TGR in Asia has always been the smallest among three continents, indicating that it has the largest gap compared with the world's best emission performance. However, the TGR in Asia is gradually increased and the gap has decreased in recent years. This trend is very similar to the performance of three continents analyzed above.

From the perspective of the TGR of all sample countries (Fig. 6), it has gone through two stages. The first stage is from 2001 to 2004, with a decent process. The second phase is since 2005, with an ascent trend and the differences of CO_2 emission performance among countries and regions being alleviated.

It should be pointed out that the total-factor CO_2 emission performance index proposed in this paper is a relative performance indicator. But in practice, carbon intensity, a single factor emission performance indicator, is often accepted by many countries and international organizations in the carbon emission reduction negotiations and practical applications. For the purpose of comparing the difference of results caused by these two indicators, the rankings of 49 countries based on *TFCP** and carbon intensity are given in Fig. 7. The rankings of most of the countries are roughly equivalent under the two comparison standards, whereas there are still some differences for some countries. The rankings of the United States, Taiwan, and Syria are 37, 39, and 48, respectively, when carbon intensity is the standard, while their rankings (7, 9, and 13) are at the front when the TFCP index is used. The situation is opposite for several other countries such as Peru and Philippines.

One important purpose for monitoring the changes of CO_2 emission performance is to judge the CO_2 reduction potential by its performance value, and further establish workable CO_2 emission reduction actions. The target amount and actual amount of CO_2 emissions can be obtained from Equation (6), from which we can further derive emission reduction potentials. Fig. 8 shows the CO_2 emission reduction potentials in Asia, Europe, and America individually. It can be found that the difference between actual emission amounts and the target is getting larger and

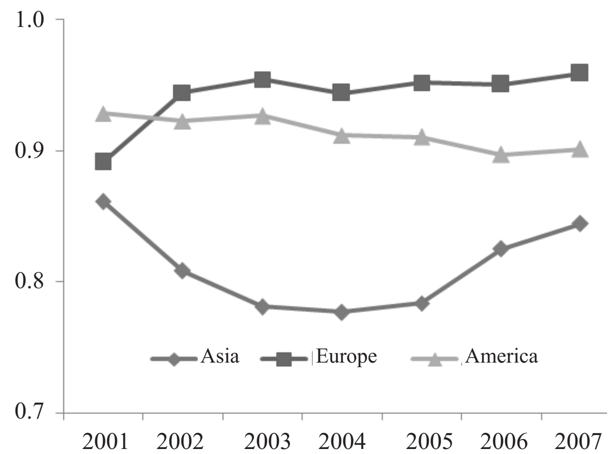

Fig. 5. The TGR of three continents.

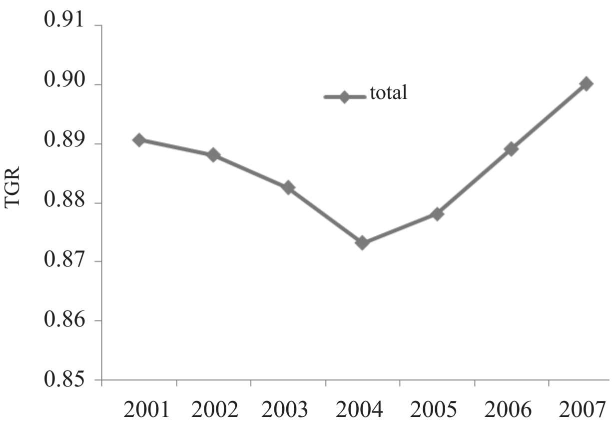

Fig. 6. The TGR of 49 emitting countries.

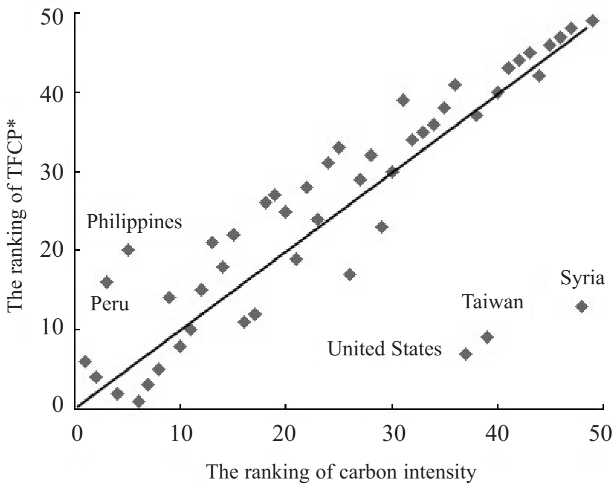

Fig. 7. Scatter plot of rankings.

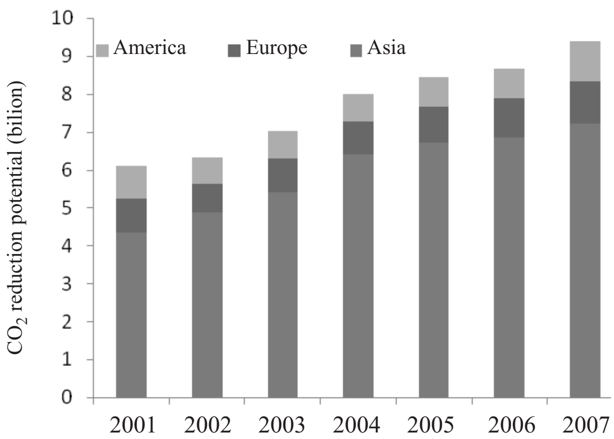

Fig. 8. CO_2 reduction potential in three continents.

larger over time. On different continents, the CO_2 reduction potential in Asia is the highest because Asia has the largest CO_2 emission amount, especially in China, India, and Japan. Another reason is that Asia showed lower emission performance. A higher emission amount and lower performance cause the most serious task for Asia. Europe and America get smaller CO_2 emission reduction potential because of their high performance and low emission amount, in which the CO_2 reduction potential is less than 1.2 billion tons.

Conclusion

This paper combines the environmental production technology and the metafrontier function and proposes a quantitative indicator for assessing the CO_2 emission performance and differences between different countries. We use the proposal indicator to empirically examine the emission performance and regional differences of 49 major emitting countries.

Compared to the region frontier, most countries have shown a higher performance than that of the metafrontier. Among them, Norway and other countries are the leaders of the world's high CO_2 emission performance while China and other countries are backward relatively. When group frontier and metafrontier are respectively taken as the reference, all the sample countries can be divided into three different categories, high-high, high-low, and "low-low," based on their performance scores. Countries within different categories are suggested to take different emission reduction categories. As a whole, the total CO_2 emission reduction potential has an upward trend for Asia, Europe, and America, while the reduction potential for Asia is much higher than those for Europe and America. Our empirical results also show that the TGR of CO_2 emissions in all sample countries have experienced two phases of first drop and then increase. The differences of CO_2 emission performance among countries and regions have been alleviated in recent years. Meanwhile, the rankings of some countries, such as United States, Taiwan, Syria, Peru, and the Philippines, change a lot when carbon intensity is regarded as the standard indicator.

Different from previous research and practices that always take carbon intensity as the comparative objects, this paper uses the total factor CO_2 emission performance indicator, which provides a new choice for the horizontal comparison among countries. Meanwhile, it is also possible to monitor the differences of CO_2 emission performance based on the technology gap ratio proposed in this paper. In order to improve the CO_2 emission performance, narrow the differences in different countries, and to better fulfill the international emission reduction obligations, countries, should strengthen their cooperation in energy savings and emission reduction technologies.

It should be pointed out that there is still a great deal of work to be done regarding the measurement of CO_2 emission performance in the future. This paper does an international comparison within a cross-sectional data framework which is a static measurement. One possible methodology extension for this study is to measure dynamic CO_2 emission performance changes incorporating heterogeneities using the meta-frontier CO_2 emission Malmquist index [39]. Besides, the division of group frontier here is based on the principle of geographical proximity. It is clear that the results may vary because of the different principals of dividing groups. Therefore, it is possible to group samples with other possible ways, such as the degree of economic development and the situation of industrial competitiveness, and do some comparisons. Investigating the convergence of CO_2 emission performance for different countries is also a possible valuable research direction in the future.

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