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RESEARCH ARTICLE

A study on emissions efficiency, emissions technology gap ratio, room for improvement in emissions intensity, and pluralized relationships

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Abstract

This study investigates the relationships among emissions efficiency (Em), the emissions technology gap ratio (TGm), and room for improvement in emissions intensity (RIm), and creates target-consideration environmental Kuznets curves (TC-EKC) which are then examined and compared for countries in the European Union (EU) that are divided into those countries in the Baltic Sea region (BSR) and those in the non-Baltic Sea region (NBSR). The research results indicate that the BSR countries exhibit an inverted-U-shaped TC-EKC, but the NBSR countries do not, implying that CO_2 emissions in the latter region do not achieve the target. The small TGm and the large RIm for the BSR countries indicate that this region has a low Em and is at the preliminary stage of emissions technology development.

Keywords Room for improvement in emissions intensity · Emissions efficiency · Emissions technology gap ratio

Introduction

Global warming and climate change caused by greenhouse gas (GHG) emissions are becoming two of the most severe challenges facing countries all around the world. The Kyoto Protocol was signed in 1997 and formally went in force in 2005, but was then replaced by the Paris Agreement in 2015 in order to realize the commitments to reduce GHG emissions. The European Union (EU) has devoted a large portion of its available resources to achieving a target of sustainable development. The EU has incorporated the goal of GHG emissions reduction into the Europe 2020 strategy, which aims to reduce the GHG emissions of 1990 by 20%, decrease primary energy use by 20%, and increase the share of renewable resources in energy consumption to 20% by the year 2020 (European Commission (EC) 2012). The EU has also pledged to achieve long-term goals that cut carbon dioxide (CO_2) equivalent pollution by 80% in comparison with 1990 levels by 2050 so as to gradually turn Europe into a low carbon society (European Commission (EC) 2011).

CO_2 is one of six kinds of regulated GHGs in the Kyoto Protocol under which countries all over the world must prioritize efforts in reducing CO_2 emissions as they execute national growth plans. Charnes et al. (1978) and Banker et al. (1984) are the leading papers in the field of data envelopment analysis (DEA). The traditional DEA approach was not suited to including an undesirable output like CO_2 because of difficulties that arose from biased efficiency measurements in DEA, but later, Zhou and Ang (2008) employed CO_2 as an output variable in their DEA study. Thereafter, the DEA approach has been appropriately extended to examine the measurement of environmental efficiency and subsequent developments, as in Chang et al. (2013) who applied the slack-based measurement (SBM) DEA approach that was first proposed by Tone (2001). The other viewpoint regarding DEA is that it directs attention to the heterogeneity feature of a decision-making unit (DMU), such as in Atici (2009) who divides his research objectives between Central and Eastern European countries and Shahbaz et al. (2015) who use the income level as a criterion to distinguish research objectives. O'Donnell et al. (2008) propose the concept of metafrontier DEA to treat the problem of heterogeneous DMUs. The literature on environmental efficiency and technology employing the metafrontier approach includes Fei and Lin (2017) and Kounetas (2015).

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During the production process, CO_2 emissions are mainly a by-product of fossil fuel energy consumption. Kerkhof et al. (2009) and Jobert et al. (2010) indicate that an increase in consumption and economic growth results in CO_2 emissions, and the amount released is determined by consumption and production levels. Hence, the intensity of energy consumption reflects the intensity of CO_2 emissions. This relation can be described by a simple index decomposition analysis (IDA) in which CO_2 emissions intensity (i.e., the ratio of CO_2 emissions to gross domestic production (GDP)) is a product of the carbonization index (i.e., the ratio of CO_2 emissions to energy consumption) and energy intensity (i.e., the ratio of energy consumption to GDP). Decomposition analysis usually refers to the field of environmental analysis applying the IDA approach, such as Li et al. (2017) and Su and Ang (2015) who investigate the impact of CO_2 emissions on emission intensity, energy intensity, and economic activity. Yan et al. (2017) employ the Generalized Divisia Index to decompose the changes in the energy-related GHG emissions of the agricultural sectors of selected European Union (EU) countries. Kwon et al. (2017) decompose CO_2 emissions into three factors, namely population, industrial structure, and energy intensity, by using the logarithmic mean Divisia index and then applying a two-stage DEA to examine both the technical efficiency and voluntary environmental consciousness of 12 European countries. The merit of decomposition analysis is that it provides some insights into the strategy of CO_2 emissions reduction. Other recent studies combining decomposition analysis and DEA include Chen and Duan (2016), Wang et al. (2015), and Zhang et al. (2013a). Zhang et al. (2013b) describe the relationships among CO_2 emissions performance, energy efficiency, and technology gaps in fossil fuel electricity generation under the DEA framework, but they do not use decomposition analysis.

It is worth noting that there have been no studies in the literature investigating the relationships among the room for improvement in CO_2 emissions intensity, emissions efficiency, and the emissions technology gap through decomposition analysis under the DEA framework. Hence, this study looks to fill the gap in the related literature. Zhang et al. (2015) consider geographical heterogeneity in China by using SBM-DEA with a metafrontier framework to investigate ecological total-factor energy efficiency. The measurement method for energy efficiency that they describe can also be extended to the measurement of carbon emissions performance. Zhang and Wei (2015) discuss carbon emissions performance, while Chang (2014, 2015) develops an indicator of the room for improvement in energy intensity to investigate energy consumption and energy efficiency at the country level. Chang (2019) studies the room for improvement in energy intensity by data envelopment analysis under the metafrontier framework where he points out the relationship among energy efficiency, energy technology gap ratio, and room for improvement in energy intensity. This study enhances his concept to the estimation of room for improvement in emissions intensity (hereafter RIm), and RIm herein also refers to relevant issues such as emissions efficiency and the emissions technology gap under the DEA model with a metafrontier framework. In the past literature, the idea for the improvement gap in energy intensity in Li and Lin (2015) is the same as that of room for improvement in energy intensity by Chang (2014). Based on Google citation count for research in early 2020, the former is 42 times and the latter is 45 times. Even so, it means that both ideas of the improvement gap in energy intensity and room for improvement in energy intensity have been cited by research studies so many times that they have also been extended toward the study of emissions intensity, such as Chang (2015). The idea behind room for improvement in energy intensity has been reconsidered by Chang (2019) under the DEA-metafrontier framework. This paper follows the idea of room for improvement in energy intensity in Chang (2014), idea of room for improvement in emissions intensity in Chang (2015), and idea of room for improvement in energy intensity under the DEA-metafrontier framework in Chang (2019) to study the room for improvement in emissions intensity under the DEA-metafrontier framework. Based on the past series of literature, the issue in this study is valuable and should be paid greater attention.

This study offers three contributions to the literature not only in terms of the approach adopted but also in terms of the choice of the empirical objective. (i) IDA is quite meaningful, and so this study builds the relationships among RIm, emissions efficiency, and the emissions technology gap through the DEA approach. Hence, the first contribution of this study is to provide a new idea regarding environmental research. (ii) This study extends the work of Chang (2019) who studies room for improvement in energy intensity under the DEA-metafrontier framework to the issue of CO_2 emissions and creates an indicator of room for improvement in emissions intensity. Hence, the second contribution of this study is to fulfill the application of an indicator of room for improvement not only in energy efficiency but also in environmental efficiency. (iii) The final one is that this study empirically investigates the regional heterogeneity of EU members. Up to now, many methods have used a homogeneous viewpoint when treating all EU members, and the results in this study show that there are significant variations among the countries. In fact, EU members should be divided based on geographic variations into countries in the Baltic Sea region (BSR) and countries in the non-Baltic Sea region (NBSR). By doing so, the research results provide correct and valuable information to policy-makers that benefits regional and organizational development.

The rest of this paper is organized as follows. The "Methodology" section describes the methodology. The "Empirical analysis" section presents the data sources, empirical results, and provides a relevant discussion. The "Conclusion" section concludes.

Methodology

This section uses index decomposition analysis to set up an indicator of room for improvement in emissions intensity. This study defines the production technology for a decision-making unit (DMU) as:

$$T(X,E)=\{(Y,B):(X,E,Y,B)\in T,X,\text{and }E\text{ can produce }Y\text{ and }B\text{ with technology }T\} \tag{1}$$

The symbols X, E, Y, and B in Eq. ((1) are the matrices of non-energy inputs, energy inputs, desirable outputs, and undesirable (bad) outputs. In terms of DMU 0, the symbols x_{h0}, e_{i0}, y_{j0}, and b_{k0} represent the hth non-energy input, ith energy input, jth desirable output, and kth bad output, respectively, where $h = 1\ldots s$, $i = 1\ldots t$, $j = 1\ldots u$, and $k = 1\ldots v$. Thus, the IDA identity used for the computation of emissions intensity for the kth emissions of DMU 0 takes the following form:

$$b_{k0}/z_0=(b_{k0}/e_{i0})(e_{i0}/z_0) \tag{2}$$

where z_0 stands for the gross domestic product of DMU 0, and $z_0 \in y_{j0} \in Y$. The terms (b_{k0}/e_{i0}) and (e_{i0}/z_0) in Eq. ((2) represent the carbonization index and energy intensity, respectively. We define the symbols f and F to represent the group frontier and metafrontier, respectively; and DMU $0 \in f \in F$. In addition, we define the target emissions level for DMU 0 for the kth emissions under the group frontier and the metafrontier as $b^{g}{}_{k0}$ and $b^{m}{}_{k0}$, respectively; where $0 \le b^{m}{}_{k0} \le b^{g}{}_{k0} \le b_{k0}$. Based on the metafrontier framework, DMU 0's RIm for the kth emissions is:

$$\begin{aligned} b_{k0}/z_0 -- b^{m}{}_{k0}/z_0 &= (b_{k0}/e_{i0})(e_{i0}/z_0) -- b^{m}{}_{k0}/z_0, \\ &= (b_{k0}/e_{i0})(e_{i0}/z_0)[1 -- (e_{i0}/b_{k0})(z_0/e_{i0})(b^{m}{}_{k0}/z_0)], \\ &= (b_{k0}/e_{i0})(e_{i0}/z_0)[1 -- (b^{m}{}_{k0}/b_{k0})], \\ &= (b_{k0}/ei0)(ei0/z0)[1-(b^{g}{}_{k0}/b_{k0})(b^{m}{}_{k0}/b^{g}{}_{k0})] \end{aligned} \tag{3}$$

where the terms $(b^{g}{}_{k0}/b_{k0})$ and $(b^{m}{}_{k0}/b^{g}{}_{k0})$ are the emissions efficiency for the kth emissions of DMU 0 (hereafter Em_{k0}) and the emissions technology gap ratio for the kth emissions of DMU 0 (hereafter TGm_{k0}). As for Eq. ((3), by dividing by b_{k0}/z_0, it can be rewritten as $(1 - b^{m}{}_{k0}/b_{k0}) \times 100\ \% = [1 - (b^{g}{}_{k0}/b_{k0})(b^{m}{}_{k0}/b^{g}{}_{k0})] \times 100\%$. Thus, a formal definition of RIm for the kth emissions of DMU 0 is:

$$\mathrm{RIm}_{k0}=(1-\mathrm{Em}_{k0}\times \mathrm{TGm}_{k0})\times 100 \tag{4}$$

The concept of RIm was initially proposed by Chang (2014, 2015), whose model framework was very different from the metafrontier framework presented in this paper. A comparison of Eqs. ((2) and (4) shows that the emissions intensity in Eq. ((2) is really related to energy consumption regardless of the carbonization index or energy intensity, while the room for improvement in emissions intensity in Eq. (4) is irrelevant to energy consumption but is related to emissions efficiency and the emissions technology gap ratio. With a view to computing RIm, this study employs the DEA approach to measure both Em and TGm.

We compute DMU 0's emissions efficiency by using model (5) as follows:

$$\begin{aligned} &\min \mathrm{Em}_0 = 1-\frac{1}{v}\textstyle\sum_{k=1}^{v}\varepsilon_{k0}/b_{k0} \\ &\text{s.t.} X\lambda \le x_{h0}, \\ &E\lambda \le e_{i0}, \\ &Y\lambda \ge y_{j0}, \\ &B\lambda = b_{k0}-\varepsilon_{k0}, \\ &\lambda \ge 0, x_{h0}\ne 0, e_{i0}\ne 0, y_{j0}\ne 0, b_{k0}\ne 0, \text{and } \varepsilon_{k0}\ge 0 \end{aligned} \tag{5}$$

In the objective function, a score for DMU 0's emissions efficiency of 1 (0) reveals that DMU 0's slack on the kth emissions is 0 (b_{k0}), i.e., ε_{k0} = 0 (b_{k0}), which means that DMU 0's emissions reduction potential is 0 (b_{k0}). It also implies that $\mathrm{Em}_0 \in [0, 1]$, because $\varepsilon_{k0} \in [0, b_{k0}]$. For model (5), one can refer to the model by Fei and Lin (2017) in which a radical DEA approach is employed to estimate a DMU's emissions efficiency, whereas the model herein is a slack-based measurement DEA approach. Based on the results in model (5), we can adjust the real emissions level to the target emissions level by:

$$b^{g}{}_{k0}=b_{k0}-\varepsilon_{k0} \tag{6}$$

The emissions efficiency score for the *k*th emissions of DMU 0 can be computed by:

$$\mathrm{Em}_{k0} = {b^{g}}_{k0} / b_{k0} \tag{7}$$

The emissions efficiency is the ratio of the target emissions level to the actual emissions level, and $\mathrm{Em}_{k0} \in [0, 1]$ since ${b^{g}}_{k0} \leq b_{k0}$.

This study next computes the emissions technology gap ratio under the metafrontier framework. To this end, we incorporate all of the DMUs' target emissions levels from the results in Eq. ((6) into the metafrontier DEA model in which DMU 0 belongs to the *r*th group, and the total number of groups is *n*. The computation of DMU 0's emissions technology gap ratio takes place through model (8) as follows:

$$\begin{aligned}
\min \mathrm{TGm}_0 &= 1 - \frac{1}{v} \sum_{r=1}^{n} \sum_{k=1}^{v} \varepsilon_{rk0} / b^{g}_{rk0} \\
&= 1 - \frac{1}{v} \sum_{r=1}^{n} \sum_{k=1}^{v} \varepsilon_{rk0} / b^{g}_{k0} \\
&\text{s.t.} X'\lambda' \leq x_{rh0}, \\
&E'\lambda' \leq e_{ri0}, \\
&Y'\lambda' \geq y_{rj0}, \\
&B^{g\prime}\lambda' = {b^{g}}_{k0} - \varepsilon_{rk0}, \\
&\lambda' \geq 0, x_{rh0} \neq 0, e_{ri0} \neq 0, y_{rj0} \neq 0, {b^{g}}_{k0} \neq 0, \varepsilon_{rk0} \geq 0, \text{and } r = 1 \ldots n
\end{aligned} \tag{8}$$

The objective function value represents DMU 0's emissions technology gap ratio, which is in effect, the emissions gap between the group frontier and the metafrontier. The symbols in the constraints $B^{g\prime}$ and ${b^{g}}_{k0}$ are denoted as the matrices and vectors of the emissions target levels under the group frontier framework. We now calculate the emissions target level under the metafrontier framework as follows:

$${b^{m}}_{k0} = {b^{g}}_{k0} - \varepsilon_{rk0} \tag{9}$$

The emissions technology gap ratio for the *k*th emissions of DMU 0 is presented as:

$$\mathrm{TGm}_{k0} = {b^{m}}_{k0} / {b^{g}}_{k0} \tag{10}$$

The emissions technology gap is the ratio of the target emissions level under the metafrontier framework to the target emissions level under the group frontier, and $\mathrm{TGm}_{k0} \in [0, 1]$ since ${b^{m}}_{k0} \leq {b^{g}}_{k0}$. This implies that if the target emissions levels with the group frontier and metafrontier are the same, then there is no emissions technology gap; on the contrary, a big emissions technology gap results from a big gap in target emissions levels between the group frontier and metafrontier.

We obtain the solution for RIm in Eq. (4) by using the solution for Em in Eq. ((7) and the solution for TGm in Eq. ((10). In addition, Eq. (4) also indicates that the way to shrink RIm is to improve Em and/or reduce TGm.

Empirical analysis

The data in this study were obtained from the World Bank database, and the data period covers the years from 2010 to 2014. The research objectives include 28 EU countries that are divided into 8 countries in the Baltic Sea region and another 20 countries in the non-Baltic Sea region. The desirable and undesirable outputs are chosen to denote the performance of economic activity, and energy consumption is also included in the analysis. All financial variables are measured under the same purchasing power standards with prices kept constant at 2010 levels. As for the details of the output and input variables, the former are real GDP expressed in millions of USD and CO_2 emissions measured in kilotons, while the latter are the real capital stock in millions of USD, the labor force in terms of the number of persons, and fossil fuel energy consumption in kilotons.

Data description

The results for the correlation coefficients among CO_2 emissions and the other variables are presented in Table 1. Here, the correlation coefficients between real GDP and CO_2 emissions and between fossil fuel energy consumption and CO_2 emissions are very high, regardless of whether for the EU, NBSR, or BSR. Moreover, the correlation coefficients for fossil fuel energy consumption and CO_2 emissions are always higher than those for real GDP and CO_2 emissions, implying that CO_2 emissions are more related to energy consumption than GDP creation. Hence, energy consumption reflects the CO_2 emissions of each economy. The interesting point is to check whether a country with a relatively high level of GDP uses energy more productively.

The results of a primary test are presented in Table 2 where the energy intensities in the BSR and NBSR countries are 75.666 and 68.295, respectively; the CO_2 emissions intensities in the BSR and NBSR countries are 0.234 and 0.191, respectively; and the results for all EU members are higher than that for the NBSR countries, but lower than that for the BSR countries. The results show that BSR countries with high GDP exhibit high intensities for CO_2 emissions and energy consumption, while NBSR countries with low GDP reveal low intensities for CO_2 emissions and energy consumption. In other words, a high GDP country does not exhibit high efficiency in regard to CO_2 emissions and energy use in the EU as a whole. This study further examines CO_2 emissions intensity, CO_2 emissions efficiency, and the CO_2 emissions technology gap in BSR and NBSR countries.

Investigating the EU's CO_2 emissions

Based on the composition of room for improvement in CO_2 emissions intensity, the results of the composition analysis in

Table 1 Correlation coefficient matrix

Item/DMU/variable		Real GDP	Real capital stock	Labor force	Fossil fuel energy consumption
CO_2 emissions	EU	0.942	0.797	0.972	0.997
	NBSR	0.964	0.783	0.973	0.998
	BSR	0.950	0.836	0.997	0.998

Table 3 show that Estonia among the BSR countries and Bulgaria among the NBSR countries always have the largest RIm during the research period. Eurostat Pocketbooks (2012) published by the European Commission indicates that Estonia and Bulgaria have the highest energy intensity in the BSR and NBSR countries, respectively. In addition, Cornille and Fankhauser (2004) and Streimikiene and Šivickas (2008) also find that Estonia has the highest energy intensity among the Baltic Sea states. This result illustrates that there is a close relationship between energy utilization and CO_2 emissions in Estonia and Bulgaria. On average, Estonia and Bulgaria also have the largest RIm, but their RIm sources are very different. Their emissions efficiency scores are similar, but Bulgaria has a larger emissions technology gap than Estonia, meaning that Estonia can shrink its RIm by employing emissions management, but Bulgaria can also do it not only by means of emissions management but also by using advanced emissions technology. Denmark and Sweden have 0% RIm on average among the BSR countries, while only Luxembourg and the UK have that among the NBSR countries. Eurostat Pocketbooks (2012) indicates that Denmark has the lowest levels of energy intensity in the EU. Hence, CO_2 emissions reduction can be implemented through an energy policy such as Denmark with the lowest energy intensity in the EU taking up the highest share of energy taxes in its final electricity price (2015).

Estonia, Latvia, and Lithuania are not only three economies in the former Soviet Union, but are also Baltic Sea states where their RIms in order from small to large are Lithuania (62%), Latvia (65%), and Estonia (89%). This result is consistent with the finding by Chang et al. (2016) in which Lithuania has the highest achievement ratio for CO_2 emissions among these three Baltic Sea states from 2005 to 2011. The smaller RIm in Lithuania may be caused by the closure of its Ignalina nuclear power plant in 2009 and its enhanced renewable energy utilization. Moreover, the Lithuanian Environmental Ministry actively deals with air pollution through stipulations on industrial plants. Mendiluce et al. (2010) indicate that Denmark had the lowest energy intensity from 2000 to 2006. In addition, Chang et al. (2016) show that Denmark had the highest achievement ratio in terms of energy utilization and the highest achievement ratio for CO_2 emissions from 2004 to 2011. Our study also finds that Denmark and Sweden have a 0% RIm from 2010 to 2014. Even though Germany has engaged in climate protection through a shift from fossil fuel and nuclear power to a renewable-based energy system, some reports cite fresh data to show that Germany is likely to miss its carbon reduction target due to unexpectedly strong economic growth, low energy prices, the continued rise in power exports, and population growth. Huang et al. (2008) confirm that although Germany's emissions did follow a decreasing trajectory, they did not conform with the environmental Kuznets curve (EKC) hypothesis. The numerical results in Table 3 show that Germany's bad performance in regard to RIm was caused by its emissions efficiency and not its emissions technology.

In terms of NBSR states, Luxembourg and the UK both have a 0% RIm during the whole of the data period, while Ireland reveals a small RIm of 7%. Countries with an RIm of over 80% include Bulgaria (89%), the Czech Republic (82%), and Romania (80%). All three have not only low emissions efficiency but also a big emissions technology gap. One way for them to reduce RIm is to enhance emissions management and to introduce advanced emissions technology. Since Luxembourg and the UK are traditionally high GDP states, the environmental policy of Ireland serves as a valuable reference for some countries with a high RIm. Ireland is ranked as having the highest average wind speeds in the EU, and hence, it has an abundance of wind energy. In addition, its mild temperate climate and long growing seasons create high productivity soils for biofuels. Moreover, Ireland is putting a lot of effort into research and development (R&D) on solar energy and offshore wave energy. Renewable energy utilization not only directly reduces GHG emissions but also

Table 2 CO_2 emissions intensity and energy intensity

DMU/indicator	CO_2 emissions (kt)	Fossil fuel energy consumption (kt)	Real GDP (millions of USD)	CO_2 emissions intensity	Energy intensity
EU	124,538.130	43,021,712.050	609,795.478	0.204	70.551
NBSR	113,115.362	40,461,615.470	592,451.301	0.191	68.295
BSR	153,095.050	49,421,953.500	653,155.920	0.234	75.666

Table 3 Emissions efficiency, emissions technology gap ratio, and room for improvement in emissions intensity

Region of EU	Country name	2010			2011			2012			2013			2014			Average		
		Em	TGm	RIm	Em	TGm	RIm	Em	TGm	RIm	Em	TGm	RIm	Em	TGm	RIm	Em	TGm	RIm
BSR	Denmark	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%
	Estonia	0.129	1.000	87%	0.113	1.000	89%	0.108	1.000	89%	0.091	1.000	91%	0.094	1.000	91%	0.107	1.000	89%
	Finland	0.466	1.000	53%	0.449	1.000	55%	0.442	1.000	56%	0.426	1.000	57%	0.423	1.000	58%	0.441	1.000	56%
	Germany	0.597	1.000	40%	0.562	1.000	44%	0.502	1.000	50%	0.517	1.000	48%	0.504	1.000	50%	0.536	1.000	46%
	Latvia	0.397	1.000	60%	0.376	1.000	62%	0.335	1.000	66%	0.323	1.000	68%	0.338	1.000	66%	0.354	1.000	65%
	Lithuania	1.000	0.404	60%	0.354	1.000	65%	0.337	1.000	66%	1.000	0.433	57%	1.000	0.395	61%	0.738	0.646	62%
	Poland	0.181	1.000	82%	0.161	1.000	84%	0.145	1.000	86%	0.147	1.000	85%	0.162	1.000	84%	0.159	1.000	84%
	Sweden	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%
NBSR	Austria	0.791	0.803	37%	0.776	0.783	39%	0.823	0.678	44%	0.802	0.639	49%	0.783	0.688	46%	0.795	0.718	43%
	Belgium	0.643	0.734	53%	0.663	0.727	52%	0.695	0.636	56%	0.662	0.607	60%	0.630	0.656	59%	0.659	0.672	56%
	Bulgaria	0.153	0.819	87%	0.139	0.821	89%	0.152	0.680	90%	0.167	0.626	90%	0.149	0.716	89%	0.152	0.732	89%
	Croatia	0.411	0.855	65%	0.388	0.824	68%	0.415	0.692	71%	0.404	0.661	73%	0.382	0.726	72%	0.400	0.752	70%
	Cyprus	0.442	0.799	65%	0.452	0.824	63%	0.514	0.718	63%	0.559	0.799	55%	0.513	0.832	57%	0.496	0.794	61%
	Czech Republic	0.248	0.799	80%	0.248	0.799	80%	0.252	0.694	82%	0.248	0.644	84%	0.226	0.698	84%	0.244	0.727	82%
	France	1.000	0.858	14%	1.000	0.811	19%	1.000	0.694	31%	1.000	0.644	36%	1.000	0.698	30%	1.000	0.741	26%
	Greece	0.654	0.924	40%	0.544	0.984	46%	0.515	0.897	54%	0.603	0.993	40%	1.000	1.000	0%	0.663	0.960	36%
	Hungary	0.381	0.852	68%	0.369	0.830	69%	0.365	0.693	75%	0.383	0.669	74%	0.359	0.722	74%	0.371	0.753	72%
	Ireland	1.000	1.000	0%	1.000	1.000	0%	1.000	0.826	17%	1.000	0.944	6%	1.000	0.856	14%	1.000	0.925	7%
	Italy	0.772	0.851	34%	0.730	0.831	39%	0.785	0.713	44%	0.822	0.771	37%	0.828	0.763	37%	0.787	0.786	38%
	Luxembourg	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%
	Malta	0.455	0.799	64%	0.459	0.824	62%	0.494	0.721	64%	0.599	0.818	51%	0.635	0.873	45%	0.528	0.807	57%
	Netherlands	0.678	0.851	42%	0.659	0.832	45%	0.685	0.712	51%	0.655	0.750	51%	0.625	0.751	53%	0.660	0.779	49%
	Portugal	0.702	0.854	40%	0.657	0.833	45%	0.670	0.722	52%	0.705	0.881	38%	0.678	0.868	41%	0.682	0.831	43%
	Romania	0.282	0.799	77%	0.244	0.799	80%	0.249	0.694	83%	0.297	0.644	81%	0.279	0.698	81%	0.270	0.727	80%
	Slovak Republic	0.329	0.799	74%	0.324	0.799	74%	0.343	0.694	76%	0.341	0.644	78%	0.345	0.698	76%	0.336	0.727	76%
	Slovenia	0.418	0.839	65%	0.407	0.817	67%	0.414	0.687	72%	0.425	0.663	72%	0.455	0.737	66%	0.424	0.749	68%
	Spain	0.705	0.799	44%	0.631	0.799	50%	0.618	0.694	57%	0.676	0.637	57%	0.648	0.713	54%	0.656	0.728	52%
	UK	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%	1.000	1.000	0%

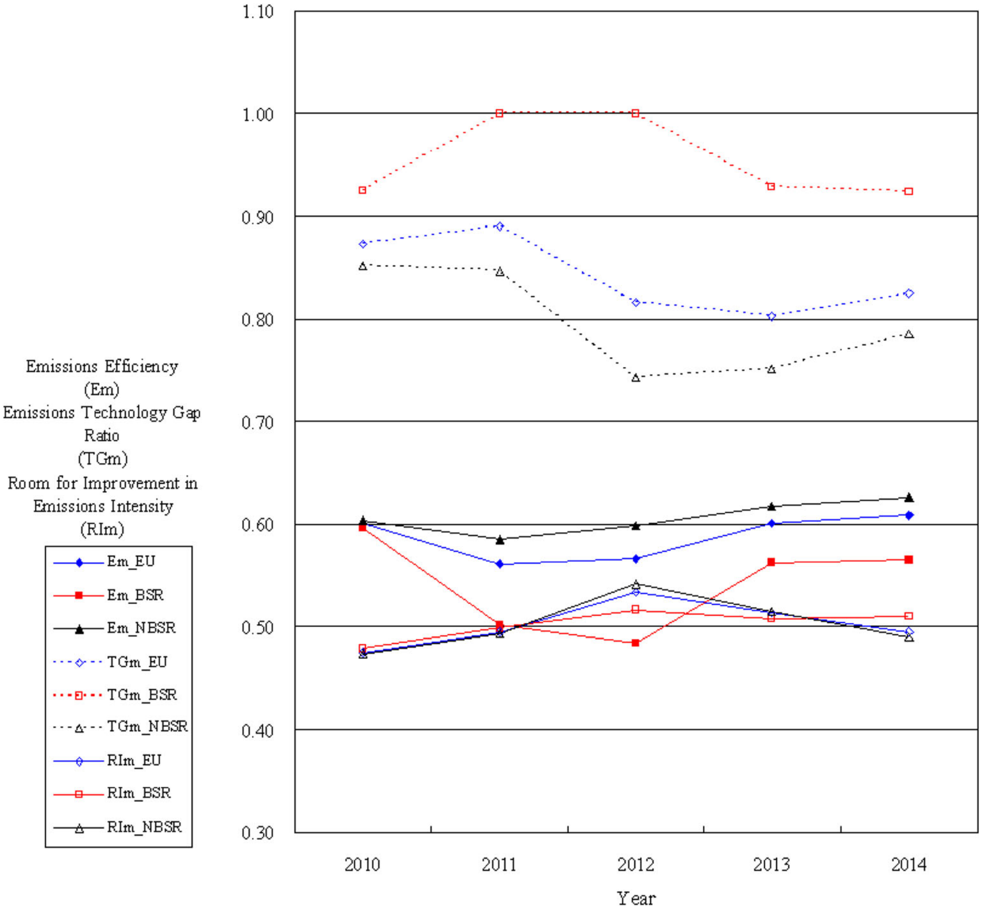

Fig. 1 A regional comparison of Em, TGm, and Rim

indirectly improves emissions technology. In other words, Ireland's renewable energy R&D results in a low RIm. This viewpoint is supported by Zhang et al. (2013b), who believe that the technological innovation for oil-fired plants not only improves energy but also boosts CO_2 emissions performance.

Regional comparison

Figure 1 shows the results of our regional analysis in which the region is considered in terms of the EU, BSR, and NBSR, and a comparison on their Em, TGm, and RIm. The trends in RIm reveal an inverted-U shape, which means that their RIm first deteriorates and then improves. For the year 2012, the RIm for the NBSR countries is larger than that for the BSR countries; the RIm for the NBSR countries is smaller than that for the BSR countries in 2014; and for the other years, the RIms are similar.

We next look at the different sources of RIms by comparing their Ems and TGms. Here, Em in the NBSR countries is always superior to Em in the BSR countries; but in terms of TGm, BSR countries are always better than NBSR countries. Hence, this study speculates that BSR countries having a small RIm in 2012 is caused by a small TGm; on the other hand, NBSR countries having a small RIm in 2014 is caused by a high Em. Figure 1 also indicates that the TGm gap between them is larger than their Em gap. Emissions technology refers to the scientific technology applied to emissions reduction; emissions efficiency refers to the result of applying emissions technology; and advanced emissions technology is helpful in improving emissions efficiency. Yoshida et al. (2003) compare the CO_2 emissions efficiency among various biomass energy conservation technologies, regarding which Australia has developed low emissions technology to improve silicon photovoltaic emissions efficiency.

Advanced emissions technology should in general be related to high emissions efficiency; however, a paradoxical phenomenon occurs in BSR and NBSR countries in which the former presents a small TGm and low Em, and the latter reveals a large TGm and high Em. This interesting result implies that the emissions technology in BSR countries is advanced,

Table 4 Correlation coefficient analysis for Em, TGm, and Rim

Region	BSR		NBSR		EU	
Item	Em	TGm	Em	TGm	Em	TGm
RIm	− 0.584	0.313	− 0.072	− 0.839	− 0.428	− 0.683

but at a preliminary stage, it creates low emissions efficiency. Although the emissions technology in NBSR countries is a little out of date, it is at the mature stage and thus results in high emissions efficiency. On the other hand, this result also implies that BSR is full of R&D momentum regarding low emissions technology, and it also indicates that NBSR countries should channel more R&D investment into low emissions technology in order to follow-up with more advanced emissions technology.

The results in Table 4 provide more evidence that the emissions technology in BSR countries is at the preliminary stage, because the small TGm induces a high RIm. Conventional thinking is that improvements in Em and TGm shrink RIm. This idea can be confirmed from the EU and NBSR countries, but it does not appear in the BSR countries. This surprising result cannot be obtained from past studies since they do not decompose RIm into Em and TGm. In fact, one available way to shrink RIm in BSR countries is through improvements in Em, while shrinking RIm in NBSR countries and the EU can be taken place through improvements in Em and TGm. One thing environmental policy-makers should note is that a reduction in RIm does not fully depend only on an increase in Em; instead, one has to examine whether there is an improvement in TGm.

Following the EKC hypothesis, an inverted-U shape between economic growth and environmental quality is analogous to the income-inequality relationship known as the Kuznets (1955) curve. Grossman and Krueger (1995) provide a formal description of the EKC hypothesis. They note that the EKC hypothesis gives rise to an inverted-U-shaped relationship between income per capita and environmental degradation, which implies that economic growth has a negative environmental impact during the early stage of economic development, and then economic growth contributes to a positive environmental impact after a critical point in economic development is reached. An EKC hypothesis test appears in Fig. 2 in which the *x*-axis and *y*-axis stand for per capita GDP and CO_2 emissions, respectively. The increase (decrease) in per capita GDP represents economic development (depression), and the increase (reduction) in CO_2 emissions represents environmental degradation (improvement).

Based on the information obtained from the scatter diagram depicted in Fig. 2, the per capita GDP in the BSR countries exhibits obvious differences, which are split into either the

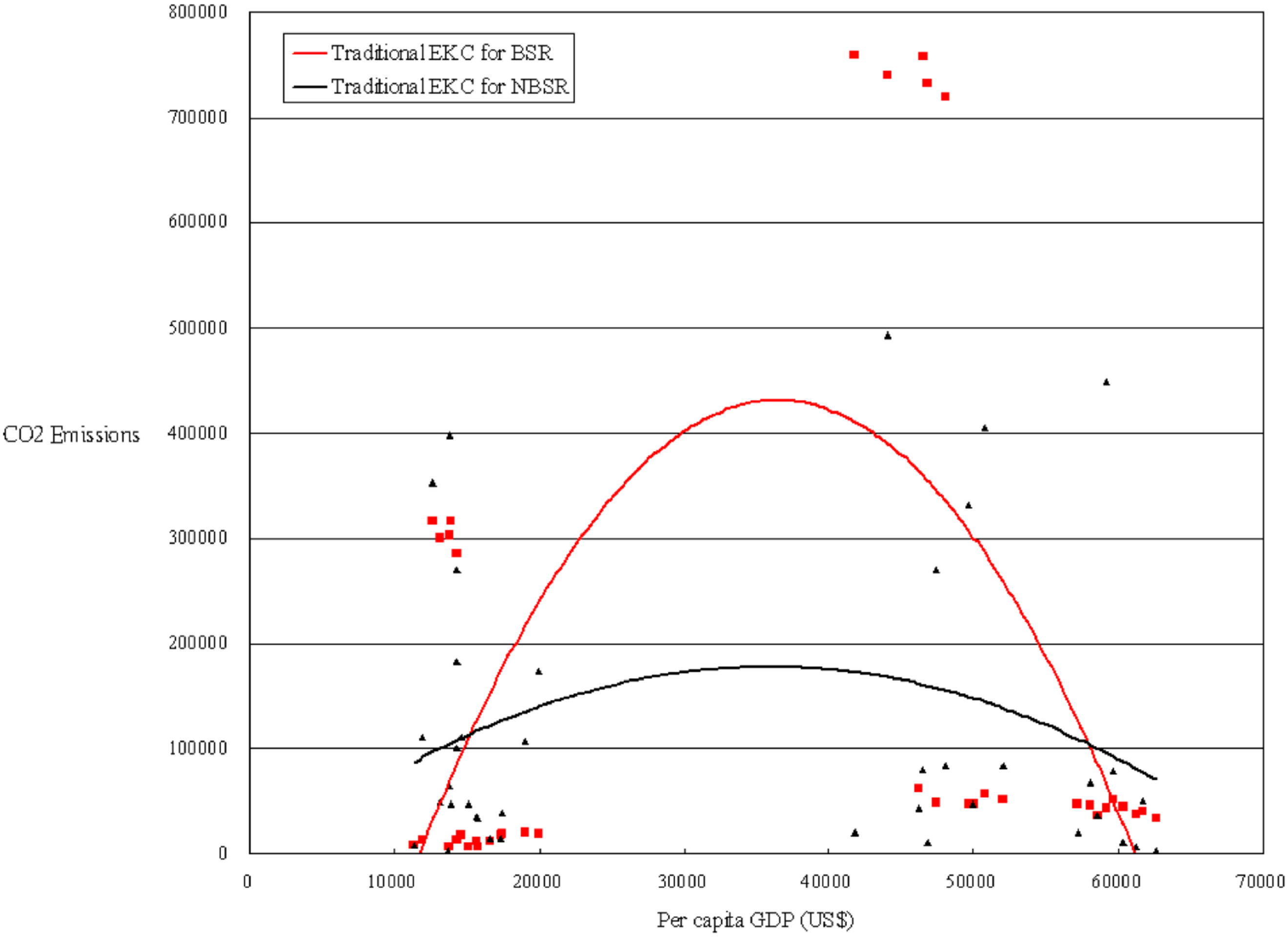

Fig. 2 Traditional EKC

high per capita GDP (hereafter H-GDP) group or the low per capita GDP (hereafter L-GDP) group. In addition, the H-GDP and L-GDP groups are further divided into the high CO_2 emissions (hereafter H-Emissions) group and the low CO_2 emissions (hereafter L-Emissions) group. In other words, the four types of countries in the BSR group are L-GDP and L-Emissions, L-GDP and H-Emissions, H-GDP and L-Emissions, and H-GDP and H-Emissions. Although this phenomenon also appears in the NBSR group of countries, it is not that obvious. In Fig. 2, we note that the EKC, regardless of whether for the BSR or NBSR countries, has an inverted-U shape that not only satisfies the EKC hypothesis but also means that economic development at the final stage benefits environmental improvement. We can say that the inverted-U-shaped relationship between per capita GDP and CO_2 emissions is a better economic development mode, and this mode also appears among the BSR and NBSR countries.

In a departure from the traditional EKC test in Fig. 2, this study next examines the target-consideration EKC (hereafter TC-EKC) relationship between per capita GDP and RIm. The TC-EKC involves utilizing the CO_2 emissions target in the traditional EKC; thus, this study uses RIm instead of CO_2 emissions to test the EKC hypothesis. The test results in Fig. 3 show that the TC-EKC for the BSR countries still reveals an inverted-U shape, but for the NBSR countries, a U-shaped TC-EKC is observed that is different from the inverted-U-shaped EKC in Fig. 2. This result shows that economic development in the BSR countries really helps CO_2 emissions achieve to the target level of CO_2 emissions. Although CO_2 emissions in the NBSR countries fall following economic growth, the target level of CO_2 emissions is not achieved. Hence, the TC-EKC in comparison with the traditional EKC is more powerful in terms of confirming the relationship between economic development and environmental improvement. The RIm indicator hence needs to be employed in the TC-EKC test. This viewpoint is this study's contribution that cannot be found in the previous literature.

Conclusion

One contribution of this paper is that it creates a target-consideration environmental Kuznets curve that is based on the indicator for room for improvement in emissions intensity. The other contribution is that it decomposes the indicator of room for improvement in emissions intensity into emissions efficiency and the emissions technology gap ratio using the metafrontier DEA approach. In other words, two effects involved in the room for improvement in emissions intensity are emissions efficiency and the emissions technology gap; the

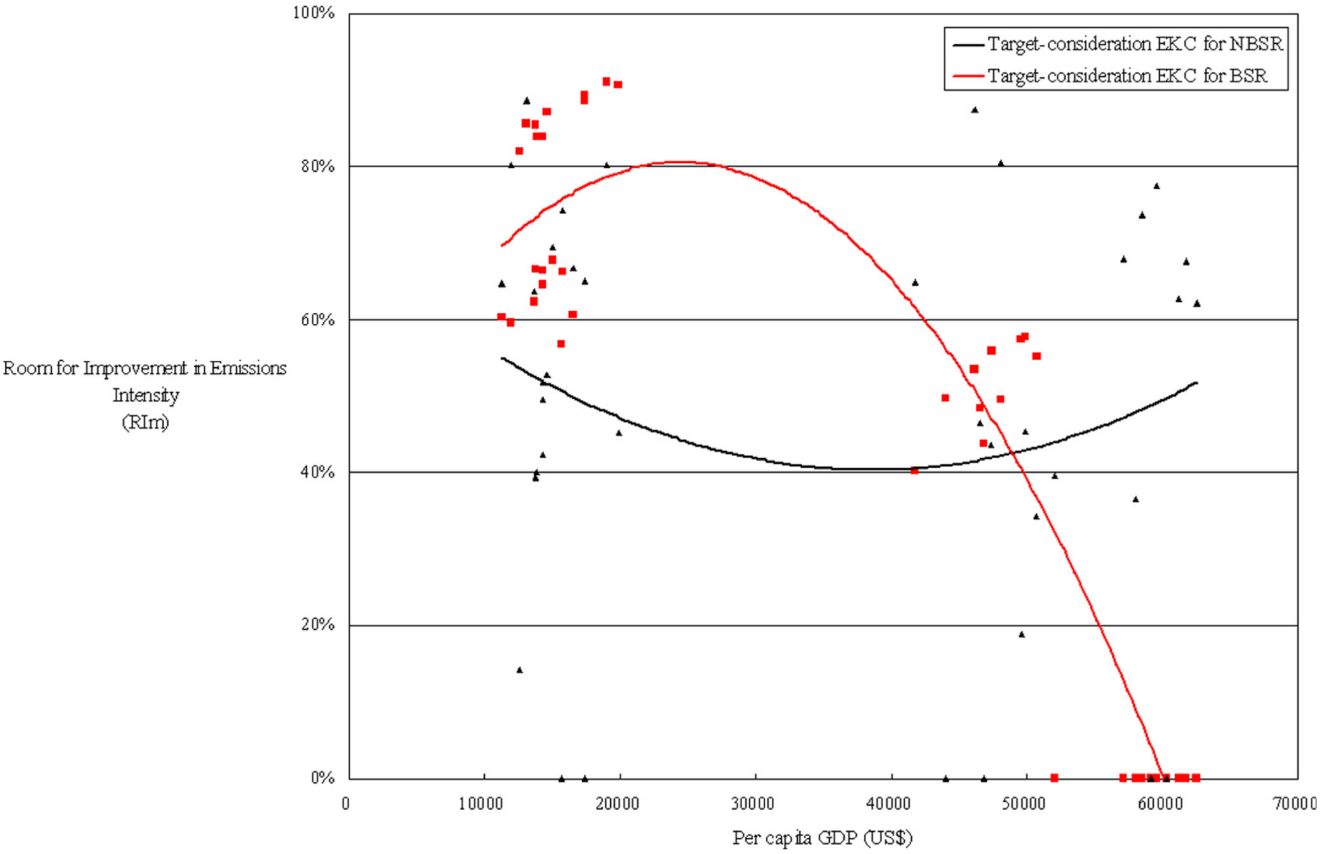

Fig. 3 Target-consideration EKC

former is related to the level of emissions management and the latter is related to the level of emissions technology. Hence, a DMU with a zero score for room for improvement in emissions intensity implies that it operates at the highest level of emissions efficiency and has the lowest emissions technology gap. Alternatively, we can say that it operates under the best emissions management and uses the most advanced emissions technology. Contrary to the case of a DMU with a zero score, a DMU with a positive non-zero score for room for improvement in emissions intensity implies that it does not operate on the best-practice metafrontier of CO_2 emissions. This type of DMU can switch to the best-practice metafrontier of CO_2 emissions by improving emissions efficiency and/or enhancing emissions technology. The indicator regarding the decomposition of the room for improvement in emissions intensity provides insights into DMUs having inefficient CO_2 emissions that can achieve the optimal CO_2 emissions in a precise way. This contribution helps fill the gap of past studies on room for improvement in energy intensity by Chang (2014), room for improvement in emissions intensity by Chang (2015), and room for improvement in energy intensity under the DEA-metafrontier framework by Chang (2019). This paper further pays attention on studying room for improvement in emissions intensity under the DEA-metafrontier framework.

The observations in this study are the 28 EU member states and, based on geographic location, they are divided into 8 Baltic Sea region states and 20 non-Baltic Sea region states. This paper not only investigates emissions efficiency and the emissions technology gap based on the room for improvement in emissions intensity among the EU members but also engages in a regional comparison. Many studies in the literature have directed more attention toward examining emissions efficiency or emissions intensity, but have seldom touched upon the issue of the room for improvement in emissions intensity. Furthermore, this paper incorporates the concept of room for improvement in emissions intensity into the traditional environmental Kuznets curve and further creates the target-consideration environmental Kuznets curve. Our research results indicate that the decline in the room for improvement in emissions intensity not only enhances emissions efficiency but also upgrades emissions technology. In addition, greater environmental reality can be revealed through the target-consideration environmental Kuznets curve. The above contribution cannot be obtained before decomposing and applying the indicator for the room for improvement in emissions intensity.

The other empirical results in this paper give rise to the following findings. (i) From the perspective of the traditional environmental Kuznets curve, the Baltic Sea region and non-Baltic Sea region countries conform to the inverted-U shape between per capita GDP and environmental degradation; however, from the perspective of the target-consideration environmental Kuznets curve, the non-Baltic Sea region countries do not conform to the inverted-U shape of the environmental Kuznets curve. (ii) The Baltic Sea region countries reveal a small emissions technology gap, but low emissions efficiency. However, the Baltic Sea region countries differ from the non-Baltic Sea region countries, since in the former there is a large emissions technology gap, but high emissions efficiency. Hence, an effective way for a country in the Baltic Sea region to reduce its room for improvement in emissions intensity is to direct more attention toward emissions management. As for countries in the non-Baltic Sea region, they should upgrade their emissions technology. (iii) Denmark and Sweden in the Baltic Sea region and Luxembourg and the UK in the non-Baltic Sea region have a zero score on average as regards the room for improvement in emissions intensity. These four countries are widely recognized to be developed economies with very high GDPs. This result implies that some emerging countries in the EU such as those in the Baltic Sea region still have not caught up with certain other countries in terms of emissions efficiency and/or emissions technology, and thus, these four countries may serve as an emissions improvement model for the countries that are falling behind to follow in their footsteps.

Future studies can place the rooms for improvement in energy intensity and emissions intensity into one model and then decompose the room for improvement in overall efficiency into the rooms for improvement in energy intensity and emissions intensity. Aside from the model innovation such as the suggestion above, future studies can also replace empirical observations with difference-level datapoints, such as company, industry, administration, province, or other international organizations.

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