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# Fossil energy saving and $CO_2$ emissions reduction performance, and dynamic change in performance considering renewable energy input

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ABSTRACT

Energy environmental and non-radial Malmquist indexes are proposed employing a non-radial directional distance function to evaluate fossil energy saving and $CO_2$ emissions reduction performance, and dynamic change in performance internationally. Renewable energy is also proposed as an essential energy input for the models. An empirical study of 26 Organization for Economic Cooperation and Development countries and Brazil, Russia, India, and China was performed, with the following outcomes: fossil energy saving and $CO_2$ emissions reduction performance is underestimated for most countries, regardless of renewable energy input, however, this underestimation has little influence on performance rankings; there is no significant correlation between the proportion of renewable energy consumption and fossil energy saving and $CO_2$ emissions reduction performance; the 30 countries can be divided into four categories with corresponding specific strategies for energy saving and emissions reduction; Generally, technological progress and efficiency improvement are out of sync, mainly because of the difficulty to achieve the efficiency improvements.

## 1. Introduction

Facing the pressure of global climate change, the 21st Conference of Parties of the United Nations Framework Convention on Climate Change reached an international agreement to restrict the rise in global average temperature "well below 2 °C". The Intergovernmental Panel on Climate Change [1] reported that $CO_2$ from fossil energy combustion is the main cause of global climate change. Currently, more than 80% of global energy consumption comes from fossil energy [2], which indicates fossil energy use reduction is extremely important for global climate change mitigation.

Governments have taken many steps to reduce fossil energy use and $CO_2$ emissions, such as exploitation of renewable resources, technological improvement, and formulation of laws and international standards. However, countries have different technologies, economic situations, and available resources, which make it difficult to achieve a uniform level of emissions reduction. Accordingly, scientific evaluation of fossil energy saving and $CO_2$ emissions reduction performance not only provides valuable information for reducing fossil use and $CO_2$ emissions, but also provides a premise and guarantee of realizing sustainable development and the global temperature control target.

Data envelopment analysis (DEA) technology, a nonparametric approach, has been applied to estimate the relative performance or efficiency of decision making units (DMUs). Fossil energy saving and $CO_2$ emissions reduction performance has also been studied using DEA at industrial, regional, and national levels [3–8]. Differently from the above literature analyzing energy and environmental performance separately, some re searchers put energy saving and $CO_2$ emissions reduction as two non-independent indices. Developing a unified efficiency measure, Goto et al. [9] investigated the operational and environmental efficiency of Japanese industries under natural and managerial disposability. Zhou et al. [10] defined an energy carbon performance index, and analyzed electricity generation performance of a range of countries. Zhang et al. [11] incorporated non-energy inputs, capital and labor, into the energy carbon performance index proposed by Zhou et al. [10] for energy and environmental performance of Chinese fossil fuel power plants. According to the idea of Zhou et al. [10], Wang et al. [12] measured and decomposed the energy saving and emissions reduction performance in Chinese cities.

Dynamic change in energy and environmental performance has also been considered. Arabi et al. [13] employed the conventional

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**Nomenclature**

| | |
|---|---|
| OECD | Organization for Economic Cooperation and Development |
| BRIC | Brazil, Russia, India and China |
| DEA | data envelopment analysis |
| DMU | decision making unit |
| DDF | directional distance function |
| RE | renewable energy |
| FE | fossil energy |
| L | labor force |
| K | capital stock |
| G | real gross domestic production |
| C | $CO_2$ emissions |
| $EEI_4$ | energy environmental index for model (4) |
| $EEI_5$ | energy environmental index for model (5) |
| TECH | technological change |
| EFFCH | efficiency change |
| MI | Malmquist index |
| MLI | Malmquist-Luenberger index |
| NMI | non-radial Malmquist index |
| $N$ | number of countries |
| $T$ | Production possibility set |
| X | a row vector of input indicators |
| Y | a row vector of output indicators |
| $\lambda_n$ | the n-th intensity variable |
| $w_n$ | the n-th intensity variable in model (5) |
| $\beta_{FE_{n_0}}$ | a non-negative variable |
| $\beta_{C_{n_0}}$ | a non-negative variable |
| $\eta_{FE_{n_0}}$ | a non-negative variable in model (5) |
| $\eta_{C_{n_0}}$ | a non-negative variable in model (5) |

Malmquist-Luenberger index (MLI), and analyzed eco-efficiency changes for thermal power plants in Iran. Similarly, Chen and Golley [14] evaluated the changing patterns of green productivity growth in 38 industrial sectors across China. Wang et al. [15] combined conventional MLI and a non-radial directional distance function (DDF) to investigate total factor energy productivity of China in three production scenarios. Yu et al. [16] incorporated salcks-based measure into conventional MLI, and assessed the change in eco-efficiency of pulp and paper industry in China between 2010 and 2013.

Methodologically, the first DEA model, CCR, was proposed by Charnes et al. [17], and subsequent models were constructed by Banker et al. [18], Färe et al. [19], and Seiford and Thrall [20]. However, undesirable outputs are ignored, because these expanded all outputs simultaneously [21]. Hence, the radial DDF were adopted to consider undesirable outputs in DEA models [3,22–24]. Nonetheless, radial DDF overestimates DMU performance in the case of non-zero slack [25,26]. In contrast, non-radial DDF reduces inputs and undesirable outputs and allows expansion of desirable outputs at different ratios, which provides an effective method to address the slack problem [3,26–28].

On the other hand, Färe et al. [29] and Chung et al. [30] proposed Malmquist index (MI) and Malmquist-Luenberger index (MLI) models, respectively, to assess dynamic change in productivity using time series data. However, MI was implemented using the Shephard distance function [31], which neglects undesirable outputs, and although MLI can consider undesirable outputs, the results may be biased due to the radial DDF [32]. Consequently, some researchers have constructed MI or MLI based on the non-radial DDF to obtain impartial results [28,33–35].

Given the prior work mentioned above, some deficiencies remain. On the one hand, the research has been focused at industrial or regional levels, with few studies from an international perspective [7]. Efforts to reduce fossil energy use and $CO_2$ emissions should be taken by all countries in response to global climate change, which makes international comparison meaningful. On the other hand, these studies have all used fossil energy as the only energy input indicator, which neglects the effect of renewables in replacing fossil energy and reducing $CO_2$ emissions. Although Wang et al. [12] considered different energy types, the concept could not be properly modelled due to non-availability of data. The ratio of global renewables to total energy consumption has increased from 6.80% in 2002 to 9.25% in 2014 [2], and is forecast to reach 18% by 2035 [36]. Thus, renewable energy has an important and growing role in energy saving and emissions reduction. Accordingly, renewable energy should be included as an energy input indicator to objectively reflect countries' performance in fossil energy saving and $CO_2$ emissions reduction.

This paper proposes energy environmental and non-radial Malmquist indexes employing a non-radial DDF to evaluate fossil energy saving and $CO_2$ emissions reduction performance, and dynamic change in performance internationally. Following the arguments above, renewable energy is included as an energy input indicator for the models, and the theoretical and empirical necessity of this inclusion is discussed. The remainder of this paper is organized as follows: Section 2 defines the energy environmental and non-radial Malmquist indexes and addresses the theoretical necessity of including renewable energy as an energy input indicator. Section 3 presents an empirical study of 26 Organization for Economic Cooperation and Development (OECD) and BRIC (Brazil, Russia, India and China) countries, and the conclusions and suggestions from this study are given in Section 4.

## 2. Methodology

### 2.1. Production possibility set

In the existing literature regarding energy and environmental performance [3–12], the main inputs include fossil energy, capital stock and labor force; the main outputs consist of economic output and environmental output. Additionally, renewable energy input is proposed as an essential energy input in this paper. Consider a production process where the inputs, renewable energy ($RE$), fossil energy ($FE$), capital stock ($K$) and labor force ($L$) as inputs are produced a desirable output, the real gross domestic product ($G$), and an undesirable output, $CO_2$ emissions ($C$). The production possibility set ($T$) can be described as:

$$T = \{(X,Y) : X\ can\ produce\ Y\} \tag{1}$$

Where $X = (RE, FE, K, L)$, $Y = (G, C)$. According to Shephard [31] and Färe et al. [37], $T$ is convex and closed. Meanwhile, inputs and desirable outputs satisfy free disposability, that is, if $(X,Y)\in T$, $\overline{X} \geq X$ and $\overline{G} \leq G$, then $(\overline{X}, \overline{G}, C)\in T$. The free disposability means that it is a feasible production process to generate less real gross domestic product by using more inputs. On the other hand, in order to consider undesirable outputs, Färe et al. [21] imposed weak disposability and null-jointness on $T$; that is, If $(X,Y)\in T$ and $0\le\theta\le 1$, then $(X,\theta Y)\in T$; If $(X,Y)\in T$ and $C=0$, then $G=0$. The weak disposability indicates that $CO_2$ emissions reduction is not free, and needs some loss of real gross domestic product. The null-jointness expresses that $CO_2$ emissions must be produced in a production process, unless no real gross domestic product is generated.

Assume that there are $N$ countries and country $n$ $(n=1,2,...,N)$ utilizes $X_n=(RE_n,FE_n,K_n,L_n)$ to generate $Y_n=(G_n,C_n)$. Based on the above assumptions, $T$ under constant returns to scale can be formulated as follows:

$$\begin{aligned} T=\Bigg\{(X,Y):\ & \sum_{n=1}^{N}\lambda_n RE_n\le RE \\ & \sum_{n=1}^{N}\lambda_n FE_n\le FE \\ & \sum_{n=1}^{N}\lambda_n L_n\le L \\ & \sum_{n=1}^{N}\lambda_n K_n\le K \\ & \sum_{n=1}^{N}\lambda_n G_n\ge G \\ & \sum_{n=1}^{N}\lambda_n C_n= C \\ & \lambda_n\ge 0, n=1,2,\ldots,N\Bigg\} \end{aligned} \tag{2}$$

where $\lambda_n$ $(n=1,2,...,N)$ are the intensity variables which weight the inputs and outputs of countries to construct the production possibility set $T$.

### 2.2. Energy environmental index

As discussed in Section 1, non-radial DDFs seem to solve the slack problem. Therefore, an energy environmental index (EEI) based on the non-radial DDF proposed by Zhou et al. [10] is defined to estimate fossil energy saving and $CO_2$ emissions reduction performance of countries.

The EEI score of country $n_0$ $(n_0=1,2,\ldots,N)$ is

$$\begin{aligned} &\overrightarrow{EEI}(X_{n_0},Y_{n_0};\vec{g})=\inf Q \\ &Q=\left\{\frac{1}{2}\frac{FE_{n_0}-FE_{n_0}\beta_{FE_{n_0}}}{FE_{n_0}}+\frac{1}{2}\frac{C_{n_0}-C_{n_0}\beta_{C_{n_0}}}{C_{n_0}}:\right. \\ &\left.\left(RE_{n_0},FE_{n_0}-FE_{n_0}\beta_{FE_{n_0}},L_{n_0},K_{n_0},G_{n_0},C_{n_0}-C_{n_0}\beta_{C_{n_0}}\right)\in T\right\} \end{aligned} \tag{3}$$

where $(FE_{n_0}-FE_{n_0}\beta_{FE_{n_0}})/FE_{n_0}$ and $(C_{n_0}-C_{n_0}\beta_{C_{n_0}})/C_{n_0}$ denote the performance of fossil energy saving and $CO_2$ emissions reduction,[1] respectively. $\beta_{FE_{n_0}}$ and $\beta_{C_{n_0}}$ $(n_0=1,2,\ldots,N)$ are non-negative variables. EEI is dimensionless and lies in the interval $(0,1]$, with larger EEI indicating better fossil energy saving and $CO_2$ emissions reduction performance.

Fig. 1 shows a graphical illustration of obtaining EEI score of country $n_0$ through Eq. (3). In Fig. 1, the set $P=\{(C,FE):(RE_{n_0},FE,L_{n_0},K_{n_0},G_{n_0},C)\in T\}$. The area ABCD comprises all points of $P$ whose two coordinate components are all not greater than $C_{n_0}$ and $FE_{n_0}$, respectively. Because the $\beta_{FE_{n_0}}$ and $\beta_{C_{n_0}}$ are non-negative variables, any point in the area ABCD can be expressed as $(C_{n_0}-C_{n_0}\beta_{C_{n_0}},FE_{n_0}-FE_{n_0}\beta_{FE_{n_0}})$. Further, the set $Q$ can be obtained based on all points in the area ABCD. Thus, EEI score of country $n_0$ is $\inf Q$.

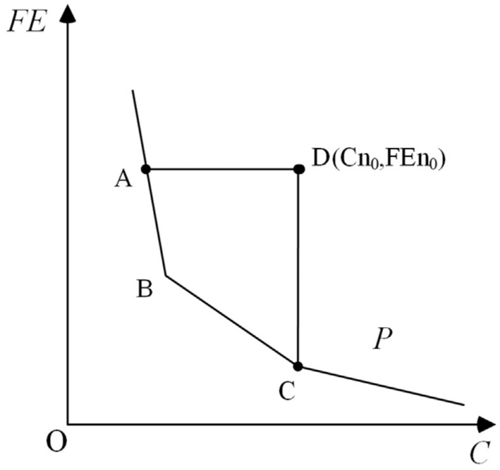

**Fig. 1.** Graphical illustration of obtaining EEI score of country $n_0$.

The value of Eq. (3) can be obtained by solving the following linear programming [10].

$$\begin{aligned} &\overrightarrow{EEI}(X_{n_0},Y_{n_0};\vec{g})=\min\frac{1}{2}\frac{FE_{n_0}-FE_{n_0}\beta_{FE_{n_0}}}{FE_{n_0}}+\frac{1}{2}\frac{C_{n_0}-C_{n_0}\beta_{C_{n_0}}}{C_{n_0}} \\ &s.t.\ \sum_{n=1}^{N}\lambda_n RE_n\le RE_{n_0} \\ &\sum_{n=1}^{N}\lambda_n FE_n\le FE_{n_0}-FE_{n_0}\beta_{FE_{n_0}} \\ &\sum_{n=1}^{N}\lambda_n L_n\le L_{n_0} \\ &\sum_{n=1}^{N}\lambda_n K_n\le K_{n_0} \\ &\sum_{n=1}^{N}\lambda_n G_n\ge G_{n_0} \\ &\sum_{n=1}^{N}\lambda_n C_n= C_{n_0}-C_{n_0}\beta_{C_{n_0}} \\ &\beta_{FE_{n_0}},\beta_{C_{n_0}}\ge 0 \\ &\lambda_n\ge 0, n=1,2,\ldots,N \end{aligned} \tag{4}$$

### 2.3. Renewable energy as an energy input indicator

The EEI score for country $n_0$ neglecting renewable energy input is[2]

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[1] Two methods are commonly used to measure energy saving and $CO_2$ emissions reduction performance: the ratio of optimal to actual energy (or $CO_2$ emissions) intensity [10,11]; and target divided by actual energy use (or $CO_2$ emissions) [4,7,34,38]. The second method is an absolute quantity and provides a more valid view of energy saving and emissions reduction performance. Hence, the second method is adopted in this paper.

[2] $\lambda_n(n=1,2,...,N)$ is replaced by $w_n(n=1,2,...,N)$ is to distinguish models (4) and (5).

$$\begin{aligned}
&\overrightarrow{EEI}(X_{n_0},Y_{n_0};\overrightarrow{g}) = \min \frac{1}{2}\frac{FE_{n_0}-FE_{n_0}\eta_{FE_{n_0}}}{FE_{n_0}} + \frac{1}{2}\frac{C_{n_0}-C_{n_0}\eta_{C_{n_0}}}{C_{n_0}}\\
&s.t.\quad \sum_{n=1}^{N} w_n FE_n \le FE_{n_0} - FE_{n_0}\eta_{FE_{n_0}}\\
&\sum_{n=1}^{N} w_n L_n \le L_{n_0}\\
&\sum_{n=1}^{N} w_n K_n \le K_{n_0}\\
&\sum_{n=1}^{N} w_n G_n \ge G_{n_0}\\
&\sum_{n=1}^{N} w_n C_n = C_{n_0} - C_{n_0}\eta_{C_{n_0}}\\
&\eta_{FE_{n_0}},\eta_{C_{n_0}} \ge 0\\
&w_n \ge 0, n = 1,2,\ldots,N
\end{aligned} \tag{5}$$

Suppose the feasible regions of model (4) and model (5) are sets A and B, respectively. Then A is formed by incorporating a constraint condition related to renewable energy into B, which means that every feasible solution of model (4) must also be a feasible solution of model (5), i.e., $A \subseteq B$, and the objective functions are identical. Therefore, EEI for model (5) ($EEI_5$) is not larger than that of model (4) ($EEI_4$), i.e., $EEI_5 \le EEI_4$.

If the optimum solutions of models (4) and (5) are $\{\lambda_1^*,\lambda_2^*,\ldots,\lambda_n^*,\beta_{C_{n_0}}^*,\beta_{FE_{n_0}}^*\}$ and $\{w_1^*,w_2^*,\ldots,w_n^*,\eta_{C_{n_0}}^*,\eta_{FE_{n_0}}^*\}$, respectively, then the benchmark points in the best practice frontier of country $n_0$ can be expressed as $M(RE_{n_0},\sum_{n=1}^{N}\lambda_n^* FE_n, L_{n_0}, K_{n_0}, G_{n_0}, \sum_{n=1}^{N}\lambda_n^* C_n)$ and $N(\sum_{n=1}^{N} w_n^* FE_n, L_{n_0}, K_{n_0}, G_{n_0}, \sum_{n=1}^{N} w_n^* C_n)$, respectively. If renewable energy is included in model (5), then the renewable energy consumption of benchmark point $N$ is $\sum_{n=1}^{N} w_n^* RE_n$, and since $EEI_5 < EEI_4$, $\sum_{n=1}^{N} w_n^* RE_n > RE_{n_0}$. Thus, the fossil energy consumption and $CO_2$ emissions of benchmark point $N$ cannot be achieved with the current renewable energy consumption of country $n_0$, and model (5) will underestimate energy saving and $CO_2$ emissions reduction performance. On the other hand, model (4) considers renewable energy input, which makes the renewable energy consumption of benchmark point $M$ equal to that of country $n_0$. Therefore, model (4) can more objectively reflect the current performance of country $n_0$.

### 2.4. Non-radial Malmquist index

Based on the non-radial DDF proposed by Zhou et al. [10], we define a non-radial Malmquist index (NMI) to analyze the dynamic change in fossil energy saving and $CO_2$ emissions reduction performance.

Let $t$ and $t+1$ denote two time periods. $\overrightarrow{EEI}^t(X_{n_0}^t,Y_{n_0}^t;\overrightarrow{g})$ (or $\overrightarrow{EEI}^{t+1}(X_{n_0}^{t+1},Y_{n_0}^{t+1};\overrightarrow{g})$) is EEI score of country $n_0$ with respect to inputs, outputs and the production possibility set at period $t$ (or $t+1$). Similarly, $\overrightarrow{EEI}^{t+1}(X_{n_0}^t,Y_{n_0}^t;\overrightarrow{g})$ (or $\overrightarrow{EEI}^t(X_{n_0}^{t+1},Y_{n_0}^{t+1};\overrightarrow{g})$) is EEI score of country $n_0$ based on inputs and outputs at period $t$ (or $t+1$) and the production possibility set at period $t+1$ (or $t$). The NMI of country $n_0$ is defined as follows[3]:

$$NMI_t^{t+1} = \left[\frac{\overrightarrow{EEI}^t\left(X_{n_0}^{t+1},Y_{n_0}^{t+1};\overrightarrow{g}\right)\times\overrightarrow{EEI}^{t+1}\left(X_{n_0}^{t+1},Y_{n_0}^{t+1};\overrightarrow{g}\right)}{\overrightarrow{EEI}^t\left(X_{n_0}^{t},Y_{n_0}^{t};\overrightarrow{g}\right)\times\overrightarrow{EEI}^{t+1}\left(X_{n_0}^{t},Y_{n_0}^{t};\overrightarrow{g}\right)}\right]^{1/2} \tag{6}$$

$NMI_t^{t+1} > 1$ (or $NMI_t^{t+1} < 1$) implies that the performance improved (or deteriorated) from period $t$ to period $t+1$. The $NEI_t^{t+1}$ can be further decomposed into efficiency change ($EFFCH$) and technological change ($TECH$).

$$EFFCH_t^{t+1} = \frac{\overrightarrow{EEI}^{t+1}\left(X_n^{t+1},Y_n^{t+1};\overrightarrow{g}\right)}{\overrightarrow{EEI}^t\left(X_n^{t},Y_n^{t};\overrightarrow{g}\right)} \tag{7}$$

$$TECH_t^{t+1} = \left[\frac{\overrightarrow{EEI}^t\left(X_n^{t+1},Y_n^{t+1};\overrightarrow{g}\right)\times\overrightarrow{EEI}^t\left(X_n^{t},Y_n^{t};\overrightarrow{g}\right)}{\overrightarrow{EEI}^{t+1}\left(X_n^{t+1},Y_n^{t+1};\overrightarrow{g}\right)\times\overrightarrow{EEI}^{t+1}\left(X_n^{t},Y_n^{t};\overrightarrow{g}\right)}\right]^{1/2} \tag{8}$$

$EFFCH_t^{t+1}$ reflects the change in efforts to catch up with the best practice frontier from period $t$ to period $t+1$. $EFFCH_t^{t+1} > 1$ (or $EFFCH_t^{t+1} < 1$) indicates that efficiency improvement (or decline). $TECH_t^{t+1}$ captures the condition of the best practice frontier shift from period $t$ to period $t+1$. $TECH_t^{t+1} > 1$ (or $TECH_t^{t+1} < 1$) means that technological progress (or regress).

## 3. Empirical study

### 3.1. Data

The OECD includes most developed counties,[4] and BRIC are the four main emerging markets. These countries include the world's main fossil energy consumers and $CO_2$ emitters, with 2002–2011 annual fossil energy consumption and $CO_2$ emissions accounting for more than 80% and 79% of the world, respectively [2]. Therefore, fossil energy saving and $CO_2$ emissions reduction of OECD and BRIC countries dominates global performance. Based on data availability and discrimination,[5] 26 OECD and BRIC countries are selected as samples including: Austria (AUT), Belgium (BEL), Czech (CZE), Denmark (DNK), Finland (FIN), France (FRA), Germany (GER), Hungary (HUN), Ireland (IRE), Italy (ITA), Netherlands (NLD), Norway (NOR), Poland (POL), Portugal (PRT), Slovak (SVK), Spain (ESP), Sweden (SWE), Turkey (TUR), United Kingdom (GBR), Australia (AUS), Japan (JPN), South Korea (KOR), Canada (CAN), Chile (CHL), Mexico (MEX), United States (USA), Brazil (BRA), India (IND), Russia (RUS) and China (CHN). In addition, these countries can be divided into four regions according to geographical location and organization category: OECD Europe (OECD EU), OECD America (OECD AM), OECD Asia & Oceania (OECD AO) and BRIC countries.

Table 1 lists descriptive statistics for inputs and outputs of the 30 selected OECD and BRIC countries from 2002 to 2011. Data related to renewable and fossil energy consumption, and $CO_2$ emissions were sourced from the BP Statistical Review of World Energy [2]. Labor force data was collected from World Development Indicators

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[3] Some mix-period linear programming might be infeasible, which is solved by window analysis technology in some literature [39–41]. However, window analysis might not absolutely solve the infeasible problem [15]. Therefore, this paper uses global Malmquist index introduced by Pastor and Lovell [42] to address the infeasible problem.

[4] According to Human Development Report 2010 [43], 28 of 44 developed counties in the world belong to OECD.

[5] Selected countries should be at least three times as many as the number of input and output indicators [7].

**Table 1**
Inputs and outputs descriptive statistics for 2002–2011.

| Inputs/Outputs | Variable | Unit | Mean | S.D. |
|---|---|---|---|---|
| Inputs | Renewable energy | Mtoe | 21.2 | 31.7 |
| | Fossil energy | Mtoe | 251.1 | 477.1 |
| | Capital stock | In bil. 2005USD | 5285.8 | 8.5 |
| | Labor force | Thousand people | 65665.0 | 155.9 |
| Desirable output | Real gross domestic product | In bil. 2005USD | 1660.2 | 2.7 |
| Undesirable output | $CO_2$ emissions | Mt | 812.9 | 1622.8 |

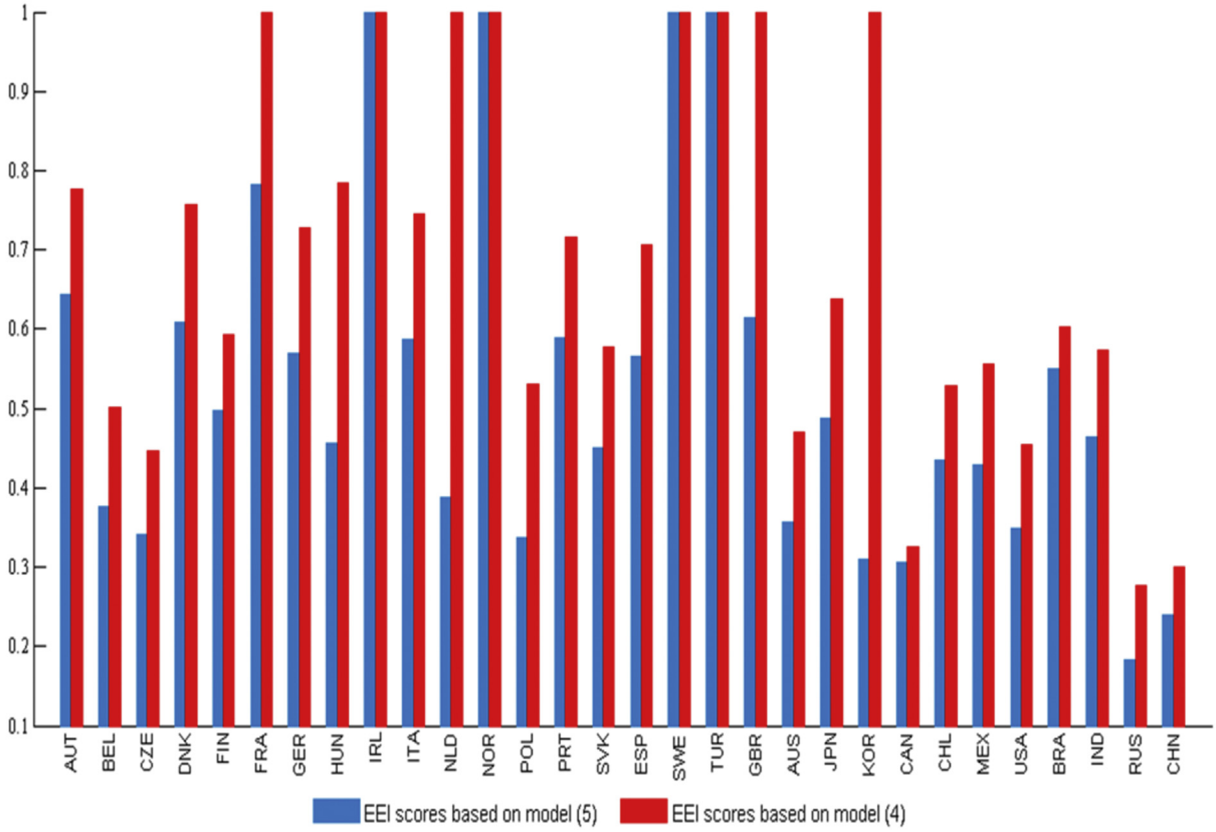

**Fig. 2.** Energy environmental index (EEI) scores for 2011.

[44]. Capital stock and real gross domestic product data were taken from Penn World Table 8.0 [45].

### 3.2. Results and discussion

#### 3.2.1. Effect of renewable energy as an energy input indicator on evaluation results

Fig. 2 shows the EEI country scores for 2011 calculated from models (4) and (5)[6]. Note that $EEI_5 \leq EEI_4$ for every country, which is consistent with the theoretical analysis in Section 2.3. Indeed, $EEI_5 < EEI_4$ except Ireland, Norway, Turkey, and Sweden. This could be attributed to the practical renewable energy consumption of these countries being less than that of corresponding benchmark points. Table 2 shows the renewable energy consumption of benchmark points and practical consumption for 2011. The renewable energy consumption of most countries is significantly less than that of corresponding benchmark points, i.e., most countries cannot achieve fossil energy consumption and $CO_2$ emissions of corresponding benchmark points with under their current renewable energy consumption. Therefore, the current performance of these countries in fossil energy saving and $CO_2$ emissions reduction are underestimated. Thus, renewable energy must be included as an energy input for accurate objective evaluation of current performance.

Spearman's correlation analysis was used to compare EEI score rankings from the two models, with correlation coefficient 0.826 and significant correlation at the 1% level. This indicates there is no significant difference in ranking between the models. Thus, although model (5) underestimates the current performance of many countries, this has little effect on performance ranking.

#### 3.2.2. Fossil energy saving and $CO_2$ emissions reduction performance

Table 3 shows the EEI scores for the 30 selected countries from 2002 to 2011. There are significant differences among the countries. The scores for France, Norway and Ireland are 1, and United Kingdom and South Korea have the largest scores except two years and one year, respectively. On the other hand, Canada, Russian, and China have the lowest scores. Although developed countries have,

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[6] The same analysis results can be attained by EEI scores for other years.

**Table 2**
Renewable energy consumption of benchmark points and practical consumption for 2011 based on model (5).

| Countries | PREC | RECBP | Countries | PREC | RECBP |
|---|---|---|---|---|---|
| AUT | 9.24 | 29.42 | ESP | 19.51 | 116.28 |
| BEL | 2.26 | 34.57 | SWE | 19.08 | 19.08 |
| CZE | 1.61 | 23.49 | TUR | 13.18 | 13.18 |
| DNK | 3.23 | 17.61 | GBR | 7.81 | 189.41 |
| FIN | 5.44 | 16.97 | AUS | 5.58 | 83.78 |
| FRA | 14.69 | 186.91 | JPN | 26.79 | 389.25 |
| GER | 28.01 | 280.71 | KOR | 1.73 | 139.62 |
| HUN | 0.61 | 15.84 | CAN | 89.07 | 121.58 |
| IRL | 1.23 | 1.23 | CHL | 5.87 | 22.74 |
| ITA | 18.77 | 161.30 | MEX | 10.52 | 139.96 |
| NLD | 2.79 | 62.33 | USA | 118.02 | 1288.42 |
| NOR | 28.03 | 28.03 | BRA | 105.94 | 170.72 |
| POL | 2.97 | 65.52 | IND | 39.02 | 346.61 |
| PRT | 5.55 | 20.94 | RUS | 37.42 | 204.02 |
| SVK | 1.11 | 10.40 | CHN | 182.80 | 1223.82 |

Note: PREC denotes practical renewable energy consumption. RECBP denotes renewable energy consumption of benchmark points.

**Table 3**
Energy environmental index scores of the 26 OECD and BRIC countries for 2002–2011.

| Regions | Countries | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| OECD EU | AUT | 0.7876 | 0.7474 | 0.7536 | 0.7502 | 0.7499 | 0.8000 | 0.8014 | 0.8055 | 0.7660 | 0.7755 |
| | BEL | 1.0000 | 0.5442 | 0.5637 | 0.6503 | 0.5587 | 0.5304 | 0.5350 | 0.5356 | 0.4892 | 0.5016 |
| | CZE | 0.4226 | 0.4165 | 0.4047 | 0.4263 | 0.4310 | 0.4490 | 0.5219 | 0.5001 | 0.4729 | 0.4475 |
| | DNK | 0.7503 | 0.7005 | 0.7673 | 0.8051 | 0.7061 | 0.7428 | 0.7685 | 0.7654 | 0.7487 | 0.7561 |
| | FIN | 0.5351 | 0.4882 | 0.5242 | 0.6266 | 0.5477 | 0.5786 | 0.6301 | 0.5994 | 0.5447 | 0.5931 |
| | FRA | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | GER | 0.8019 | 0.7564 | 0.7472 | 0.7441 | 0.7244 | 0.7460 | 0.7634 | 0.7545 | 0.7528 | 0.7284 |
| | HUN | 1.0000 | 1.0000 | 1.0000 | 0.6065 | 0.8055 | 0.7018 | 0.7009 | 0.6805 | 0.6383 | 0.7836 |
| | IRL | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | ITA | 0.8655 | 0.8210 | 0.8046 | 0.7930 | 0.7829 | 0.7843 | 0.7886 | 0.7953 | 0.7911 | 0.7456 |
| | NLD | 0.7754 | 0.5819 | 0.5610 | 0.5497 | 0.5489 | 0.6076 | 0.6406 | 0.6084 | 0.5784 | 1.0000 |
| | NOR | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | POL | 0.4592 | 0.4347 | 0.6489 | 0.6286 | 0.6197 | 0.5645 | 0.5762 | 0.5791 | 0.5214 | 0.5312 |
| | PRT | 0.7348 | 0.7513 | 0.7424 | 0.7101 | 0.7370 | 0.7353 | 0.7650 | 0.7425 | 0.7731 | 0.7159 |
| | SVK | 0.4076 | 0.4404 | 0.4663 | 0.4651 | 0.5082 | 0.5750 | 0.5981 | 0.5950 | 0.5830 | 0.5777 |
| | ESP | 0.7372 | 0.7271 | 0.7035 | 0.6916 | 0.6987 | 0.6758 | 0.7197 | 0.7514 | 0.8027 | 0.7056 |
| | SWE | 0.9514 | 0.9147 | 0.8978 | 0.9456 | 0.9547 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | TUR | 0.8016 | 0.7512 | 0.7652 | 0.7922 | 0.7192 | 0.6774 | 0.6906 | 0.6246 | 1.0000 | 1.0000 |
| | GBR | 1.0000 | 0.9209 | 0.9180 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | **Mean** | **0.7911** | **0.7367** | **0.7510** | **0.7466** | **0.7417** | **0.7457** | **0.7632** | **0.7546** | **0.7612** | **0.7822** |
| | **S.D.** | **0.2055** | **0.2050** | **0.1881** | **0.1805** | **0.1820** | **0.1799** | **0.1665** | **0.1736** | **0.1954** | **0.1942** |
| OECD AO | AUS | 0.4943 | 0.5113 | 0.5043 | 0.4894 | 0.4631 | 0.4668 | 0.4838 | 0.4958 | 0.5024 | 0.4702 |
| | JPN | 0.7585 | 0.7196 | 0.7220 | 0.7072 | 0.7385 | 0.8166 | 0.6965 | 0.7268 | 0.7083 | 0.6382 |
| | KOR | 1.0000 | 0.6321 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| | **Mean** | **0.7509** | **0.6210** | **0.7421** | **0.7322** | **0.7339** | **0.7611** | **0.7268** | **0.7409** | **0.7369** | **0.7028** |
| | **S.D.** | **0.2529** | **0.1046** | **0.2485** | **0.2562** | **0.2685** | **0.2709** | **0.2594** | **0.2524** | **0.2500** | **0.2707** |
| OECD AM | CAN | 0.3443 | 0.3252 | 0.3269 | 0.3405 | 0.3337 | 0.3347 | 0.3476 | 0.3447 | 0.3439 | 0.3258 |
| | CHL | 0.6120 | 0.6065 | 0.5941 | 0.6206 | 0.5675 | 0.5593 | 0.5847 | 0.5676 | 0.6097 | 0.5286 |
| | MEX | 0.8207 | 0.7095 | 0.7004 | 0.6530 | 0.6416 | 0.6497 | 0.6647 | 0.6070 | 0.6139 | 0.5556 |
| | USA | 0.5048 | 0.4924 | 0.4863 | 0.4947 | 0.4903 | 0.4787 | 0.4938 | 0.5127 | 0.4864 | 0.4534 |
| | **Mean** | **0.5705** | **0.5334** | **0.5269** | **0.5272** | **0.5083** | **0.5056** | **0.5227** | **0.5080** | **0.5135** | **0.4659** |
| | **S.D.** | **0.1998** | **0.1647** | **0.1594** | **0.1420** | **0.1318** | **0.1336** | **0.1360** | **0.1155** | **0.1276** | **0.1029** |
| BRIC | BRA | 0.7401 | 0.7344 | 0.7158 | 0.7291 | 0.7042 | 0.7928 | 0.6904 | 0.6959 | 0.6562 | 0.6021 |
| | IND | 0.6365 | 0.6424 | 0.6301 | 0.6427 | 0.6338 | 0.6301 | 0.6135 | 0.5917 | 0.6228 | 0.5742 |
| | RUS | 0.1966 | 0.2088 | 0.2179 | 0.2312 | 0.2308 | 0.2437 | 0.2553 | 0.2449 | 0.2457 | 0.2758 |
| | CHN | 0.3394 | 0.3221 | 0.2964 | 0.2823 | 0.2797 | 0.2857 | 0.3045 | 0.3134 | 0.3245 | 0.2996 |
| | **Mean** | **0.4782** | **0.4769** | **0.4651** | **0.4713** | **0.4621** | **0.4881** | **0.4659** | **0.4615** | **0.4623** | **0.4379** |
| | **S.D.** | **0.2531** | **0.2514** | **0.2447** | **0.2511** | **0.2414** | **0.2669** | **0.2180** | **0.2166** | **0.2076** | **0.1741** |

in principle, technological and funding advantages over the less developed countries, EEI scores for Czech, Slovak, Australia, Canada, and United States are generally lower than for Turkey, Mexico, Chile, and Brazil. Turkey and Brazil also have better fossil energy saving and $CO_2$ emissions reduction than other developing countries.

The reasons may be due to national differences in production technology, renewable energy development, and resources endowment. Most developed countries have more advanced production technology that makes it easier to use less fossil energy, realizing more economic outputs with less environmental impact. In terms of renewable energy development, France, South Korea, and Brazil had policies in place for feed-in tariffs, tax incentives, and investment grants for developing renewable energy over the observed years, whereas Canada only instigated similar policies after 2005, and Russia had no relevant policies before 2011 [46]. France, United Kingdom, and Brazil spent \$200 M, \$257 M, and \$261 M, respectively, on renewable energy RD&D[7] in 2010, the largest amongst the 30 countries. From the perspective of energy endowment, Canada, United States, Russia, and China have enormous proven reserves of fossil energy [2]. Accordingly, these countries paid less attention to reduce fossil energy use in the long term, whereas those countries largely importing fossil energy have strong focus on fossil energy saving and renewable energy development, e.g. Turkey imports most of its fossil fuels, while has abundant renewable resources, especially geothermal, wind, and

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[7] According to IEA Guide to Reporting Energy RD&D Budget/Expenditure [47], the concept of renewable energy RD&D differs from R&D, in that: (1) it only focuses on programs related to renewable energy; (2) it includes demonstration projects; (3) it includes state-owned companies. The Data on renewable energy RD&D expenditure are collected from Clean energy Progress Report [46].

hydro [48].

EEI scores may be segregated into four regions that differ significantly. OECD EU countries have the largest average scores. Many OECD EU countries import the bulk of their fossil energy, and have serious environmental problems because of previous excessive fossil energy consumption. Thus, most OECD EU countries have strong focus on energy saving and emissions reduction.

The Intergovernmental Panel on Climate Change [1] reported that exploitation of renewable resources has been an important means to alleviate dependence on fossil energy and reduce $CO_2$ emissions. Table 4 shows Pearson correlation analysis for the proportion of renewable energy use against the performance of fossil energy saving and $CO_2$ emissions reduction. All p-values are larger than 0.05. Thus, the null hypothesis: there is no significant correlation between EEI scores and proportion of renewable energy, was accepted at the 5% significance level. This indicates that only replacing renewable energy for fossil energy is unable to achieve optimal energy saving and emissions reduction performance. Technical and management improvement should be considered.

Fig. 3 shows the 30 countries divided into four types according to their proportion of renewable energy consumption and EEI scores, to assist in developing specific strategies for energy saving and emissions reduction.

- Type 1 denotes high proportion and score, and includes Austria, Brazil, Norway, Portugal, and Sweden. Compared to other countries, these countries realize practical coordination between renewable energy development and energy saving and emissions reduction, and should maintain this condition. These countries belong to the OECD EU, aside from Brazil, which confirms that OECD EU countries have made significant contributions to sustainable development. Brazil, as a developing country, outperforms many developed countries. Its development mode is worth reference for other developing countries.
- Type 2 denotes low proportion and high score, and includes Denmark, France, Germany, Hungary, Ireland, Italy, Japan, Korea, Spain, and United Kingdom. These countries have a good performance with a relatively low proportion of renewable energy, which implies they have advanced technology and management that offset the deficiency of low proportion. To further improve performance, they should increase the rate of adjustment of their energy structure.
- Type 3 denotes low proportion and score, and includes Australia, Belgium, China, Czech, India, Mexico, Netherlands, Poland, Russia, and Slovak. To augment their performance, these countries not only need to introduce new technology and management ideologies, but also make more effort to facilitate energy saving and emissions reduction.
- Type 4 denotes high proportion and low score, and includes Canada, Chile, and Finland. Although these countries have high renewable energy proportion, their energy saving and emissions reduction performance is unsatisfying. Hence, technology and management should be focused upon to improve their performance.

**Table 4**
The results of Pearson correlation analysis.

| Time | Correlation coefficient | p-value |
|---|---|---|
| 2002 | 0.108 | 0.570 |
| 2003 | 0.242 | 0.197 |
| 2004 | 0.169 | 0.371 |
| 2005 | 0.239 | 0.272 |
| 2006 | 0.209 | 0.268 |
| 2007 | 0.275 | 0.141 |
| 2008 | 0.255 | 0.174 |
| 2009 | 0.271 | 0.147 |
| 2010 | 0.270 | 0.149 |
| 2011 | 0.204 | 0.280 |

### 3.2.3. *Dynamic change in fossil energy saving and $CO_2$ emissions reduction performance*

Table 5 shows the non-radial Malmquist index (NMI) of the selected countries from 2002/2003 to 2010/2011, obtained using Eq. (6). Every country shows at least one period with NMI greater than 1. Nineteen countries have geometric mean NMI larger than 1, and there are 7 periods where the frequency of NMI larger than 1 exceed half number of selected countries, excluding 2002/2003 and 2009/2010. These imply every country tried its best to improve energy saving and emissions reduction performance over the observed periods. United States, Russia and Slovak have NMI >1 for 8 periods, the maximum among the countries, whereas Hungary and Norway have NMI >1 only twice. A possible explanation may be that the low EEI for United States, Russia, and Slovak make it easier to improve performance, whereas it is difficult for Norway and Hungary to further improve performance because their EEI is already large.

None of the four regions have the largest or smallest NMI over the observed periods. Specifically, BRIC countries have 8 times average NMI >1, the most often of the four regions. OECD EU countries is 6 times that are the same as OECD AO, followed by OECD AM countries, 5 times. As can be seen, BRIC countries made more contribution to performance improvement in energy saving and emissions reduction. Although OECD countries have had a good energy and environmental performance, they were still working to enhance the performance. Energy technologies have been promoted heavily with economic development of BRIC countries, and they are also changing their previous economic models. OECD EU countries are the main advocates of the Kyoto Protocol and have been devoted to climate change mitigation.

### 3.2.4. *Technological change and efficiency change analysis*

NMI can be decomposed into technological change (TECH) and efficiency change (EFFCH) using Eqs. (7) and (8). Four situations were defined for the same period:

- Situation 1: TECH $>1$ and EFFCH $<1$;
- Situation 2: TECH $<1$ and EFFCH $>1$;
- Situation 3: TECH $>1$ and EFFCH $>1$;
- Situation 4: TECH $\leq 1$ and EFFCH $\leq 1$.

Fig. 4 shows the situation frequency of occurrence from 2002/2003 to 2010/2011 period. Twenty-three countries have situations 1 and 2 occurrence exceeding half the number of observed periods. For Finland, Ireland, Sweden, and United Kingdom, the frequency of situations 1 and 2 account for approximately 1/3 of the periods, the least among the countries. The average frequency of situations 1 and 2 is 5.7 occurrences over the 9 periods. In contrast, situation 3 occurs for just 2.1 periods on average. Thus, technological progress and efficiency improvement are generally out of sync within the same period. Since Malmquist index theory holds that both technological change and efficiency change impact dynamic change in fossil energy saving and $CO_2$ emissions reduction performance, the situations 1 and 2 seem to be conducive to performance enhencement.

Fig. 5 shows the frequency of technological progress (TECH $> 1$), technological regression (TECH $< 1$), efficiency improvement (EFFCH $> 1$) and efficiency decline (EFFCH $< 1$) for each country from 2002/2003 to 2010/2011. Of the 30 countries, 25 showed technological progress in most of the observed periods. There were

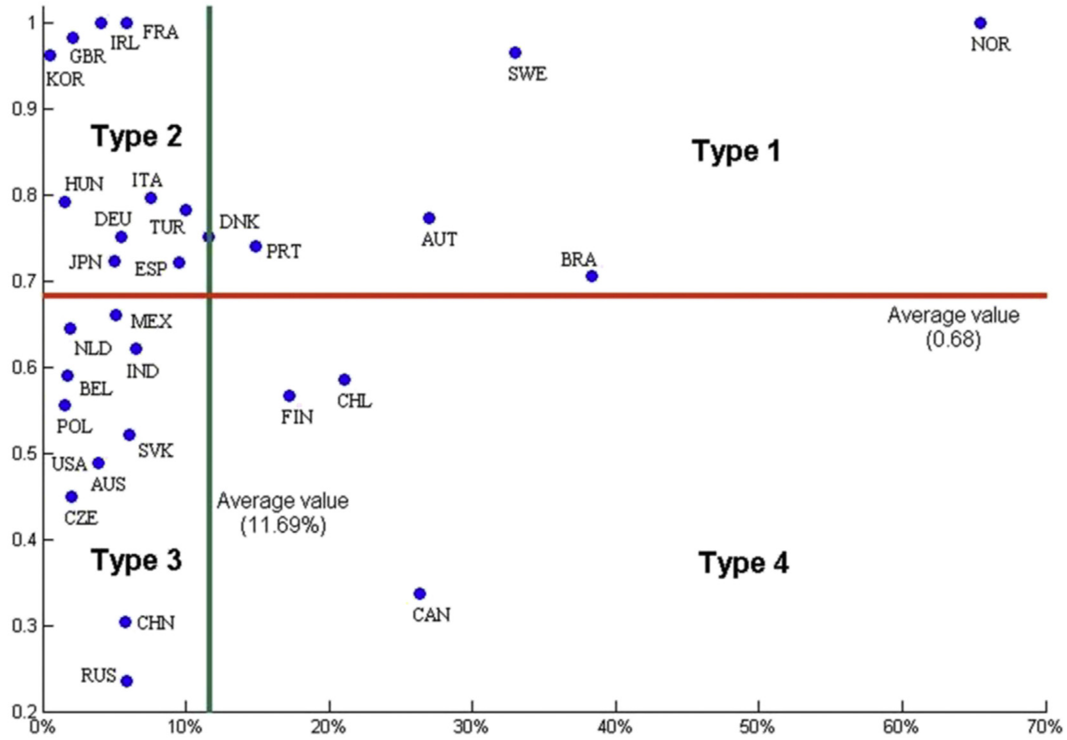

**Fig. 3.** Country distribution based on average proportion of renewable energy and energy environmental index scores for 2002–2011.

**Table 5**
Non-radial Malmquist index of the selected countries from 2002/2003 to 2010/2011 period.

| Regions | Countries | 02/03 | 03/04 | 04/05 | 05/06 | 06/07 | 07/08 | 08/09 | 09/10 | 10/11 | Geometric mean | Frequency |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OECD | AUT | 0.9499 | 1.0294 | 1.0024 | 1.0485 | 1.0913 | 1.0020 | 1.0229 | 0.9561 | 1.0879 | 1.0201 | 7 |
| EU | BEL | 0.9991 | 0.9749 | 1.0312 | 0.8260 | 0.9571 | 0.9403 | 1.0232 | 0.9247 | 1.0612 | 0.9685 | 3 |
| | CZE | 1.0469 | 1.0004 | 1.0680 | 1.0516 | 1.0668 | 1.0611 | 0.9454 | 0.9612 | 1.0007 | 1.0215 | 7 |
| | DNK | 0.9232 | 1.1118 | 1.0735 | 0.9124 | 1.0880 | 1.0330 | 1.0091 | 0.9792 | 1.0982 | 1.0229 | 6 |
| | FIN | 0.9108 | 1.0961 | 1.2029 | 0.9162 | 1.0824 | 1.0892 | 0.9678 | 0.9127 | 1.1773 | 1.0338 | 5 |
| | FRA | 0.9871 | 1.0143 | 1.0363 | 1.0284 | 1.0095 | 0.9993 | 1.0127 | 0.9377 | 1.1636 | 1.0194 | 6 |
| | GER | 0.9905 | 1.0128 | 1.0195 | 1.0082 | 1.0623 | 1.0170 | 1.0039 | 0.9953 | 1.0625 | 1.0188 | 7 |
| | HUN | 0.9509 | 0.7601 | 0.8129 | 1.2834 | 0.8862 | 0.9160 | 0.9488 | 0.9584 | 1.1698 | 0.9534 | 2 |
| | IRL | 1.0000 | 1.0000 | 0.9801 | 1.0161 | 1.0041 | 0.9566 | 1.0070 | 1.0133 | 1.0244 | 1.0000 | 5 |
| | ITA | 0.9612 | 1.0025 | 1.0092 | 1.0310 | 1.0370 | 0.9976 | 1.0205 | 0.9957 | 1.0320 | 1.0094 | 6 |
| | NLD | 1.0169 | 0.8819 | 0.9244 | 1.0323 | 1.1042 | 1.0094 | 0.9595 | 0.9659 | 1.0363 | 0.9903 | 5 |
| | NOR | 0.9468 | 1.0592 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.9982 | 1.0018 | 1.0000 | 1.0003 | 2 |
| | POL | 1.0295 | 1.3173 | 0.8625 | 1.0027 | 0.9215 | 0.9498 | 0.9957 | 0.9006 | 0.9727 | 0.9878 | 3 |
| | PRT | 1.0136 | 1.0041 | 0.9797 | 1.0797 | 1.0298 | 1.0409 | 0.9859 | 1.0443 | 1.0024 | 1.0196 | 7 |
| | SVK | 1.0767 | 1.0780 | 1.0165 | 1.1400 | 1.1641 | 1.0328 | 1.0183 | 0.9783 | 1.0923 | 1.0648 | 8 |
| | ESP | 0.9806 | 0.9819 | 1.0079 | 1.0497 | 1.0013 | 1.0655 | 1.0599 | 1.0588 | 0.9655 | 1.0184 | 6 |
| | SWE | 1.0126 | 1.0169 | 1.0237 | 1.0606 | 1.0482 | 0.9643 | 1.0045 | 0.9928 | 1.1290 | 1.0271 | 7 |
| | TUR | 0.9855 | 1.0502 | 1.0405 | 0.9525 | 0.9622 | 0.9785 | 0.8850 | 1.0920 | 1.0384 | 0.9965 | 4 |
| | GBR | 1.0216 | 0.9003 | 0.9994 | 0.9989 | 1.0567 | 0.9961 | 1.0071 | 0.9735 | 1.0452 | 0.9989 | 4 |
| | **Mean** | **0.9896** | **1.0154** | **1.0048** | **1.0231** | **1.0301** | **1.0026** | **0.9934** | **0.9812** | **1.0610** | | **6** |
| OECD | AUS | 1.0577 | 1.0087 | 0.9931 | 0.9880 | 1.0419 | 1.0224 | 1.0528 | 1.0087 | 1.0255 | 1.0218 | 7 |
| AO | JPN | 0.9642 | 1.0033 | 0.9897 | 1.0777 | 1.0786 | 0.9382 | 1.0686 | 0.9709 | 0.9892 | 1.0077 | 4 |
| | KOR | 0.8879 | 1.1022 | 1.2273 | 1.1555 | 0.9615 | 1.1037 | 0.9281 | 0.7748 | 0.8663 | 0.9905 | 4 |
| | **Mean** | **0.9699** | **1.0380** | **1.0700** | **1.0738** | **1.0273** | **1.0214** | **1.0165** | **0.9182** | **0.9603** | | **6** |
| OECD | CAN | 0.9899 | 1.0429 | 1.0043 | 1.0532 | 0.9974 | 1.0229 | 1.0248 | 1.0114 | 1.0027 | 1.0164 | 7 |
| AM | CHL | 1.0199 | 1.0065 | 1.0437 | 0.9648 | 1.0026 | 1.0394 | 0.9891 | 1.0776 | 0.9487 | 1.0095 | 6 |
| | MEX | 0.9260 | 1.0096 | 0.9491 | 1.0248 | 0.9923 | 1.0786 | 0.9356 | 1.0085 | 0.9990 | 0.9905 | 4 |
| | USA | 1.0251 | 1.0191 | 1.0311 | 1.0405 | 1.0047 | 1.0208 | 1.0477 | 0.9671 | 1.0360 | 1.0211 | 8 |
| | **Mean** | **0.9902** | **1.0195** | **1.0071** | **1.0208** | **0.9993** | **1.0404** | **0.9993** | **1.0162** | **0.9966** | | **5** |
| BRIC | BRA | 1.0073 | 1.0039 | 1.0034 | 1.0256 | 1.0630 | 0.9280 | 1.0057 | 0.9529 | 0.9778 | 0.9957 | 6 |
| | IND | 1.0509 | 1.0077 | 1.0321 | 1.0316 | 1.0189 | 0.9644 | 0.9948 | 1.0476 | 0.7618 | 0.9858 | 6 |
| | RUS | 1.0582 | 1.0634 | 1.0761 | 1.0426 | 1.0869 | 1.0475 | 0.9731 | 1.0056 | 1.1090 | 1.0507 | 8 |
| | CHN | 0.9423 | 0.9350 | 0.9735 | 1.0314 | 1.0551 | 1.0620 | 1.0419 | 1.0363 | 1.0061 | 1.0082 | 6 |
| | **Mean** | **1.0147** | **1.0025** | **1.0213** | **1.0328** | **1.0560** | **1.0005** | **1.0039** | **1.0106** | **0.9637** | | **8** |
| Total | **Mean** | **0.9911** | **1.0165** | **1.0138** | **1.0291** | **1.0292** | **1.0092** | **0.9979** | **0.9835** | **1.0294** | | **6** |
| | Frequency | 13 | 23 | 19 | 22 | 22 | 17 | 17 | 12 | 21 | 19 | |

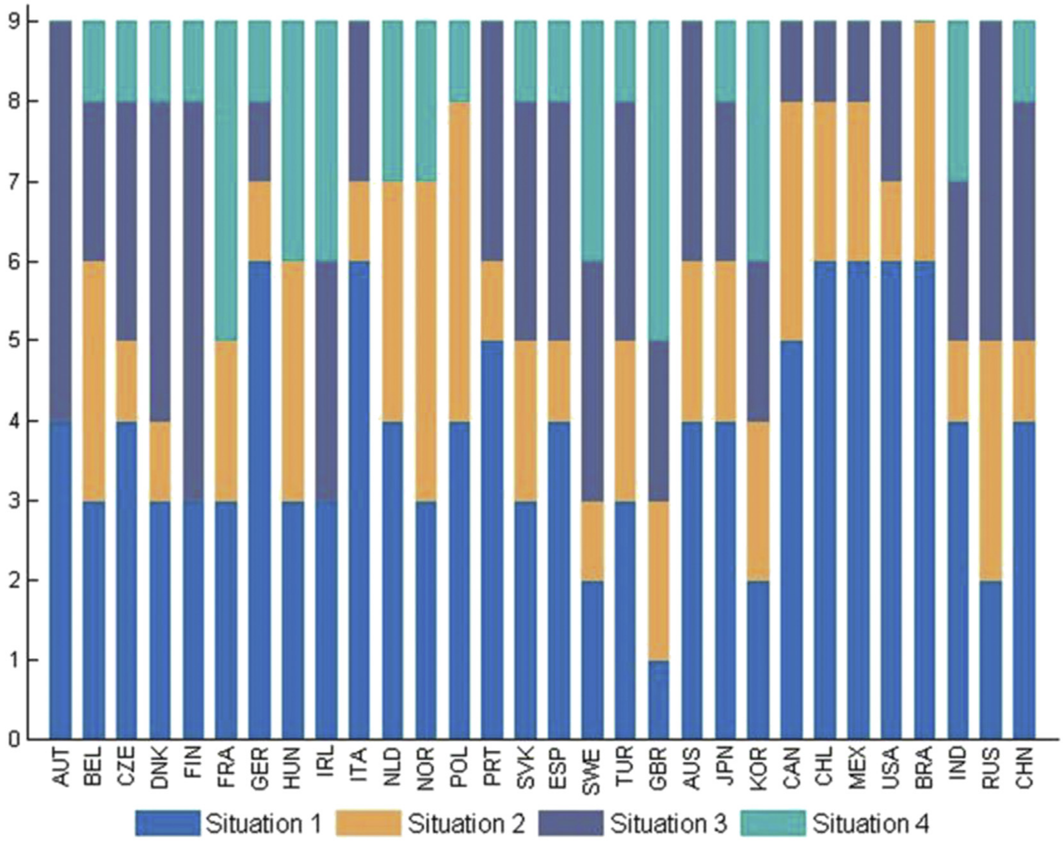

**Fig. 4.** Frequency of the four situations occurrence from 2002/2003 to 2010/2011 period. Note: situation 1 denotes TECH >1 and EFFCH <1; situation 2 denotes TECH <1 and EFFCH >1; situation 3 denotes TECH >1 and EFFCH >1; situation 4 denotes TECH $\leq$1 and EFFCH $\leq$1.

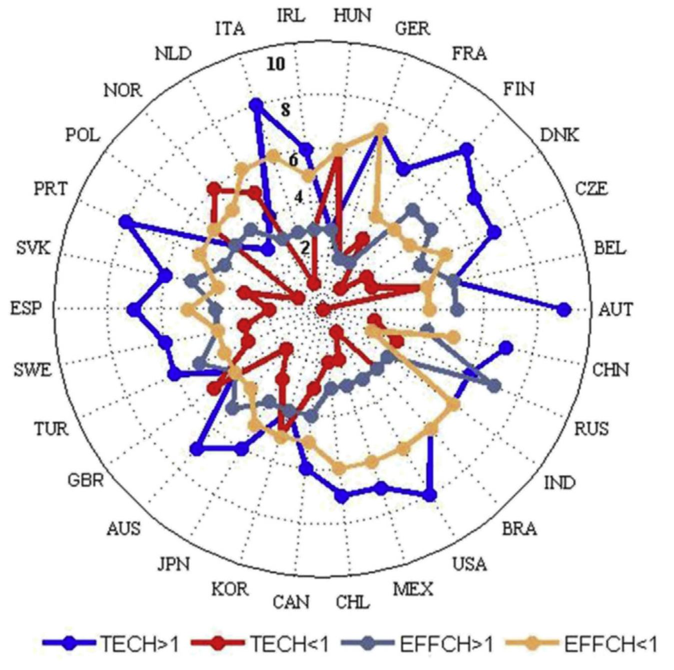

**Fig. 5.** Frequency of technological change (TECH) and efficiency change (EFFCH) from 2002/2003 to 2010/2011 period.

6.1 periods, on average, where countries realized technological progress. This indicates it is not difficult for countries to achieve a forward shift of the best practice frontier. Conversely, generally efficiency change of countries is not satisfying. Only 8 countries achieve efficiency improvement for most of the observed periods. The average frequency of efficiency decline was 4.9 of 9 periods.

Thus, efficiency improvement for most countries is not easily achieved, and the main cause of the out-of-sync between technological progress and efficiency improvement is the difficultly to achieve efficiency improvement. According to Xie et al. [40], the efficiency change reflects the change in efforts to catch up with the most advanced technology and management between two periods. Accordingly, efficiency decline means that the most advanced technology and management are not well extended. Therefore, countries should accelerate the introduction of new technology and management improvements to realize efficiency improvements.

## 4. Conclusions

This paper proposes energy environmental and non-radial Malmquist indexes based on a non-radial DDF to evaluate fossil energy saving and $CO_2$ emissions reduction performance and dynamic change in performance for 26 OECD and BRIC countries from 2002 to 2011. In contrast to existing approaches, renewable energy was explicitly included as an energy input. The necessity of this approach was theoretically analyzed, and verified by the empirical study.

Fossil energy saving and $CO_2$ emissions reduction performance of most countries is underestimated when renewable energy inputs are not considered. However, the underestimation has little influence on country performance ranking.

There is also no significant correlation between the proportion of renewable energy consumption and fossil energy saving and $CO_2$ emissions reduction. The 30 countries can be divided into 4 groups based on their performance and proportion of renewable energy consumption. Each country grouping should adopt different strategies to realize better energy saving and emission reduction.

Technological progress and efficiency improvement are generally out of synch within the same time period, which is conducive to performance enhencement. The main cause for this lack of synch is the difficultly to achieve efficiency improvement. Accordingly, policymakers should concentrate on increasing advanced technology uptake and improved management to more closely sync technology and efficiency, and thereby realize a better fossil energy and $CO_2$ emissions reduction performance.

It should be noted that this study does not evaluate fossil energy saving and $CO_2$ emissions rudction performance after 2011 due to the restriction of capital stock data. In addition, the results in this paper lack statistical inference because of the conceptual limits of the DEA approach. These issues will be addressed in the future research.

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