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A Comparative Study of Different Energy Efficiency of OECD and Non-OECD Countries

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Abstract

Greater and greater attention is being paid to air pollution problems, because of their negative impact on the environment and human health. This article measures energy efficiency, carbon dioxide emissions efficiency, and particulate matter ($PM_{2.5}$) concentration efficiency to compare the energy efficiency differences between Organisation for Economic Co-operation and Development (OECD) member countries and non-OECD member countries from 2010 to 2014 using a metafrontier dynamic Data Envelopment Analysis model. We calculate technology gap ratio and input and output efficiency values to measure the energy efficiencies of each economy, finding that (a) OECD countries have a technology gap ratio of 1 or very close to 1; and except for the United Arab Emirates and Singapore, both of which exhibit annual improvements, the non-OECD countries have a significant need for efficiency improvements; (b) the average technology gap ratio of OECD is higher than that of non-OECD countries; that is, while OECD countries' technology gap ratio (TGR) changes are relatively stable, non-OECD countries' TGRs are gradually increasing; (c) non-OECD countries have large $PM_{2.5}$ concentration efficiency gaps, with the annual efficiencies in China, India, and Nepal being less than 0.2; (d) Switzerland, Denmark, France, the United Kingdom, Iceland, Luxembourg, Norway, the United States, and the United Arab Emirates all have new and traditional energy efficiency values of 1; and (e) Botswana, Algeria, and Cambodia have poor traditional energy efficiencies, but better new energy efficiencies, whereas Hungary, South Korea, Slovakia, and Slovenia have poor new energy efficiencies and better traditional energy efficiencies.

Keywords
energy efficiency, performance, OECD countries, technology gap, dynamic DEA

Introduction

The 20th century saw the most significant rise in global warming in recent human history, primarily due to the rapid increase in industry and mass-produced manufactured goods, rises in animal husbandry, and massive population increases. Due to the growing global concerns first highlighted in the 1970s, in 1988, the Intergovernmental Panel on Climate Change was finally established with the aim of gaining global agreements on emissions reductions. The Intergovernmental Panel on Climate Change fifth assessment report in 2013 stated from 1880 to 2012 that the global average surface temperature had risen by about 0.85°C, primarily because of the large amounts of greenhouse gases such as carbon dioxide (CO_2) and methane, 75% of which were found to be a direct result of human activities from the combustion of fossil fuels, methane emissions from coal and natural gas production processes, landfills, ruminants, rice farming, and biomass burning. To achieve greenhouse gas reduction targets, the United Nations Framework Convention on Climate Change

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established the Kyoto Protocol at the Third Conference of States Parties held in Kyoto, Japan in 1997 in an attempt to mitigate the greenhouse effects and the consequential climate change impacts. Even though there was a specification to control total global carbon emissions within a certain limit, because of unstable international political and economic situations, a consensus could not be reached at the 2009 Copenhagen Climate Conference (COP15) except to extend the Kyoto Protocol to 2012 and establish a new climate treaty.

Under pressure from the international community, the validity of the Kyoto Protocol was again extended to 2020, but in 2015, the Paris Agreement replaced the Kyoto Protocol at the United Nations Climate Summit. Because air pollution has also been recognized as having a disastrous effect on the environment and human health, the United States adopted Clean Air Act Amendments in 1990 that required states and local governments to monitor air pollution, and the U.S. Environmental Protection Agency developed an air quality index to assess air quality. Over time, there has been a general agreement to lower global greenhouse gas emissions by reducing fossil fuel use, improving energy efficiencies, and developing new renewable energy sources.

Environmental energy efficiency analyses have been conducted on regional economies and on Organisation for Economic Co-operation and Development (OECD) and European Union (EU) members, with the focus on environmental energy efficiency comparisons, energy impacts, and environmental efficiency factors. To compare environmental energy efficiencies, Färe, Grosskopf, Norris, and Zhang (1994) used the Malmquist Productivity Index to classify production efficiency into technological changes and efficiency changes, which was then applied to 17 OECD countries between 1979 and 1988, finding that technological changes resulted in higher productivity growth rates in the United States, and efficiency changes brought about higher productivity growth rates in Japan. Zofı́o and Prieto (2001) used a Data Envelopment Analysis (DEA) method to study environmental efficiencies in 14 OECD countries from 1990 to 1995. Zhou, Poh, and Ang (2007) employed a nonoriented DEA model to measure environmental carbon emissions performances and the efficiency of nonincreasing returns and variable returns, dividing the research objects into eight regions: OECD member countries, the Middle East, former Soviet Union countries, European non-OECD member countries, China, other Asian countries, Latin America, and Africa.

Bampatsou, Papadopoulos, and Zervas (2013) analyzed cross-sectional data from 15 EU countries from 1980 to 2008 using the Technical efficiency (TE) Index to measure energy efficiency. Makridou, Andriosopoulos, Doumpos, and Zopounidis (2015) assessed the energy efficiency in EU countries from 2000 to 2010, utilizing a combined nonparametric DEA and multiple criteria decision aiding approach to provide energy efficiency estimates. Cantore, Calì, and Te Velde (2016) used a large manufacturing sample data set from 29 developing countries to analyze energy efficiency and found that the low-energy intensities in most of these countries are associated with high total factor productivity. Suzuki and Nijkamp (2016) developed an extended DEA to assess energy sustainability and environmental and economic efficiencies in the EU, Asia-Pacific Economic Cooperation countries, and Association of South East Asian Nations, presenting that the EU countries as a whole have greater efficiencies than those of Association of South East Asian Nations. Makridou, Andriosopoulos, Doumpos, and Zopounidis (2016) used DEA to assess the energy efficiency trends in five energy-intensive industries in 23 EU countries from 2000 to 2009 and found compared with 2000 that the efficiencies in all sectors had improved by 2009. Guo, Lu, Lee, and Chiu (2017) utilized a dynamic DEA model to assess the intertemporal efficiency in OECD countries, finding that most countries have improved efficiencies. To identify the factors associated with energy and environmental efficiencies, Parker and Liddle (2016) assessed the impact of OECD manufacturing prices on energy efficiencies from 1980 to 2009 and concluded that energy efficiency is a major driver for energy intensity reductions and that price increases improve efficiency. Škare and Rabar (2017) used DEA to compare the time series of 30 OECD countries from 2002 to 2011 and employed four different hypothetical models to compare economic, social, and environmental goals, noting that the most frequent inefficiency scores result from gross domestic product (GDP) and that inflation has the least effect on inefficiency.

In addition to economic research, single-country environmental energy efficiency analyses have been conducted in Asia, with the research direction being mainly based on regional energy and environmental efficiency comparisons, the impact of new energy on GDP or CO_2 emissions, and new energy policy assessments (Yu, Jia, You, & Zhang, 2018). Honma and Hu (2008) used DEA for a comparative analysis of regional energy efficiency, environmental efficiency, and Target Fabric Energy Efficiency in 47 metropolitan areas in Japan from 1993 to 2003, presenting that the inland sea and coastal areas are more energy efficient than the Pacific coast areas. Sueyoshi and Goto (2011) compared a newly proposed energy performance assessment method with other previous DEA methods to measure the uniform efficiencies of Japan's fossil fuel power generation, finding that many empirical studies confirmed that the Kyoto Protocol implementation has not been effective at improving Japan's fossil fuel power generation uniform efficiency during the 2004 to 2008 observation period. K. Wang, Wei, and Zhang (2013) set up a new DEA method to assess technology gaps in China and found that the energy efficiency and technology gaps in the eastern, central, and western regions are significantly different, with most Chinese provinces in the east being energy-efficient and having advanced production technologies, while those in the west are the opposite. Zhou, Xing, Fang, Liang, and Xu (2013) proposed a new nonradial DEA method combined with a slacks-based measure (SBM) to evaluate the environmental efficiency of China's power industry in various provinces from 2005 to 2010 and found that the power industry environmental efficiencies across China are significantly different. Bi, Song, Zhou, and Liang (2014) examined total factor energy efficiency without considering the environmental constraints and showed that as environmental efficiency has an important impact on the energy performances of China's thermal power industry, reducing major pollutant emissions could increase energy and environmental efficiencies. Li and Lin (2015) used an improved directional distance function to measure the energy efficiency of CO_2 emissions in 30 Chinese provinces between 1997 and 2011 and found that the efficiencies in the eastern region are the lowest followed by the western and central regions. Goto, Otsuka, and Sueyoshi (2014) noted that Japanese industries need technological innovation to reduce air pollution. Zhang and Xie (2015) used a nonradial directional distance function method to explore renewable energy and sustainable development issues in China from 1991 to 2005 and found that its environmental supervision costs need to be increased. Sueyoshi and Goto (2015) employed DEA to assess Japan's energy efficiency and future possible fuel combinations, with the results showing that (a) fossil fuel production is between 34.5% and 56.1%, (b) hydropower production ranges from 22.4% to 40.5%, (c) nuclear power generation ranges from 10.4% to 13.7%, (d) pumping power generation ranges from 3.9% to 6.9%, and (e) renewable power generation ranges from 3.7% to 8.4%.

Environmental energy performance assessments therefore have primarily focused on energy or environmental efficiency analyses (Wang, Zhao, Shen, & Liu, 2015), the impact of new energy on GDP or CO_2 and new energy policies, and efficiency evaluations, most of which used capital stock, labor, and energy consumption as the inputs and GDP and CO_2 emissions as the outputs. However, there has been less research comparing the energy consumption of new and traditional energy sources. Furthermore, many analyses have employed static comparative analysis, which means that it is not possible to understand whether new energy efficiencies are improving over time or becoming an important energy source. Therefore, this article employs a meta-frontier dynamic DEA (MFD-DEA) model to assess the technology gap ratio and individual variable efficiency values in OECD and non-OECD countries and offers recommendations. The contributions of this article are as the follows: (a) We fill the gap in the literature and use new energy consumption as an input to assess the efficiency of EU countries and non-EU countries and (b) this article adopts a new model, namely, the MFD-DEA model. The model considers time and the efficiency evaluation of each country and compares the different systems of efficiency in each country.

The remainder of this article is organized as follows: The next section details the research methods. Then, the empirical results and the discussions are explained. Finally, the conclusions are presented.

Methods

DEA Method

Farrell (1957) first proposed an efficiency concept that measured the production frontier by dividing production efficiency into TE and allocative efficiency, after which Charnes, Cooper, and Rhodes (1978) developed the CCR model, which was then further modified by Banker, Charnes, and Cooper (1984) into the BCC model. Both the CCR and BCC models measure radial efficiency, which allows for the input or output items to be increased or decreased in equal proportions; however, this assumption is not proven to be applicable in all cases. Consequently, Tone proposed an SBM in 2001 that uses a difference variable as the measurement basis, accounts for the differences between the inputs and outputs (slack), and utilizes a nonradial estimation method and scalar to present SBM efficiency values between 0 and 1.

Malmquist (1953) first developed the Malmquist index to explain the dynamic efficiency, and Färe et al. (1994) extended the concept to measure intertemporal efficiency changes. However, these models did not consider the effects of intertemporal continuation activities and are less suitable for measuring long-term efficiencies. Färe and Grosskopf (1996) first set up a dynamic DEA concept to design a form of dynamic analysis, and then they proposed carryover variables for the dynamic models (Färe & Grosskopf, 1997). Tone and Tsutsui (2010) subsequently extended to a weighted slacks-based dynamic DEA method that includes four types of linking activities: (a) desirable (good), (b) undesirable (bad), (c) discretionary (free), and (d) nondiscretionary (fixed). The basic dynamic DEA model is described in the following.

In the model, there are n decision-making units (DMUs) ($j = 1, 2, \ldots, n$) over T periods ($t = 1, 2, \ldots, T$), with each DMU having multiple different and independent inputs and outputs in each time period, with the z-good being the carryover from period t to period $t+1$.

The nonoriented overall efficiency (δ^*) is calculated using Equation 1, and ω^t and ω_i are the weights for each period t and the inputs:

$$\delta^* = \frac{\frac{1}{T}\sum_{t=1}^{T}\omega^t\left[1-\frac{1}{m+n\text{bad}}\left(\sum_{i=1}^{m}\frac{\omega_i^- s_{ij}^-}{x_{iot}}+\sum_{i=1}^{n\text{bad}}\frac{s_{it}^{\text{bad}}}{z_{iot}^{\text{bad}}}\right)\right]}{\frac{1}{T}\sum_{t=1}^{T}\omega^t\left[1+\frac{1}{s+n\text{good}}\left(\sum_{i=1}^{s}\frac{\omega_i^+ s_{ij}^+}{y_{iot}}+\sum_{i=1}^{n\text{good}}\frac{s_{it}^{\text{good}}}{z_{iot}^{\text{good}}}\right)\right]} \tag{1}$$

s.t.

$$x_{it} \geq \sum_{j=1}^{n} x_{ijt}\lambda_{jt} \ \ (i=1,\ldots,k; t=1,\ldots,T)$$

$$x_{it}^{\text{fix}} = \sum_{j=1}^{n} x_{ijt}^{\text{fix}}\lambda_{jt} \ \ (i=1,\ldots,p; t=1,\ldots,T)$$

$$y_{it} \leq \sum_{j=1}^{n} y_{ijt}\lambda_{jt} \ \ (i=1,\ldots,m; t=1,\ldots,T)$$

$$y_{it}^{\text{fix}} = \sum_{j=1}^{n} y_{ijt}^{\text{fix}}\lambda_{jt} \ \ (i=1,\ldots,r; t=1,\ldots,T)$$

$$z_{it}^{\text{good}} \leq \sum_{j=1}^{n} z_{ijt}^{\text{good}}\lambda_{jt} \ \ (i=1,\ldots,n\text{good}; t=1,\ldots,T)$$

$$z_{it}^{\text{bad}} \geq \sum_{j=1}^{n} z_{ijt}^{\text{bad}}\lambda_{jt} \ \ (i=1,\ldots,n\text{bad}; t=1,\ldots,T)$$

$$z_{it}^{\text{free}} : \text{free} \ \ (i=1,\ldots,n\text{free}; t=1,\ldots,T)$$

$$z_{it}^{\text{fix}} = \sum_{j=1}^{n} z_{ijt}^{\text{fix}}\lambda_{jt} \ \ (i=1,\ldots,n\text{fix}; t=1,\ldots,T)$$

$$\lambda_{jt} \geq 0 \ \ (j=1,\ldots,n; t=1,\ldots,T)$$

$$\sum_{j=1}^{n}\lambda_{jt} = 1 \ \ (t=1,\ldots,T) \tag{2}$$

The nonoriented term efficiency (ρ^*) follows in Equation 3.

$$\rho^* = \frac{1-\frac{1}{m+n\text{bad}}\left(\sum_{i=1}^{m}\frac{\omega_i^- s_{iot}^{-*}}{x_{iot}}+\sum_{i=1}^{n\text{bad}}\frac{s_{iot}^{\text{bad}*}}{z_{iot}^{\text{bad}}}\right)}{1+\frac{1}{s+n\text{good}}\left(\sum_{i=1}^{s}\frac{\omega_i^+ s_{iot}^+}{y_{iot}}+\sum_{i=1}^{n\text{good}}\frac{s_{iot}^{\text{good}*}}{z_{iot}^{\text{good}}}\right)} \tag{3}$$

Metafrontier dynamic DEA

As different countries have different social cultures, economic environments, management models, and production structures, different manufacturers also have different production technologies. Ruttan, Binswanger, Hayami, Wade, and Weber (1978) defined the metafrontier (MF) as an envelope curve that contains the production fronts of all groups that could enable efficiency measurements for the different groups under a common benchmark. Battese and Rao (2002) and Battese, Rao, and O'donnell (2004) then demonstrated that the TE of different groups could be compared using an MF model. Portela and Thanassoulis (2008) proposed a convex MF concept that could account for the technology of all groups, the most advanced technological production levels, and the communication between groups, and it could be further expanded to improve business performance. O'Donnell, Rao, and Battese (2008) proposed an MF model that defined technical efficiencies using an output distance function that could accurately calculate both the group and MF technical efficiencies, finding that the technical level of all groups is superior to the technical level of any one group. Therefore, based on Tone and Tsutsui's (2010) SBM dynamic DEA, O'Donnell et al.'s (2008) MF model, and a weighted SBM MFD-DEA model, we establish the model used herein as follows.

1. Meta-frontier:

Under different management types, resources, regulations, and environmental factors, it is assumed that all units (N) are composed of DMUs ($j=1\ldots n$) over T terms ($t=1\ldots T$) in g groups ($N=N_1+N_2+\cdots+N_G$). At each term, a DMU has m input and s output, respectively. Let x_{iot} ($i=1, 2, \ldots, m$), y_{jot} ($i=1, 2, \ldots, s$) indicate the observed input and output, the DMU being chosen as the most favorable weight to ensure maximum efficiency value. Moreover, z_{iot}^{bad} ($i=1, 2,\ldots,n\text{bad}$; $o=1\ldots .n$; $t=1\ldots .T$) denotes bad link values, where $n$bad is the number of bad links. Here, W^t, w^-, and w^+ are weights to term t, input I, and output I. The MF k for the DMU efficiency is solved using the following linear programming:

$$\text{Min}: \quad \rho^*$$

$$= \frac{\frac{1}{T}\sum_{t=1}^{T}W^t\left[1-\frac{1}{m+n\text{bad}}\left(\begin{array}{c}\sum_{g=1}^{G}\sum_{i=1}^{m}\frac{w_i^- s_{it}^-}{x_{iot}}\\ +\sum_{g=1}^{G}\sum_{i=1}^{n\text{bad}}\frac{s_{it}^{\text{bad}}}{z_{iot}^{\text{bad}}}\end{array}\right)\right]}{\frac{1}{T}\sum_{t=1}^{T}W^t\left[1+\frac{1}{s}\left(\sum_{g=1}^{G}\sum_{i=1}^{s}\frac{w_i^+ s_{it}^+}{y_{iot}}\right)\right]}$$

s.t.

$$\sum_{g=1}^{G}\sum_{\partial=1}^{n} Z_{ijtg}\lambda_{jg}^{t} = \sum_{g=1}^{G}\sum_{\partial=1}^{n} Z_{ijtg}\lambda_{jg}^{t+1}(vi|t = 1\cdots i-1) \quad (4)$$

$$X_{iot} = \sum_{g=1}^{G}\sum_{\partial=1}^{n} X_{ijtg}\lambda_{jg}^{t} + S_{it}(i = 1\cdots m, t = 1\cdots i)$$

$$Y_{iot} = \sum_{g=1}^{G}\sum_{\partial=1}^{n} Y_{ijtg}\lambda_{jg}^{t} - S_{it}^{t}(i = 1\cdots s, t = 1\cdots i)$$

$$Z_{iot}^{\mathrm{bad}} = \sum_{g=1}^{G}\sum_{\partial=1}^{n} Z_{ijtg}^{\mathrm{bad}}\lambda_{jg}^{t} - S_{it}^{t}(i = 1\cdots n\mathrm{bad}; t = 1\cdots i)$$

$$\sum_{g=1}^{G}\sum_{\partial=1}^{n} \lambda_{jg}^{t} = 1(t = 1\cdots i)$$

$$\lambda_{jt} \geq 0, \quad s_{it}^{-} \geq 0, \quad s_{it}^{+} \geq 0, \quad s_{it}^{\mathrm{bad}} \geq 0 \quad (5)$$

Here, s_{it}^{-}, s_{it}^{+}, s_{it}^{bad} are slack variables denoting input excess, output shortfalls, and carryover excess, respectively. Using Equations 4 and 5, the overall TE of the MF(MFE) for all DMUs under the MF is then determined.

2. Group frontier:

All DMUs are divided into g groups. Each DMU under the group frontier (GF) chooses the most favorable final output weight so that the efficiency of the DMUs under the GF can be solved using the following equation:

$$\rho_0^{*g} = \frac{\frac{1}{T}\sum_{t=1}^{T} W^t\left[1 - \frac{1}{m+n\mathrm{bad}}\left(\sum_{i=1}^{m}\frac{w_i^- s_{it}^-}{x_{iot}} + \sum_{i=1}^{n\mathrm{bad}}\frac{s_{it}^{\mathrm{bad}}}{z_{iot}^{\mathrm{bad}}}\right)\right]}{\frac{1}{T}\sum_{t=1}^{T} W^t\left[1 + \frac{1}{s}\left(\sum_{i=1}^{s}\frac{w_i^+ s_{it}^+}{y_{iot}} +\right)\right]} \quad (6)$$

$$\text{s.t.} \quad \sum_{j=1}^{n} z_{ijt}^{\alpha}\lambda_{jt} = \sum_{j=1}^{n} z_{ijt}^{\alpha}\lambda_{j}^{t+1}(\forall i;\ t = 1,\ldots,T-1) \quad (7)$$

$$x_{iot} = \sum_{j=1}^{n} x_{ijt}\lambda_{jt} + s_{it}^{-}(i = 1,\ldots,m;\ t = 1,\ldots,T)$$

$$y_{iot} = \sum_{j=1}^{n} y_{ijt}\lambda_{jt} - s_{it}^{+}(i = 1,\ldots,s;\ t = 1,\ldots,T)$$

$$z_{iot}^{bad} = \sum_{j=1}^{n} z_{iot}^{bad}\lambda_{jt} - s_{it}^{bad}(i = 1,\ldots,nbad;\ t = 1,\ldots,T) \quad (8)$$

$$\sum_{j=1}^{n}\lambda_{it} = 1\ (t = 1,\ldots,T)$$

$$\lambda_{jt} \geq 0, \quad s_{it}^{-} \geq 0, \quad s_{it}^{+} \geq 0, \quad s_{it}^{bad} \geq 0 \quad (9)$$

Here, s_{it}^{-}, s_{it}^{+}, s_{it}^{bad} are slack variables denoting input excess, output shortfalls, and carryover excess, respectively, and W^t, w^-, and w^+ are weights to term t, input I, and output I. Therefore, the TE of the GF is defined the group TE (GFE).

Technology Gap Ratio

As the MF contains the GF for g groups, the MFE is less than the GFE. The ratio value, called the technology gap ratio (TGR), is as follows:

$$\mathrm{TGR} = \frac{\rho^*}{\rho_o^{*g}} = \frac{\mathrm{MFE}}{\mathrm{GFE}} \quad (10)$$

Traditional Energy, New Energy, CO$_2$, PM$_{2.5}$, and GDP Efficiencies

According to Hu and Wang's (2006) total factor energy efficiency indicators, the possible deviations associated with traditional energy efficiency indicators can be overcome. Our study has five main features: traditional energy efficiency, new energy efficiency, CO_2 emissions efficiency, particulate matter ($PM_{2.5}$) concentration efficiency, and GDP efficiency in which i is the region and t is the time.

1. Traditional energy efficiency

By definition, traditional energy efficiency is the ratio of the target traditional energy input to the actual traditional energy input; therefore, the traditional energy efficiency model is defined as follows:

$$\text{Traditional energy efficiency} = \frac{\text{Target Traditional energy input } (i,t)}{\text{Actual Traditional energy input } (i,t)}$$

If the target traditional energy input is equal to the actual input, then the traditional energy efficiency value is 1, indicating that it is efficient; if the target traditional energy input is less than the actual input, then the traditional energy efficiency value is less than 1, indicating that it is inefficient.

2. New energy efficiency

By definition, new energy efficiency is the ratio of the target new energy input to actual new energy input;

therefore, the new energy efficiency model is defined as follows:

$$\text{New energy efficiency} = \frac{\text{Target New energy input} \ \ (i, t)}{\text{Actual New energy input} \ \ (i, t)}$$

If the target new energy input is equal to the actual input, then the new energy efficiency value is 1, indicating that it is efficient; if the target new energy input is less than the actual input, then the new energy efficiency value is less than 1, indicating that it is inefficient.

3. CO_2 efficiency

By definition, CO_2 emissions efficiency is the ratio of the target undesirable CO_2 emissions output to the actual undesirable CO_2 emissions output; therefore, the CO_2 emissions efficiency model is defined as follows:

$$\text{CO}_2\,\text{emissions efficiency} = \frac{\text{Target undesirable CO}_2\ \text{output} \ \ (i, t)}{\text{Actual undesirable CO}_2\ \text{output} \ \ (i, t)}$$

If the target undesirable CO_2 emissions output equals the actual undesirable CO_2 emissions output, then the CO_2 emissions efficiency value is equal to 1, indicating that it is efficient; if the target undesirable CO_2 emissions output is less than the actual undesirable CO_2 emissions output, then the CO_2 emissions efficiency value is less than 1, indicating that it is inefficient.

4. $PM_{2.5}$ concentration efficiency

$PM_{2.5}$ represents fine particulate matter that is 2.5 µm or less in diameter. By definition, $PM_{2.5}$ concentration efficiency is the ratio of the target undesirable $PM_{2.5}$ concentration output to the actual undesirable $PM_{2.5}$ concentration output; therefore, the $PM_{2.5}$ concentration efficiency model is defined as follows:

$$\text{PM}_{2.5}\ \text{efficiency} = \frac{\text{Target undesirable PM}_{2.5}\ \text{output} \ \ (i, t)}{\text{Actual undesirable PM}_{2.5}\ \text{output} \ \ (i, t)}$$

If the target undesirable $PM_{2.5}$ concentration output is equal to the actual undesirable $PM_{2.5}$ concentration output, then the $PM_{2.5}$ concentration efficiency value is equal to 1, indicating that it is efficient. If the target undesirable $PM_{2.5}$ concentration output is less than the actual undesirable $PM_{2.5}$ concentration output, then the $PM_{2.5}$ concentration efficiency value is less than 1, indicating that it is inefficient.

5. GDP efficiency

By definition, GDP efficiency is the ratio of actual desirable GDP output to target desirable GDP output; therefore, the GDP efficiency model is defined as follows:

$$\text{GDP efficiency} = \frac{\text{Actual desirable GDP output} \ \ (i, t)}{\text{Target desirable GDP output} \ \ (i, t)}$$

If the target desirable GDP output equals the actual desirable GDP output, then the GDP efficiency value is equal to 1, indicating that it is efficient; if the actual desirable GDP output is less than the target desirable GDP output, then the GDP efficiency value is less than 1, indicating that it is inefficient.

Results

Sources and Variables

This study compares nonenergy use efficiency and traditional and new energy consumption efficiencies in OECD and non-OECD countries from 2010 to 2014. The data are extracted from the World Development Indicators of the World Bank (2017) and the climate analysis indicators tool of the World Resource Institute. Currently, there are 35 OECD member countries and 27 non-OECD countries. The OECD is an intergovernmental international organization of 35 market economy countries that produce two thirds of the world's goods and services. The organization has become one of the world's largest and most reliable sources of global economic and social statistics. Therefore, the research objects selected in this study have distinct importance. This study was designed based on Tone and Tsutsui's (2010) assumptions. Suppose there are n DMUs over T terms, with each DMU having different inputs and outputs over a period and a carryover (link) to the next period $(t+1)$. Figure 1 shows the framework for the SBM dynamic model for intertemporal efficiency measurements and variables.

In this study, the number of employees, fixed asset investment, traditional energy consumption, and new energy consumption are the input items, GDP is the output, and CO_2 and $PM_{2.5}$ concentrations are the connections between each period (carryover). Table 1 lists the definitions of input and output variables, and the reference literature from which these variables are drawn.

Employees: This study takes the number of employees in each OECD and non-OECD country at the end of each year; unit: 10,000 people.

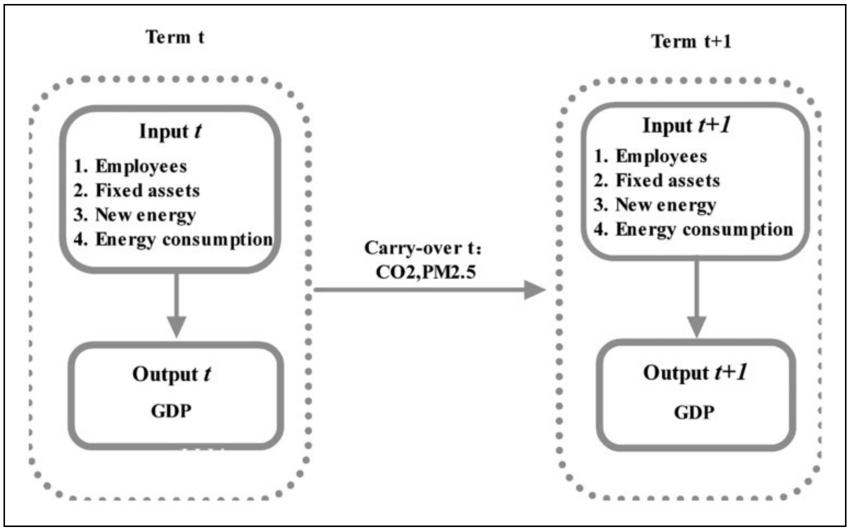

Figure 1. SBM dynamic model. GDP = gross domestic product; PM = particulate matter.

Table 1. Input and Output Variables.

Variable	Description	Reference(s)
Inputs	Employees	Hu and Wang (2006) and Zhou et al. (2012)
	Fixed assets	Chiu et al. (2012), Liou et al. (2015), and Wang et al., 2017
	Traditional energy consumption	Hu and Wang (2006), Chiu et al. (2012), and Wang et al. (2017)
	New energy consumption	Suzuki and Nijkamp (2016) and Wang et al. (2015)
Output	Gross domestic product	Hu and Wang (2006), Zhou et al. (2012), and Li et al. (2018)
Undesirable outputs	Carbon dioxide (CO_2)	Zhou and Ang (2008), Chiu et al. (2012), and Suzuki and Nijkamp (2016)
	Particulate matter ($PM_{2.5}$)	Li et al. (2018) and Yu et al. (2018)

Fixed assets: Calculated based on the fixed asset investments in each OECD and non-OECD country.

Traditional energy consumption: Technologically mature and widely used energy resources, such as coal, oil, natural gas, water, and other energy, are called traditional energy.

New energy consumption: According to the definition of the United Nations Conference on Energy and Renewable Energy in 1980, new energy resources are defined as follows. Based on new technologies and new materials, traditional renewable energy resources can be modernized and utilized, and inexhaustible and recurring renewable energy resources can be used to replace fossil energy resources with limited resources and pollution to the environment. New energy generally refers to renewable energy that is developed and utilized on the basis of new technology, including solar, biomass, wind, geothermal, wave, ocean current, and tidal energies.

Output variable: GDP in each OECD and non-OECD country; GDP data are extracted from each country's statistical yearbook for the given period.

Undesirable output variables:

1. CO_2 emissions for each OECD and non-OECD countries are estimated from the energy consumption. CO_2 emissions are a primary cause for the changes being experienced in global temperatures and the consequential rising sea levels. CO_2, unlike other air pollutants, has been used as the sole carbon emissions measure for global solutions to climate change.
2. $PM_{2.5}$ is an important index in the air quality index, which refers to atmospheric particulate matter (PM) that has a diameter of less than 2.5 μm.

Statistical Analysis and Efficiency Analysis

From Table 2, we see the number of employees increases gradually, and the average number rises from 1,723 in 2010 to 1,774 in 2014. The growth in employment is relatively slow, and so the 5-year trend is slightly upward. In addition, we find the CO_2 emission also appears in the similar phenomenon, showing a slow growth. On the contrary, $PM_{2.5}$ is almost stable. The

Table 2. Descriptive Statistics of Inputs and Outputs.

Year		Variable	Average	Standard	Maximum	Minimum
2010	Inputs	Employees (persons)	1,723	2,899	15,702	19
		Fixed assets (US$ million)	262,860	498,777	2,752,636	1,837
		Traditional energy (kt)	72.82	20.25	96.35	11.52
		New energy (kt)	18.47	16.14	75.42	1.32
	Output	GDP (US$ million)	1,274,464	2,658,110	14,964,372	13,255
	Undesirable output	CO_2 (thousand tons)	458,058	1,294,352	8,776,040	1,962
		$PM_{2.5}$ (micrograms per cubic meter)	21	15	74	5
2011	Inputs	Employees (persons)	1,730	2,902	15,714	19
		Fixed assets (US$ million)	290,503	529,495	2,877,762	2,285
		Traditional energy (kt)	72.02	20.82	96.48	10.26
		New energy (kt)	18.92	16.34	76.48	1.35
	Output	GDP (US$ million)	1,369,239	2,773,612	15,517,926	14,675
	Undesirable output	CO_2 (thousand tons)	477,525	1,392,953	9,733,538	1,881
		$PM_{2.5}$ (micrograms per cubic meter)	21	16	73	5
2012	Inputs	Employees (persons)	1,747	2,926	15,843	19
		Fixed assets (US$ million)	288,512	565,588	3,126,140	2,289
		Traditional energy (kt)	71.25	21.07	96.66	10.33
		New energy (kt)	19.89	16.9	77.36	1.61
	Output	GDP (US$ million)	1,366,529	2,866,245	16,155,255	14,219
	Undesirable output	CO_2 (thousand tons)	485,388	1,419,904	10,028,574	1,800
		$PM_{2.5}$ (micrograms per cubic meter)	21	16	75	5
2013	Inputs	Employees (persons)	1,761	2,941	15,899	19
		Fixed assets (US$ million)	291,638	581,970	3,298,621	2,389
		Traditional energy (kt)	70.6	21	96.57	10.4
		New energy (kt)	20.45	16.46	76.36	1.92
	Output	GDP (US$ million)	1,383,006	2,907,223	16,691,517	15,479
	Undesirable output	CO_2 (thousand tons)	487,268	1,446,511	10,258,007	1,900
		$PM_{2.5}$ (micrograms per cubic meter)	22	16	71	5
2014	Inputs	Employees (persons)	1,774	2,957	15,977	20
		Fixed assets (US$ million)	301,055	613,511	3,510,758	2,978
		Traditional energy (kt)	69.58	21.3	96.43	10.93
		New energy (kt)	20.89	16.41	76.42	2.84
	Output	GDP (US$ million)	1,410,574	3,012,199	17,393,103	17,179
	Undesirable output	CO_2 (thousand tons)	490,500	1,457,596	10,291,927	1,984
		$PM_{2.5}$ (micrograms per cubic meter)	22	16	72	6

Note. GDP = gross domestic product; PM = particulate matter.

input of fixed assets is large and significantly increases over the years. Capital investment also exhibits an increasing trend. Traditional energy consumption declines, while new energy consumption increases slightly. We also show that total GDP rises significantly over the years.

This study first divides the 62 countries into OECD and non-OECD members, after which we compile the five annual metaboundary TEs, with the main objective being to compare energy performance differences. Because of the differences between the individual factors and invested resources in the two groups, we are unable to directly measure or compare technical level differentiation; therefore, we use the TGR to attain the difference between the GF and MF. A relatively objective measurement benchmark is also developed to compare the technology level and the energy efficiency in each group and the intergroup efficiency of each country in each group.

Table 3 shows the GFE for the OECD countries. Switzerland, Denmark, France, United Kingdom, Iceland, Luxembourg, Norway, and the United States have the same efficiency values each year of 1, while Chile, the Czech Republic, Latvia, Mexico, Poland, Slovakia, and Turkey perform poorly each year.

Table 4 shows the GFE for the non-OECD countries. The United Arab Emirates is totally efficient at 1 each year, while China, Indonesia, India, Sri Lanka, Morocco, Nepal, Peru, and Thailand, and the others all perform poorly each year. The annual average OECD and non-OECD efficiencies are shown in Figure 2, from which we see that the average efficiency

Table 3. The Technical Efficiency of the Group Frontier for OECD Countries During 2010 to 2014.

	2010	2011	2012	2013	2014	Average
Australia	0.8511	1	1	1	1	0.9702
Austria	0.6261	0.6251	0.5934	0.5817	0.5823	0.6017
Belgium	0.8680	0.8595	0.8260	0.8486	0.8177	0.8440
Canada	0.7003	0.6975	0.6965	0.6946	0.6847	0.6947
Switzerland	1	1	1	1	1	1
Chile	0.4444	0.4217	0.4180	0.4237	0.4394	0.4295
Czech Republic	0.4726	0.4767	0.4775	0.5002	0.4906	0.4835
Germany	0.7466	0.7515	0.7613	0.8521	0.8394	0.7902
Denmark	1	1	1	1	1	1
Spain	0.6561	0.6505	0.6486	0.6885	0.6765	0.6640
Estonia	0.7886	0.7704	0.7516	0.7717	0.7771	0.7719
Finland	0.7247	0.7118	0.7057	0.7281	0.7349	0.7211
France	1	1	1	1	1	1
United Kingdom	1	1	1	1	1	1
Greece	0.6294	1	1	1	1	0.9259
Hungary	0.5153	0.5194	0.5346	0.5505	0.5361	0.5312
Ireland	1	1	0.8824	1	0.8727	0.9510
Iceland	1	1	1	1	1	1
Israel	0.6191	0.6018	0.5957	0.6545	0.6622	0.6267
Italy	0.7375	0.7601	0.7162	0.7542	0.7540	0.7444
Japan	1	1	1	1	0.7730	0.9546
Republic of Korea	0.5834	0.5885	0.5766	0.5829	0.5570	0.5777
Luxembourg	1	1	1	1	1	1
Latvia	0.5548	0.4959	0.4944	0.4991	0.5229	0.5134
Mexico	0.4365	0.4382	0.4364	0.4688	0.4743	0.4508
Netherlands	1	1	0.8449	1	0.8772	0.9444
Norway	1	1	1	1	1	1
New Zealand	0.7855	0.7790	0.7254	0.7594	0.7756	0.7650
Poland	0.4432	0.4326	0.4486	0.4885	0.4908	0.4607
Portugal	0.5656	0.5809	0.7255	1	0.7690	0.7282
Slovak Republic	0.4945	0.5010	0.5561	0.5688	0.5561	0.5373
Slovenia	0.5286	0.5558	0.6094	0.5603	0.5805	0.5669
Sweden	0.8888	1	1	1	1	0.9778
Turkey	0.4156	0.3898	0.4158	0.4222	0.4217	0.4130
United States	1	1	1	1	1	1
Annual average	0.7450	0.7602	0.7555	0.7828	0.7622	0.7611

in OECD countries is higher than in non-OECD countries. The efficiency in the OECD countries remains relatively steady throughout the period, while in the non-OECD countries, it is gradually increasing.

As most OECD countries are developed and because the regional differences and input resources are different from those of the non-OECD countries, they have different technology standards. Therefore, we calculate cross-group efficiency reflecting the technology level and energy efficiency by using the technology gap ratio for the countries in each region. Tables 5 and 6 list the TGR and annual average efficiency calculation of the OECD and non-OECD countries.

As shown in Table 5, in 2010, only two OECD countries have a technology gap ratio of less than 1: South Korea and Mexico. In 2011, three OECD countries have technology gap ratios less than 1: South Korea, Mexico, and Turkey of which the largest GDP nation is South Korea. In 2012, five OECD countries have a technology gap ratio of less than 1: Belgium, South Korea, Mexico, the Netherlands, and Turkey of which the largest GDP nation is again South Korea. In 2013, three OECD countries have a technology gap ratio of less than 1: South Korea, Mexico, and Turkey of which the largest GDP nation is again South Korea. In 2014, seven OECD countries have a technology gap ratio of less than 1: Belgium, Japan, South Korea, Mexico, the Netherlands, Poland, and Turkey of which the largest GDP nation is again South Korea. In summary, the TE in most OECD countries is close to the performance level on the MF boundary; that is, the relative efficiency is high. Only a few countries have technical standards that do not reach the technical level on the MF, with the biggest gap to the metatechnology border being South Korea.

Table 4. The Technical Efficiency of the Group Frontier for Non-OECD Countries During 2010 to 2014.

	2010	2011	2012	2013	2014	Average
United Arab Emirates	1	1	1	1	1	1
Argentina	0.5152	0.5131	0.5506	0.5669	0.5705	0.5433
Brazil	0.5207	0.5391	0.5298	0.5084	0.5126	0.5221
Botswana	0.4677	0.5636	0.5421	0.5860	0.6183	0.5555
China	0.2706	0.2927	0.3058	0.3183	0.3258	0.3026
Colombia	0.4122	0.4024	0.4131	0.4129	0.3977	0.4077
Costa Rica	0.5908	0.5966	0.6256	0.6295	0.6230	0.6131
Dominican Republic	0.3657	0.3889	0.3895	0.4008	0.4137	0.3917
Algeria	0.6752	0.7625	0.7527	0.7557	1	0.7898
Indonesia	0.3047	0.2982	0.2921	0.3026	0.3006	0.2996
India	0.2419	0.2469	0.2548	0.2722	0.2735	0.2579
Islamic Republic of Iran	0.4109	0.4441	0.4392	0.4008	0.3952	0.4180
Kenya	0.4372	0.4125	0.4425	0.4559	0.4526	0.4401
Cambodia	0.4071	0.4248	0.4169	0.3939	0.3845	0.4054
Sri Lanka	0.3771	0.3575	0.3174	0.3449	0.3245	0.3443
Morocco	0.2981	0.2929	0.3026	0.3200	0.3457	0.3119
Malaysia	0.4940	0.4858	0.4759	0.4896	0.4861	0.4863
Nigeria	0.5704	0.5629	1	1	1	0.8267
Nepal	0.3270	0.3148	0.3149	0.2996	0.2799	0.3068
Pakistan	0.4312	1	0.4250	0.4212	0.4499	0.5454
Peru	0.3585	0.3662	0.3737	0.3770	0.3788	0.3709
Philippines	0.3887	0.3828	0.4107	0.3935	0.3904	0.3932
Romania	0.3871	0.3780	0.3875	0.4170	0.4192	0.3978
Russian Federation	0.4875	0.5085	0.5241	0.5399	0.5376	0.5195
Singapore	0.8714	1	1	1	1	0.9743
Thailand	0.3457	0.3324	0.3291	0.3399	0.3662	0.3426
South Africa	0.4123	0.4127	0.4120	0.4108	0.4201	0.4136
Annual average	0.4581	0.4919	0.4990	0.4947	0.5061	0.4882

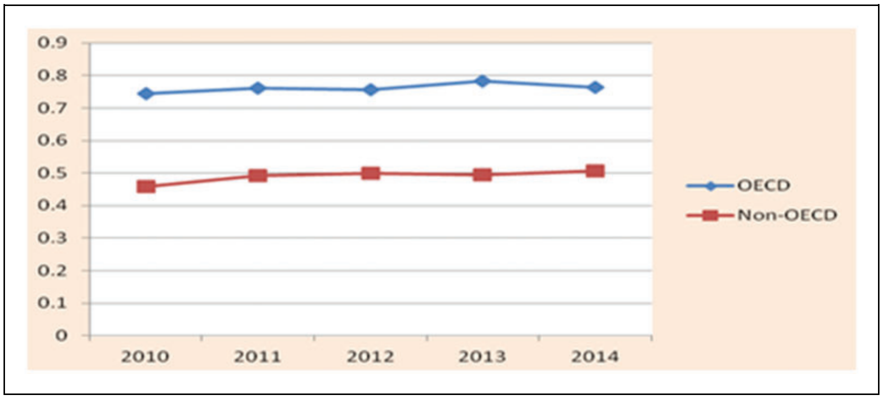

Figure 2. Annual average efficiency of OECD and non-OECD countries. OECD = Organisation for Economic Co-operation and Development.

Table 6 shows that among non-OECD countries, in 2010, only one has a technology gap ratio of 1: the United Arab Emirates. In 2011, three non-OECD countries have a technology gap ratio of 1: the United Arab Emirates, Pakistan, and Singapore. In 2012, three non-OECD countries have a technology gap ratio of 1: the United Arab Emirates, Nigeria, and Singapore. In 2013, three non-OECD countries have a technology gap ratio of 1: the United Arab Emirates, Nigeria, and Singapore. In 2014, four non-OECD countries have a technology gap ratio of 1: the United Arab Emirates, Algeria, Nigeria, and Singapore. In general, only a few non-OECD countries have total efficiencies close to the performance level on the MF boundary, with the remaining countries having TGR less than 1.

Table 5. Technology Gap Ratio of OECD Countries.

	2010	2011	2012	2013	2014	Average
Australia	1	1	1	1	1	1
Austria	1	1	1	1	1	1
Belgium	1	1	0.9967	1	0.9999	0.9993
Canada	1	1	1	1	1	1
Switzerland	1	1	1	1	1	1
Chile	1	1	1	1	1	1
Czech Republic	1	1	1	1	1	1
Germany	1	1	1	1	1	1
Denmark	1	1	1	1	1	1
Spain	1	1	1	1	1	1
Estonia	1	1	1	1	1	1
Finland	1	1	1	1	1	1
France	1	1	1	1	1	1
United Kingdom	1	1	1	1	1	1
Greece	1	1	1	1	1	1
Hungary	1	1	1	1	1	1
Ireland	1	1	1	1	1	1
Iceland	1	1	1	1	1	1
Israel	1	1	1	1	1	1
Italy	1	1	1	1	1	1
Japan	1	1	1	1	0.9528	0.9906
Republic of Korea	0.7252	0.7258	0.7139	0.7141	0.6964	0.7151
Luxembourg	1	1	1	1	1	1
Latvia	1	1	1	1	1	1
Mexico	0.9946	0.9923	0.9915	0.9797	0.9599	0.9836
Netherlands	1	1	0.993	1	0.9980	0.9982
Norway	1	1	1	1	1	1
New Zealand	1	1	1	1	1	1
Poland	1	1	1	1	0.9983	0.9997
Portugal	1	1	1	1	1	1
Slovak Republic	1	1	1	1	1	1
Slovenia	1	1	1	1	1	1
Sweden	1	1	1	1	1	1
Turkey	1	0.9995	0.9997	0.9961	0.9733	0.9937
United States	1	1	1	1	1	1
Annual average	0.9920	0.9919	0.9913	0.9911	0.9880	0.9909

Figure 3 illustrates the annual average TGRs for the OECD and non-OECD countries, from which we see that the average TGR in OECD countries is higher than in non-OECD countries. Over the period, there are relatively few TGR changes for OECD countries. However, for non-OECD countries, there is a gradual increase, indicating that the technology gap in non-OECD countries is gradually shrinking and energy efficiency is improving.

Energy, CO_2 Emissions, $PM_{2.5}$ Concentrations, and GDP Efficiencies

Following Hu and Wang's (2006) total factor energy efficiency indicators, to overcome the possible deviations in traditional energy efficiency indicators, we next discuss the efficiency of individual energy-related variables.

1. Energy efficiency

Table 7 shows the efficiency for the traditional and new energy consumption. Among OECD countries, Switzerland, Denmark, France, the United Kingdom, Iceland, Luxembourg, Norway, and the United States have new and traditional energy efficiency of 1, while in non-OECD countries, only the United Arab Emirates achieves 1 for both new and traditional energy efficiencies. The new energy consumption efficiencies in Botswana and Algeria are benchmarks for the other countries, but their traditional energy consumption efficiencies are 0.65 and 0.8, respectively.

Table 6. Technology Gap Ratio of Non-OECD Countries.

	2010	2011	2012	2013	2014	Average
United Arab Emirates	1	1	1	1	1	1
Argentina	0.5152	0.5131	0.5506	0.5669	0.5705	0.5433
Brazil	0.5207	0.5391	0.5298	0.5084	0.5126	0.5221
Botswana	0.6179	0.7283	0.7255	0.7743	0.8076	0.7307
China	0.2706	0.2927	0.3058	0.3183	0.3258	0.3026
Colombia	0.6070	0.6966	0.6855	0.6809	0.6949	0.6730
Costa Rica	0.5908	0.5966	0.6256	0.6295	0.6230	0.6131
Dominican Republic	0.4832	0.4995	0.5075	0.5195	0.5314	0.5082
Algeria	0.9804	0.9241	0.9482	0.9450	1	0.9595
Indonesia	0.6225	0.6205	0.6179	0.6194	0.6272	0.6215
India	0.5644	0.5998	0.6345	0.6768	0.6158	0.6183
Islamic Republic of Iran.	0.5709	0.6535	0.6722	0.7732	0.7588	0.6911
Kenya	0.5337	0.5141	0.5428	0.5634	0.5649	0.5438
Cambodia	0.4976	0.5222	0.5222	0.5043	0.5117	0.5116
Sri Lanka	0.6944	0.7137	0.6682	0.6497	0.6223	0.6697
Morocco	0.5737	0.5987	0.5716	0.5871	0.6118	0.5886
Malaysia	0.7205	0.7305	0.7911	0.8116	0.7957	0.7699
Nigeria	0.5704	0.5629	1	1	1	0.8267
Nepal	0.4335	0.4207	0.4342	0.4257	0.4442	0.4316
Pakistan	0.4312	1	0.5703	0.5580	0.4499	0.6019
Peru	0.6321	0.6617	0.6777	0.6647	0.6792	0.6631
Philippines	0.6313	0.6275	0.6693	0.6574	0.6454	0.6462
Romania	0.6962	0.7460	0.6626	0.6527	0.6577	0.6830
Russian Federation	0.4875	0.5085	0.5241	0.5399	0.5376	0.5195
Singapore	0.8714	1	1	1	1	0.9743
Thailand	0.7011	0.7175	0.7231	0.7210	0.7383	0.7202
South Africa	0.6557	0.6766	0.7233	0.7517	0.7761	0.7167
Annual average	0.6102	0.6542	0.6623	0.6703	0.6714	0.6537

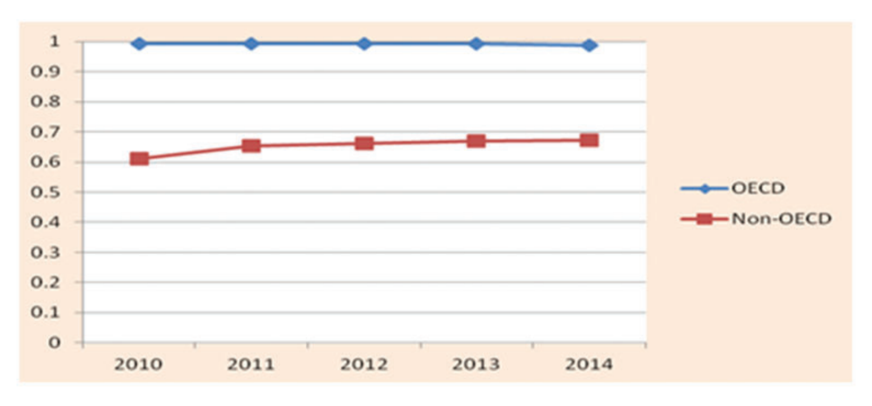

Figure 3. Annual average TGR of OECD and non-OECD countries. OECD = Organisation for Economic Co-operation and Development.

Cambodia also has a poor traditional energy efficiency ratio, but a new energy consumption of 0.85. South Korea, Slovakia, and Slovenia all have poor new energy efficiency and better traditional energy efficiency.

On the whole, we can see that the average traditional energy consumption efficiency is declining year on year, while the average new energy consumption efficiency is increasing, with the efficiency gap between the two gradually narrowing. An analysis of the standard deviations for the energy consumption efficiencies in Table 6 reveals that the standard deviation for the traditional energy consumption efficiency is small but shows a gradually

Table 7. Comparison of Traditional and New Energy Consumption Efficiencies During 2010 to 2014.

	2010		2011		2012		2013		2014	
Countries	T	N	T	N	T	N	T	N	T	N
Australia	0.75	0.83	1	1	1	1	1	1	1	0.75
Austria	0.51	0.57	0.47	0.56	0.51	0.55	0.53	0.54	0.50	0.51
Belgium	0.96	0.77	0.84	1	1	0.45	0.96	0.76	0.85	0.96
Canada	0.35	0.74	0.36	0.68	0.34	0.73	0.34	0.71	0.32	0.35
Switzerland	1	1	1	1	1	1	1	1	1	1
Chile	0.29	0.68	0.28	0.63	0.31	0.59	0.29	0.59	0.23	0.29
Czech	0.88	0.30	0.88	0.30	0.91	0.31	0.90	0.38	0.89	0.88
Germany	0.85	0.33	0.88	0.32	0.90	0.34	0.79	0.76	0.84	0.85
Denmark	1	1	1	1	1	1	1	1	1	1
Spain	0.89	0.29	0.90	0.28	0.92	0.28	0.94	0.31	0.59	0.89
Estonia	0.76	1	0.77	1	0.77	1	0.78	0.10	0.79	0.76
Finland	0.54	0.62	0.53	0.59	0.58	0.54	0.54	0.59	0.47	0.54
France	1	1	1	1	1	1	1	1	1	1
Kingdom	1	1	1	1	1	1	1	1	1	1
Greece	0.80	0.37	1	1	1	1	1	1	1	0.80
Hungary	0.95	0.32	0.95	0.31	0.97	0.33	0.98	0.46	0.98	0.95
Ireland	1	1	1	1	0.78	0.90	1	1	0.76	1
Iceland	1	1	1	1	1	1	1	1	1	1
Israel	0.73	0.34	0.72	0.34	0.72	0.39	0.70	0.49	0.69	0.73
Italy	0.57	0.62	0.61	0.61	0.83	0.29	0.81	0.40	0.89	0.57
Japan	1	1	1	1	1	1	1	1	0.72	1
Republic of Korea	0.99	0.62	0.93	0.65	0.93	0.55	0.92	0.51	0.93	0.99
Luxembourg	1	1	1	1	1	1	1	1	1	1
Latvia	0.61	0.94	0.82	0.57	0.98	0.38	0.88	0.50	0.80	0.61
Mexico	0.80	0.23	0.78	0.31	0.77	0.34	0.80	0.29	0.80	0.80
Netherlands	1	1	1	1	0.78	0.74	1	1	0.77	1
Norway	1	1	1	1	1	1	1	1	1	1
New Zealand	0.52	0.77	0.50	0.75	0.31	0.78	0.43	0.85	0.47	0.52
Poland	0.76	0.31	0.75	0.31	0.76	0.32	0.74	0.41	0.82	0.76
Portugal	0.87	0.25	0.93	0.19	0.65	0.71	1	1	0.70	0.87
Slovak Republic	1	0.29	1	0.32	1	0.40	1	0.47	1	1
Slovenia	1	0.21	1	0.25	1	0.38	1	0.26	1	1
Sweden	0.89	0.69	1	1	1	1	1	1	1	0.89
Turkey	0.79	0.20	0.79	0.22	0.80	0.21	0.79	0.26	0.83	0.79
United States	1	1	1	1	1	1	1	1	1	1
Arab	1	1	1	1	1	1	1	1	1	1
Argentina	0.79	0.33	0.78	0.31	0.78	0.35	0.76	0.46	0.75	0.79
Brazil	0.75	0.20	0.74	0.20	0.66	0.26	0.58	0.39	0.57	0.75
Botswana	0.66	1	0.67	1	0.66	1	0.65	1	0.65	0.66
China	0.76	0.35	0.76	0.40	0.76	0.40	0.75	0.42	0.76	0.76
Colombia	0.33	0.62	0.33	0.64	0.33	0.64	0.33	0.67	0.30	0.33
Costa Rica	0.61	1	0.63	1	0.69	1	1	0.58	1	0.61
Dominican	0.81	0.16	0.80	0.17	0.80	0.19	0.78	0.26	0.77	0.81
Algeria	0.80	1	0.80	1	0.80	1	0.80	1	1	0.80
Indonesia	0.54	0.36	0.33	0.47	0.34	0.47	0.30	0.47	0.27	0.54
India	0.45	0.40	0.44	0.41	0.41	0.42	0.36	0.44	0.34	0.45
Iran	0.78	0.84	0.78	0.88	0.78	0.91	0.80	0.51	0.80	0.78
Kenya	0.55	0.77	0.51	0.78	0.58	0.77	0.54	0.77	0.60	0.55
Cambodia	0.32	0.88	0.29	0.90	0.29	0.90	0.41	0.85	0.41	0.32
Sri Lanka	0.41	0.49	0.25	0.76	0.41	0.37	0.38	0.48	0.28	0.41
Morocco	0.81	0.20	0.78	0.25	0.78	0.29	0.77	0.38	0.75	0.81
Malaysia	0.73	0.77	0.80	0.17	0.80	0.13	0.80	0.19	0.80	0.73
Nigeria	0.91	0.61	1	0.52	1	1	1	1	1	0.91

(continued)

Table 7. Continued

	2010		2011		2012		2013		2014	
Countries	T	N	T	N	T	N	T	N	T	N
Nepal	0.82	0.68	0.68	0.70	0.59	0.72	0.68	0.70	0.61	0.82
Pakistan	0.28	0.87	1	1	0.75	0.32	0.72	0.33	0.88	0.28
Peru	0.30	0.60	0.28	0.62	0.28	0.64	0.26	0.69	0.22	0.30
Philippines	0.39	0.62	0.37	0.61	0.36	0.60	0.33	0.61	0.28	0.39
Romania	0.94	0.12	0.89	0.15	0.91	0.16	0.28	0.77	0.24	0.94
Russian	0.85	0.31	0.84	0.40	0.84	0.42	0.84	0.41	0.85	0.85
Singapore	0.80	0.88	1	1	1	1	1	1	1	0.80
Thailand	0.88	0.13	0.86	0.14	0.86	0.15	0.38	0.65	0.30	0.88
South Africa	0.81	0.17	0.80	0.19	0.80	0.21	0.78	0.29	0.77	0.81
Mean	0.76	0.62	0.78	0.64	0.77	0.63	0.76	0.67	0.74	0.76
Standard deviation	0.22	0.31	0.24	0.32	0.23	0.31	0.25	0.28	0.26	0.22

Note. T = traditional energy consumption efficiency; N = new energy consumption efficiency.

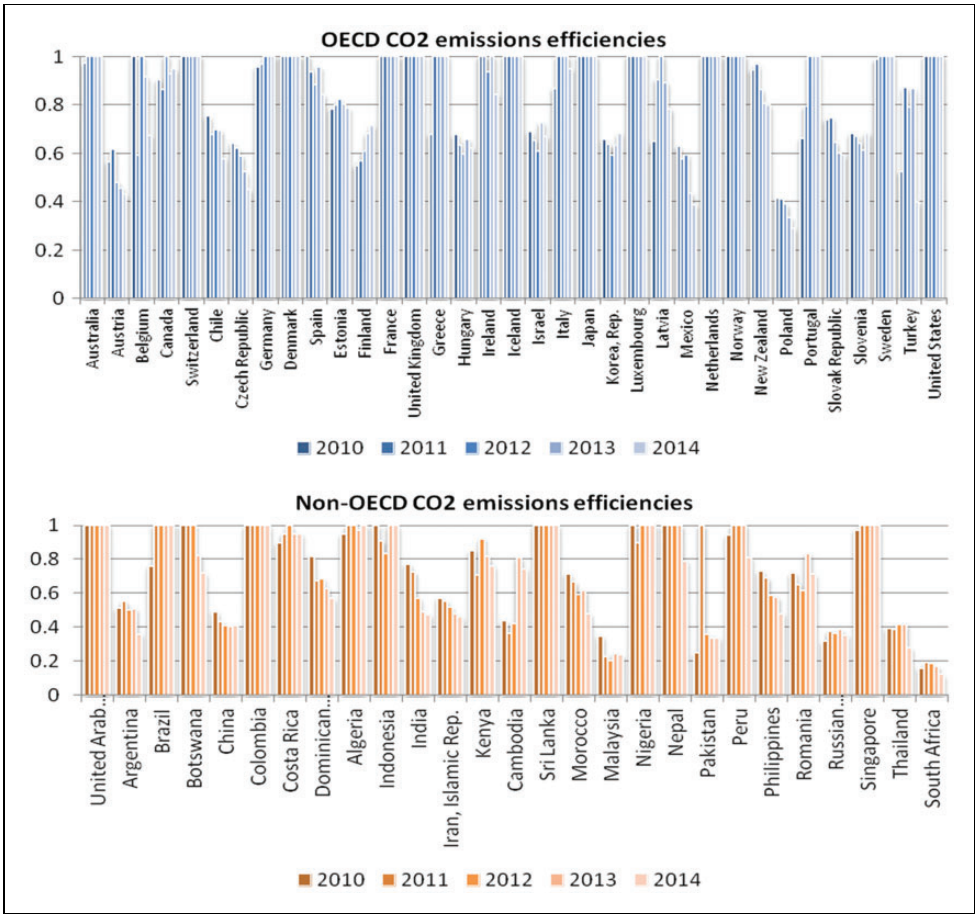

Figure 4. CO_2 differences between actual efficiency and target efficiency. OECD = Organisation for Economic Co-operation and Development.

increasing trend and that the standard deviation for the new energy consumption efficiency is larger but declining. Because new energy developments have only been focused in the late-20th and early-21st centuries and also because new energy production is limited by the natural environmental conditions in the different countries, the overall new energy standard deviation is higher.

2. CO_2 emissions efficiency

Figure 4 shows in the OECD countries that Australia, Switzerland, Germany, Denmark, France, the United Kingdom, Iceland, Japan, Luxembourg, the Netherlands, Norway, Sweden, and the United States have CO_2 emission efficiency of 1 in each year. Countries with poor performance include Austria, Czech Republic, Finland, Hungary, Israel, South Korea, Mexico, Poland, and Slovenia. Their annual CO_2 emissions efficiencies are less than 0.7, with Poland's being less than 0.4. Of the non-OECD countries, United Arab Emirates, Cambodia, Algeria, Sri Lanka, Nigeria, Nepal, and Singapore have annual target CO_2 emissions efficiencies close to the actual CO_2 emissions efficiencies, while China, Malaysia, Russia, Thailand, and South Africa have poor CO_2 emissions efficiencies at less than 0.5 each year.

3. $PM_{2.5}$ concentration efficiency

Figure 5 shows that the $PM_{2.5}$ concentration efficiencies in Australia, Switzerland, Denmark, Finland, France, the United Kingdom, Iceland, Luxembourg, Norway, New Zealand, Sweden, and the United States among OECD countries are 1 in each year. However, the annual $PM_{2.5}$ concentration efficiencies in Austria, Hungary, South Korea, Mexico, and Poland are less than 0.6, and the annual efficiencies in Chile and Turkey are worse at less than 0.4.

4. GDP efficiency

Figure 6 shows in the OECD countries that the actual GDP of the Czech Republic, Estonia, Hungary, Luxembourg, and Slovakia is less than the target GDP, indicating relative inefficiency. Mexico, Poland, and Turkey are improving year on year, with their actual GDP being equal to the target GDP in 2014. The GDP in most OECD countries is efficient in all years.

The gap between OECD countries and non-OECD countries is relatively wide. Non-OECD countries that have better GDP performances are the United Arab Emirates, Argentina, Brazil, Costa Rica, Nigeria, Pakistan, Russia, and Singapore in which their annual target GDP is quite close to the real GDP and therefore is relatively efficient. Malaysia's GDP efficiency in 2010

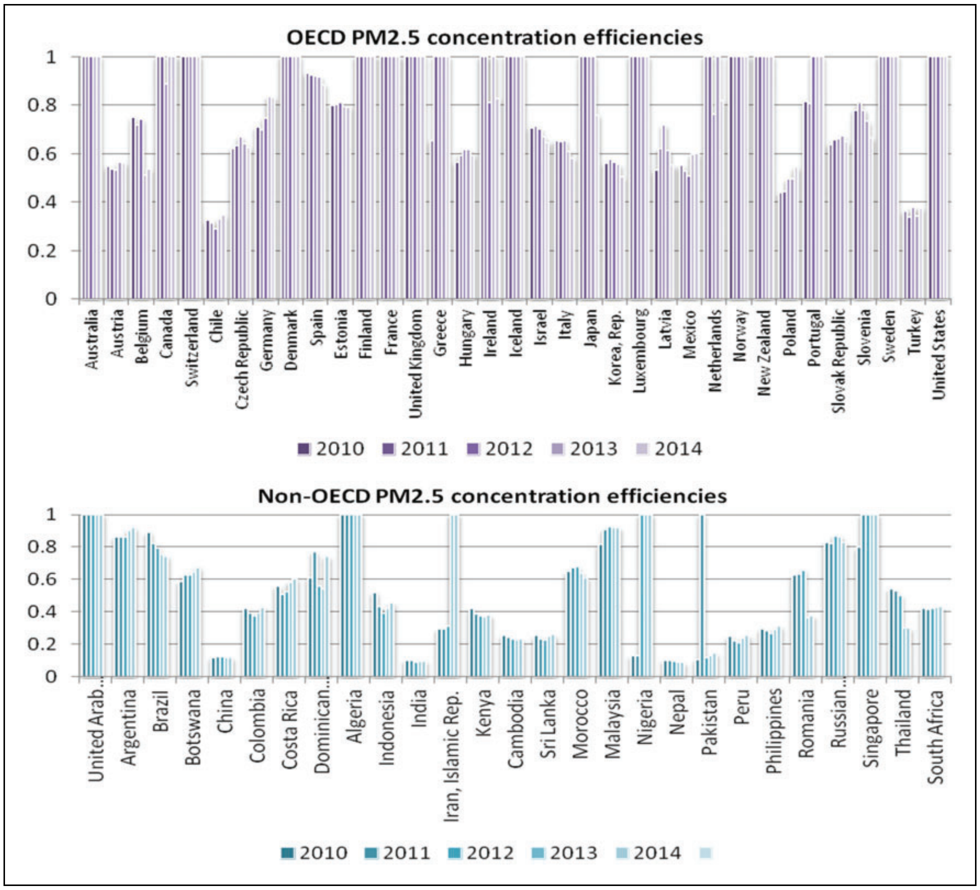

Figure 5. $PM_{2.5}$ differences between actual and target efficiencies. OECD = Organisation for Economic Co-operation and Development; PM = particulate matter.

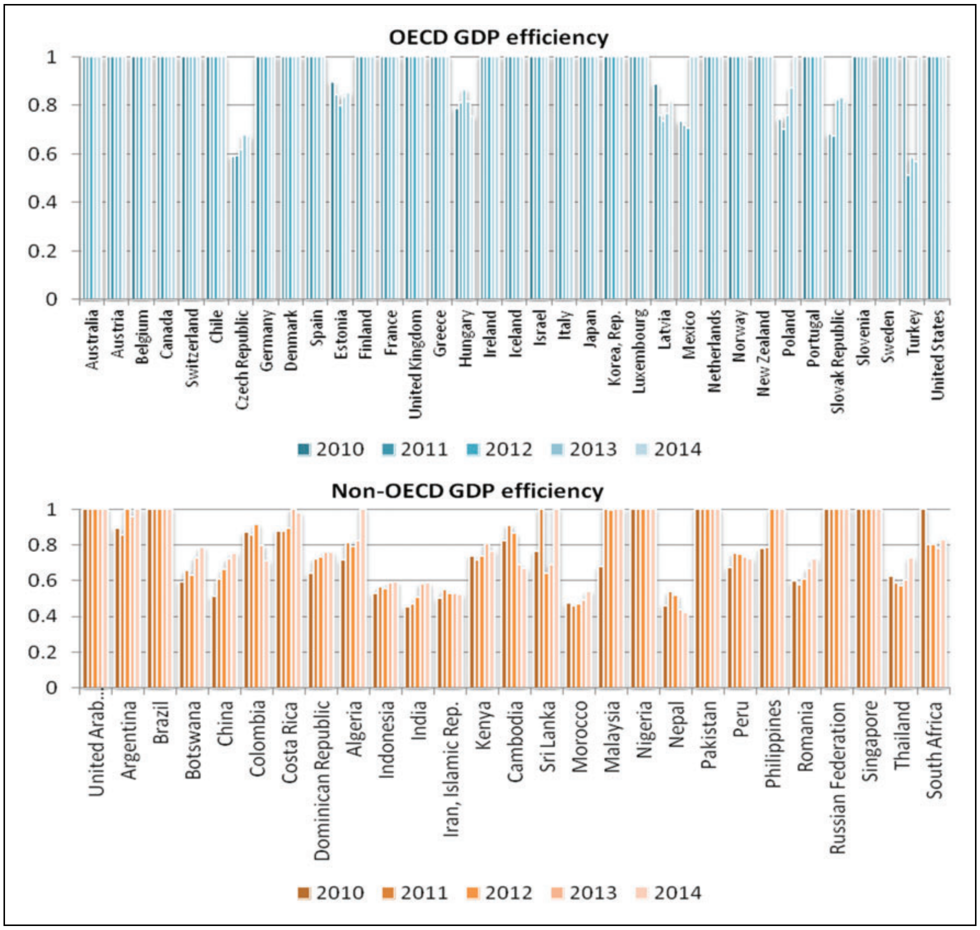

Figure 6. GDP efficiencies of OECD and non-OECD countries. OECD = Organisation for Economic Co-operation and Development; GDP = gross domestic product.

is only 0.68, and the GDP efficiency in the Philippines in 2010 and 2011 is only 0.78; however, the GDP efficiencies in these two countries are increasing year on year. South Africa's GDP efficiency, however, is decreasing year on year, and there are poor overall performances in Indonesia, India, Iran, Morocco, and Nepal, all of which have annual GDP efficiencies less than 0.6, indicating that efficiency improvements are needed.

Discussion

This study focuses on energy efficiencies in OECD and non-OECD countries from 2010 to 2014. With an application of a MFD-DEA model, we calculate the inputs and outputs, with the CO_2 emissions and $PM_{2.5}$ concentrations being the undesirable outputs and energy consumption being divided into new and traditional energy sources. We use technology gap ratio and efficiency values to compare the energy efficiencies and the new and traditional energy source differences between the two groups. The conclusions from the empirical analysis are as follows.

1. Average efficiency in OECD countries is higher than in non-OECD countries. The efficiency in the former remains relatively steady throughout the period, while, in the latter, it is gradually increasing.
2. Overall efficiency in most OECD countries is close to the performance level on the MF boundary, showing that the relative efficiency level is high. However, except for South Korea (which is relatively inefficient among OECD countries), the technology gap ratios of the other OECD countries are equal to or very close to 1, which *i* very close to the technical level on the metatechnology border for all countries.
3. Among all non-OECD countries (except the United Arab Emirates and Singapore) that performed better each year, most countries require significant improvements.
4. The average TGR is higher than in the non-OECD countries, but the technology gap ratio in these non-OECD countries is gradually increasing.
5. There are 13 OECD members with CO_2 emissions efficiency value of 1: Australia, Switzerland, Germany, Denmark, France, the United Kingdom,

Iceland, Japan, Luxembourg, the Netherlands, Norway, Sweden, and the United States. There are eight countries among them that have very poor efficiency below 0.4: Austria, the Czech Republic, Finland, Hungary, Israel, South Korea, Mexico, and Slovenia, with the worst performing country being Poland with annual efficiency values of less than 0.4.

6. There are seven non-OECD countries that have efficiency values of 1: United Arab Emirates, Cambodia, Algeria, Sri Lanka, Nigeria, Nepal, and Singapore. However, China, Malaysia, Russia, Thailand, and South Africa all have poor performances.
7. In terms of $PM_{2.5}$ concentration efficiency values, 12 among the OECD countries have a value of 1 in each year, while Chile and Turkey have poor $PM_{2.5}$ concentration efficiencies. Among non-OECD countries, there are much wider disparities in terms of $PM_{2.5}$ concentration efficiencies. Three countries (United Arab Emirates, Algeria, and Singapore) achieve 1, while China, India, and Nepal have annual efficiency values lower than 0.2.
8. Among OECD countries, eight countries (Switzerland, Denmark, France, the United Kingdom, Iceland, Luxembourg, Norway, and the United States) have new and traditional energy efficiency values of 1. Among non-OECD countries, only the United Arab Emirates has new and traditional energy efficiency values of 1.
9. The average traditional energy consumption efficiency is declining by year, while the average new energy consumption efficiency is increasing, with the efficiency gap between the two gradually narrowing.

Implications for Conservation

Based on the above discussions, we provide the following managerial suggestions.

1. Mitigating climate change and reducing greenhouse gas emissions are urgent issues in all countries throughout the world. With different economic levels and diverse levels of technologies, the non-OECD countries have much poorer levels of efficiencies compared with OECD countries. More support should be given by international organizations and OECD countries to help out non-OECD countries. And further countries should work together to reduce the use of fossil fuels, promote energy transformation, and improve energy efficiency.
2. With a diversity of natural resource endowments, energy development strategies should be adapted to the local conditions of each country. For example, countries with long sunshine hours should develop solar power generation. Areas with strong ocean currents can develop hydropower. Biomass energy and geothermal energy are also alternative energy sources that could be considered.
3. International institutional environment can encourage OECD countries to provide financial and technical resources to assist non-OECD countries in developing renewable energies, improve energy efficiencies, reduce greenhouse gas emissions, and reduce efficiency gaps. International organizations can also play a role to enhance and mobilize the financial resource and technologies.
4. New technology for lean use of traditional energy and the development of new forms of energy should also be medium- to long-term strategies for countries. For many non-OECD countries, the development of new energy is much harder due to limited access of technology and financial resource, along with relatively low levels of economy and social development. As a result, it may take a much longer time and more fundamentals provided to help change countries' industrial structure.
5. Further encouragement should also be given to promote and reward private investment in area of new technology development. Further attention should be given to increasing research and development funding for state-owned power plants and to raise energy transformation incentives.
6. With China's one-belt one-road initiative that may affect EU and southwestern Asian countries, further extensive cooperation can be built up in terms of international trade and environmental protection among one-belt one-road countries.

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