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Will economic development enhance the energy use efficiency and CO_2 emission control efficiency?

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ABSTRACT

This study employs data envelopment analysis approach to construct the meta-frontier global technical efficiency of energy use index and global technical efficiency of CO_2 emission control index to measure the energy use efficiency and CO_2 emission control efficiency at country level. Destruction of these efficiency indices into pure technical efficiency and scale efficiency sub-indices is to capture sources of inefficiency in relation to the development of an economy. The results indicate that for developed countries the enhancement of the pure technical efficiency in the energy use and the scale efficiency of CO_2 emission control are important tasks to pursue. On the contrary, developing countries have to seek the improvement of the pure technical efficiency of CO_2 emission control and scale efficiency of energy use.

1. Introduction

More and more scientific evidence verifies the causal relationship between the emission of greenhouse gases (GHG) and global warming. The United Nations Framework Convention on Climate Change (UNFCCC) ratified in 1992 Summit in Rio, Brazil, started tackling this emissions problem. At the third Conference of Parties in 1997, numerous countries committed to reduce CO_2 emissions by signing the Kyoto Protocol. The average emission level of the six greenhouse gases, including carbon dioxide (CO_2), must fall by 5.2%, relative to 1990 levels by 2012 (United Nations, 2007). Thus, minimising CO_2 emissions is an important challenge for many countries.

Fossil fuels have been the most important energy resource, generating rapid economic development for many developed countries. The higher the development of the economy, the more energy is required. This also indicates more GHG emissions are expected. Under such circumstances, maintaining the use of energy technology and/or complying with the emission reduction commitment will slow down or even sacrifice the development of the economy.

Currently, most of the 38 countries that ratified Kyoto Protocol to commit to reducing emissions are developed countries. The bounded emissions of GHG and CO_2 in particular will slow down the use of energy and development of the economy for these countries (United Nations, 2007). Other developing countries with high GHG emissions, however, are expected to be brought into future emission reduction commitments (Tonn, 2003).

To achieve the objectives of both economic development and a commitment to CO_2 emission reduction, policies designed to change the production structure through the change of energy use and control of CO_2 emission are foreseeable. Most research in this area uses decomposition approach to destruct the carbon intensity index into carbonization index and energy intensity to measure the amount of CO_2 emissions and the energy requirement for every domestic national product (GDP) created[2] (Kaya, 1990; Mielnik & Goldemberg, 1999; Zhang, 2000).

However, the decomposition of the carbon intensity index have been challenged for being too subjective, for not taking the production process into account and could not be applied to the cross units comparison (Dietz & Rosa, 1994; York, Rosa, & Dietz, 2005). Tyteca (1996), Yunos and Hawdon (1997), and Lozano and Gutiérrez (2008) have resolved these deficiencies using the efficiency measure index based on productive efficiency perspective. The focuses of these studies can be divided into two categories. One type is to analyse the energy use and its relationship with economic output, and the other type is to focus on the importance of control on CO_2 emission.

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[2] Kaya identity can be represented as $CO_2/GDP = (Energy/GDP) \times (CO_2/Energy)$ to measure the influences of energy intensity, i.e. *Energy/GDP*, and carbonization index, i.e. $CO_2/Energy$, on the carbon intensity, i.e. *Energy/GDP*.

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It can be concluded that the common framework for these two streams of literature is to utilise the theory of production to construct an efficiency index for relative efficiency comparisons among the country or firm decision-making units (DMU) and/or along the time trends. The difference between all these works is that some studies examine the efficiency comparison at the country level (e.g., Arcelus & Arocena, 2005; Barla & Perelman, 2005; Färe, Grosskopf, & Heranadez-Sancho, 2004; Hawdon, 2003; Hu & Kao, 2007; Kumar, 2006; Murillo-Zamorano, 2005; Zhou, Ang, & Poh, 2008), and others focus on the firm level (e.g., Coelli, Lauwers, & Huylenbroeck, 2007; Vaninsky, 2008; Wossink & Denaux, 2006).

In addition, the change in technology and institutions through the progress of economic development will have an impact on the consumption of energy and transformation of technology (Suri & Chapman, 1998). All these changes will further influence the efficient use of energy and efficient control of CO_2 emission. As a result, the development of the economy should have a certain linkage between the energy use efficiency and the CO_2 emission control efficiency. The existing efficiency analysis literature, however, has not investigated the interaction between the energy use efficiency, CO_2 emission control efficiency, and economic development in a theoretical or empirical aspect.

As such, this study employ the data envelopment analysis approach (DEA) to construct the global technical efficiency (TE) of energy use index (denoted as EU_{TE}) and global technical efficiency of CO_2 emission control index (denoted as CEC_{TE}) to measure the energy use efficiency and CO_2 emission control efficiency at the DMU of country level. Furthermore, in order to capture the sources and factors of inefficiencies of energy use and CO_2 emission control and to understand how these factors change in relation to the development of an economy, this study further deconstructs the index of EU_{TE} into pure technical efficiency (PTE) of energy use (denoted as EU_{PTE}) and scale efficiency (SE) of energy use (denoted as EU_{SE}) to capture the DMU's management performance and production scale's influence on energy use efficiency. Similarly, deconstruction of the index of CEC_{TE} into pure technical efficiency of CO_2 emission control (denoted as CEC_{PTE}) and scale efficiency of CO_2 emission control (denoted as CEC_{SE}) is employed to measure how those factors affect the CO_2 emission control efficiency and to identify their relations with the economic development.

In sum, there are three purposes to this study. Our first goal is to construct the possible interrelationship among economic development, energy use efficiency, and CO_2 emission control efficiency. Secondly, we estimate the EU_{TE}, EU_{PTE}, EU_{SE} and explore their relationship with economic development. Similarly, we perform this analysis for the CO_2 emission control efficiency. Finally, we identify the relationships among global technical efficiency, pure technical efficiency, scale efficiency, and economic development both for energy use and CO_2 emission control.

In order to conduct the empirical analyses, we utilise data from The Climate Analysis Indicator Tool (CAIT) (World Resource Institute, 2008), United Nations Statistics Division (2008) and the World Development Indicators (WDI) from the World Bank (2008). The selection of countries and the corresponding years follows the rules of representation, completeness, and consistency for analysing the issues of global change (Levett, 1998). The empirical analyses hereafter use 57 countries in total, including all the countries on the Kyoto Protocol, during the years of 1990 through 2005.

2. The correlations among economic development, energy use efficiency, and CO_2 emission control efficiency

Utilisation of fossil energy is the main power for a society's economy. It is also the major source of GHG, primarily CO_2. It is expected that every country will have a different responsibility for the reduction of GHG in general or CO_2 in particular (United Nations, 2007). Decreasing the use of fossil energy could be necessary to reduce emissions worldwide. However, it is essential to achieve the ideal emission reduction goals without sacrificing economic development.

From input–output production structure, energy can be treated as one of important factor in the development of economy. The development of the economy is a desired outcome in this process, but the emission of CO_2 is not. Within the production structure, the commitment to reduce emissions and the desire for persistent economic development implies that there are two goals existing for each DMU at country level in the use of energy. The first goal is to generate more output from a lower input of energy, i.e. increases for the energy use efficiency. The second goal is to decline CO_2 emissions generated from fossil energy, i.e. increases for the CO_2 emission control efficiency. Both policy goals described above are summarised in Fig. 1 below.

To achieve both policy goals, it is necessary to control the factors that influence the energy use efficiency and CO_2 emission control efficiency. These factors mainly fall into three categories. The first category is the pressure from the general public while the economy is reaching a certain stage of development. Relatively rigorous environmental regulations are required. That is, fewer environmentally harmful types of energies would be in demand (Suri & Chapman, 1998; Vaninsky, 2008). The second category of these factors is the improvement in efficiency from new technologies. The same amount of production output can be produced from less energy, or the same amount of energy can generate less CO_2 (Mielnik & Goldemberg, 1999; Richmond & Kaufmann, 2006). The third category relates to the change of the industrial structure that decreases the high demand of energy. This could be a change from a manufacturing sector to a service sector. High economic values are not necessarily accompanied by high levels of CO_2; instead, the composition effect of changing sectors is created (Grossman & Krueger, 1995).

Economic development makes possible the opportunity to increase the energy use efficiency and CO_2 emission control

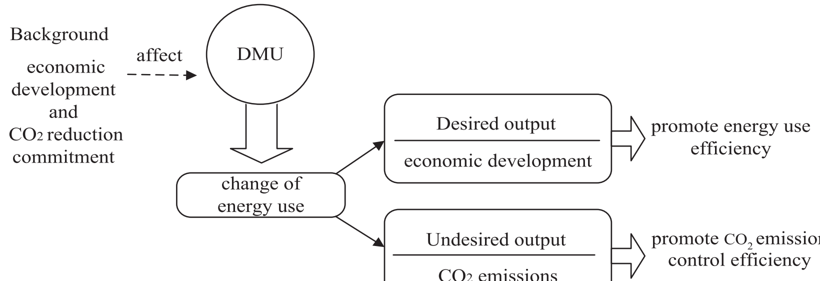

Fig. 1. Policy goals of considering both sides in economic development and CO_2 missions reduction commitment.

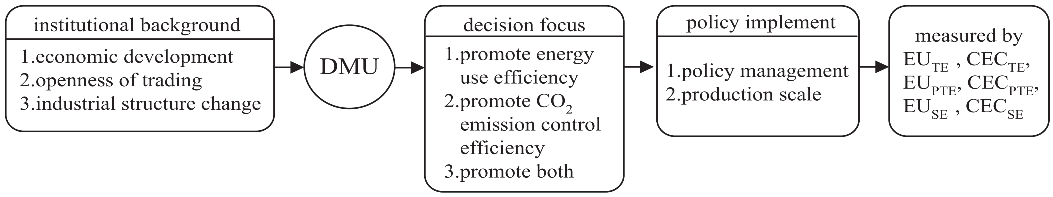

Fig. 2. Relationship among economic development, energy use efficiency, and CO_2 emission control efficiency.

efficiency, but the efficiency increments will rely upon the determination of DMU (Friedl & Getzner, 2003; Grossman & Krueger, 1995; Heerink, Mulatu, & Bulte, 2001; Heil & Selden, 2001; Lindmark, 2002; Ravallion, Heil, & Jalan, 2000; Schmalensee, Stoker, & Judson, 1998). That is, the interference and management of policies are required for an ideal efficient status to be realised (Dinda, 2004; Panayotou, 1997). Since the increase in the energy use efficiency and CO_2 emission control efficiency are different concerns and policy focuses, the relationship between these two efficiencies, along with economic development, might be compatible or substitutes for one another. From a normative viewpoint, to achieve the committed amounts of CO_2 reduction, it is a win–win scenario to increase both of these two efficiency indices, as Fig. 2 summarises. This study's analyses of the relationship among various efficiency indices can inform the policy's focus.

3. Construction of empirical models

The environmental Kuznets curve (EKC) is the most popular and traditional curve used to portray the relationship between economic development and environmental quality. The emission of CO_2 is one of the indices used in the analysis of environmental quality, while the relationship between economic development and the emission of CO_2 is examined in the EKC literature (Dijkgraaf & Vollebergh, 2005; Ravallion et al., 2000; Rezek & Rogers, 2008; Schmalensee et al., 1998). The emission of CO_2 is the negative output of economic development, and a reduced form model is normally used in those studies.

However, the emission of CO_2 and economic development are an input–output production structure connected with each other. A reduced form neither fully reflects the input of energy use to its transformation of corresponding environmental quality nor reflects its contribution to the overall development of the economy. That is, traditional EKC studies only capture the relationship and path of economic development and environmental quality. It is unable to provide a possible explanation beyond this path. Additionally, it is difficult to assess the potential policy implications by using a single environmental quality index. Multiple input and output efficiency measured indices are therefore suggested (Färe et al., 2004; Zaim & Taskin, 2000).

As a result, constructions of energy use efficiency indices and CO_2 emission control efficiency indices will be used in the substitution for a traditional single environmental quality index. The model of EKC is specified to associate the relationship between the energy use efficiency indices and economic development with the relationship between the CO_2 emission control efficiency indices and economic development. It will also connect the interrelationships among the three.

3.1. Constructions of the indices of energy use efficiency and CO_2 emission control efficiency

Based on the input and output interrelationship among the use of energy, emission of CO_2 and gross product of a nation, we employ DEA approach to construct the indices of energy use efficiency and CO_2 emission control efficiency. DEA approach is a non-parametric method developed by Farrell (1957) from the output distance function (Zhou et al., 2008). The DMU located on the production frontier is described as the most efficient production unit. The value of efficiency is thus defined to be 1. The relative efficiency between 0 and 1 is also determined. For those with a positive contribution to output, such as the use of energy, values close to 0 indicate relatively less efficiency, and values close to 1 mean relatively greater efficiency. On the contrary, for those with negative impact on output, such as CO_2 emission control, values close to 1 indicate relatively less efficiency, and values close to 0 denote relatively more efficiency.

It is assumed that there are K DMU using N kinds of inputs with M types of output. The ith DMU uses X_{ni} inputs to produce Y_{mi} outputs. The input-oriented efficiency value of each unit can be maximised from (1)

$$\begin{aligned}
&\max \sum_{m=1}^{M} \phi_{mi} y_{mi} \\
&s.t \quad \sum_{n=1}^{N} \varphi_{ni} x_{ni} = 1 \\
&\qquad \sum_{m=1}^{M} \phi_{mi} y_{mi} - \sum_{n=1}^{N} \varphi_{ni} x_{ni} \leqslant 0; \quad i = 1,2,\ldots,K \\
&\qquad \phi_{mi}, \varphi_{ni} \geqslant 0; \quad n = 1,2,3\ldots,N; \quad m = 1,2,3\ldots,M
\end{aligned} \tag{1}$$

where ϕ_{mi} is the weighted coefficient for mth output, and φ_{ni} is the weighted coefficient for the nth input. The principle of duality is applied to obtain the related information for slack variables. Eq. (2) is transformed accordingly:

$$\begin{aligned}
&\min \theta_i - \varepsilon\left(\sum_{n=1}^{N} s_n + \sum_{m=1}^{M} s_m\right) \\
&s.t \quad \sum_{i=1}^{K} y_{mi}\lambda_i - s_m = y_{mi}; \quad m = 1,2\ldots,K; \; m = 1,2,3\ldots,M \\
&\qquad \theta_i x_{ni} - \sum_{j=1}^{K} x_{ni}\lambda_i - s_n = 0; \quad n = 1,2,3\ldots,N \\
&\qquad \lambda_i, s_m, s_n \geqslant 0
\end{aligned} \tag{2}$$

where θ_i is the relative efficiency for the ith unit, s_m is the slack variable of output, s_n is the slack variable of input, and λ_i is the scale weighted coefficient for each unit.

Index θ_i is the global technical efficiency, and it is assumed that each DMU follows constant return to scale (CRS) to continue the production. This is the CCR model (Charnes, Cooper, & Rhodes, 1978). However, it is unable to identify the sources of global technical inefficiency under such an assumption. As a result, Banker, Charnes, and Cooper (1984) suggest the variable-return-to-scale technology (VRS), also known as the BCC model; as such, a limitation of (2) $\sum_{j=1}^{K} \lambda_i = 1$ is added. Under the BCC model, pure technical efficiency and scale efficiency can be distinguished from global technical efficiency to capture the influence from policy manage and production scale. Along with global technical efficiency, the relationship between pure technical efficiency and scale efficiency can be described as (3)

$$TE = PTE \times SE \tag{3}$$

3.2. Empirical models for the interrelationship among economic development, energy use efficiency, and CO_2 emission control efficiency

The empirical models are specified for the interrelationship among economic development, energy use efficiency, CO_2 emission control efficiency, and their sub-efficiency indices: PTE and SE. These efficiency indices are used as dependent variables. The independent variables include economic development and all other variables that are deemed to influence the various efficiency indices described above. The EKC equation is the base on which to frame the interaction between economic development and the different types of efficiency indices. All the possible combinations of the interactions are outlined in Fig. 3.

The general form linking all the efficiency indices and economic development can be specified as (4) and (5):

$$EU_l = f(Y, Z); \quad l = TE, PTE, SE \tag{4}$$

$$CEC_l = g(Y, Z); \quad l = TE, PTE, SE \tag{5}$$

where, Y is the variable of economic development, and Z is the vector of all other variables affecting the above efficiency indices.

The explanatory variables have been compiled from the past studies. The GDP per capita is used to represent the variable of economic development. A variable for the openness of trade is also included as it could be a driving force, either positively or negatively, for the energy use and CO_2 emission control (Grossman & Krueger, 1995; Suri & Chapman, 1998; Zaim & Taskin, 2000). Furthermore, the areas with higher population density normally have relatively active economic transactions. This has led to higher demand and supply of energy use and consumption. Population density is deemed to be an important factor affecting the energy use efficiency and CO_2 control efficiency (Cropper & Griffiths, 1994; Scruggs, 1998; Selden & Song, 1994). Finally, the energy use is also affected by the industrial structure. In general, the higher the ratio of industry value to the share of GDP, the higher the related efficiency indices (Grossman & Krueger, 1995). As a result, the variable of this ratio is also included in the analysis.

Among the above variables, there are six relationships connecting various efficiency indices and economic development. The functional form for the relationship between efficiency indices and economic development can be specified as linear, quadratic, and cubic, respectively listed in (6-1)–(7-3):

$$EU_{lit} = \alpha_{1i} + \alpha_2 GDP_{it} + \alpha_3 Dens_{it} + \alpha_4 Indus_{it} + \alpha_5 Open + \varepsilon_{it} \tag{6-1}$$

$$EU_{lit} = \alpha'_{1i} + \alpha'_2 GDP_{it} + \alpha'_3 GDP^2_{it} + \alpha'_4 Dens_{it} + \alpha'_5 Indus_{it} + \alpha'_6 Open + \varepsilon'_{it} \tag{6-2}$$

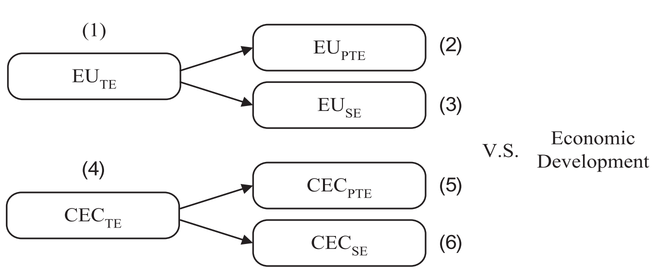

Fig. 3. All potential frameworks of the enhancement of the energy use efficiency and CO_2 emission control efficiency.

$$EU_{lit} = \alpha''_{1i} + \alpha''_2 GDP_{it} + \alpha''_3 GDP^2_{it} + \alpha''_4 GDP^3_{it} + \alpha''_5 Dens_{it} + \alpha''_6 Indus_{it} + \alpha''_7 Open + \varepsilon''_{it} \tag{6-3}$$

$$CEC_{lit} = \beta_{1i} + \beta_2 GDP_{it} + \beta_3 Dens_{it} + \beta_4 Indus_{it} + \beta_5 Open + \nu_{it} \tag{7-1}$$

$$CEC_{lit} = \beta'_{1i} + \beta'_2 GDP_{it} + \beta'_3 GDP^2_{it} + \beta'_4 Dens_{it} + \beta'_5 Indus_{it} + \beta'_6 Open + \nu'_{it} \tag{7-2}$$

$$CEC_{lit} = \beta''_{1i} + \beta''_2 GDP_{it} + \beta''_3 GDP^2_{it} + \beta''_4 GDP^3_{it} + \beta''_5 Dens_{it} + \beta''_6 Indus_{it} + \beta''_7 Open + \nu''_{it} \quad l = TE, PTE, SE \tag{7-3}$$

where α, α', α'', β, β', and β'' are coefficients to be estimated. *Dens* is the population density, *Indus* is the industrial value to the share of GDP, and *Open* is the openness of trading. The subscripts i and t designate country and year respectively, and ν, ν', ν'', ε, ε', and ε'' are random variables. The best fits of estimated results are selected for all the analyses henceforth.

3.3. Data sources

There are two parts of data required for all the analyses. The first part of the data is for constructing the related efficiency indices. The second part is for preparing the estimations of EKC for all the frameworks proposed in Fig. 3.

In order to construct the indices of efficiencies, the index of energy use efficiency requires the input items of labour, real capital formation, and total energy use. The output items are real GDP, which are GDP deflated by the price level of 1990. As with the index of CO_2 emission control efficiency, the input requires fossil fuel energy consumption, and the output is the emission of CO_2.

We use cross-country CO_2 emissions data for our analysis. A relatively complete data bank with all the climate indicators is currently collected by World Resource Institute (WRI). This data bank contains the cumulative emissions of all GHG since 1950, yearly emission, energy density, and various socio-economic variables, such as health status, education level, population, etc. The newest data in this data bank has been updated to 2005 and covers 186 countries, including Taiwan. Data for real capital formation, labour input, energy use, and consumption of fossil fuels come from WDI. The variable for real capital formation is deflated by the 1990 price level from the United Nations Statistics Division (2008) to eliminate the price effect.

Data for population density, openness of trade, and the industrial value to the share of GDP are also obtained from WDI. Among these, there is no existing variable for openness of trade to use. We therefore follow Zaim and Taskin's (2000) idea to construct it by dividing the sum of export and import values by the total value of GDP. Except for the Taiwanese CO_2 emission data, which can be found in the CAIT data bank, the data for all the above variables for Taiwan have been collected from the relevant agencies in the country. These variables thus required preparation to make them comparable to the corresponding variables collected from other sources for final use. Variables for real capital formation, labour input, population density, industrial value to share of GDP, openness of trade, and GDP are collected from the Directorate-General of Budget, Accounting, and Statistics (2009) of Taiwan. Variable of labour input is rearranged by multiplying the quantity of labour by the employment rate. The industrial value to the share of GDP is the value of industry divided by the corresponding GDP value and is deflated by the price level. The variable of openness of trade is constructed by dividing the sum of export and import values to the total value of gross national product. The data for the use of energy and consumption of fossil energy are obtained from the Bureau of Energy, Ministry of Economic Affairs (2009) of Taiwan.

Table 1
All the sample countries and their corresponding total CO_2 emission percentage.[a]
Source: Arranged from World Resource Institute (2008).

Country[b]	Total emission percentage (%)	Country[b]	Total emission percentage (%)
United States	26.67	Taiwan	0.52
China	9.88	Belarus	0.42
Russian Federation*	9.44	Sweden*	0.38
Germany*	5.74	Thailand	0.37
Japan*	4.82	Hungary*	0.37
United Kingdom*	3.61	Egypt	0.34
India	2.59	Bulgaria*	0.34
Ukraine*	2.40	Austria*	0.32
France*	2.29	Denmark*	0.31
Canada*	2.21	Slovakia*	0.28
Poland*	1.93	Greece*	0.28
Italy*	1.83	Malaysia	0.26
South Africa	1.33	Pakistan	0.26
Mexico	1.24	Finland*	0.26
Australia*	1.19	Algeria	0.24
Kazakhstan	1.05	Colombia	0.23
Spain*	1.02	Switzerland*	0.22
South Korea	1.00	Portugal*	0.17
Brazil	0.99	Norway*	0.16
Iran	0.84	Ireland*	0.15
Czech Republic*	0.82	New Zealand*	0.12
Netherlands*	0.80	Estonia*	0.11
Romania*	0.71	Lithuania*	0.09
Belgium*	0.70	Croatia*	0.08
Saudi Arabia	0.69	Luxembourg*	0.07
Indonesia	0.66	Slovenia*	0.06
Uzbekistan	0.63	Latvia*	0.06
Argentina	0.56	Iceland*	0.01
Venezuela	0.55		
		Total percentage	93.73

[a] Countries are listed according to the descending order of the cumulative total CO_2 emissions percentages in 1950–2005.
[b] Names of countries with asterisk '*'are the Annex B countries in the Kyoto Protocol. Among these, Morocco and Liechtenstein are not included due to lack of data in the related data banks.

The fossil energy consumption variable is defined as the total consumption of coal, all coal products, petroleum products, indigenous natural gas, and imported liquefied natural gas.

The selection of the countries includes not only the countries in Annex B of the Kyoto Protocol, but also those countries with the 50 highest cumulative total CO_2 emissions from 1950 to 2005. There are 57 countries in the final data set. These countries, listed in Table 1, produce 93.73% of the world's total CO_2 emissions. The most complete and consistent data for all these countries exist between 1990 and 2005. As such, the sample analysed is a set of panel data consisting of 912 observations from 57 countries over 16 years.

4. Analyses of empirical results

Due to the use of pooling countries and time series panel data in this study, a fixed effect model (FE) and random effect model (RE) are suitable methods to estimate Eqs. (6-1)–(7-3). In addition, to avoid the endogeneity problem between GDP per capita and various efficiency indices, a variable of (GDP_{t-1}) along with other explanatory variables are used as the instrument variables. A two-stage approach is used for estimation. Tables 2 and 3 report the estimated results. The test statistics show that, for all equations, the fixed effect models have better fit than their random effect model counterparts.

4.1. The interaction between energy use efficiency and economic development

The estimated results presented in Table 2 show that various forms of GDP per capita (*GDP*), the industry value to the share of GDP (*Indus*), population density (*Den*), and openness of trade (*Open*) do have significant impacts on EU_{TE}. The higher the industry value to the share of GDP and the higher the population density, the higher the EU_{TE} is. An increase in population density and open trading will increase the EU_{TE}. As shown in Table 2, the cubic form of (6-3) performs better than their linear and quadratic counterparts. This form is thus used in Fig. 4 to depict the relationship between EU_{TE} and economic development. This indicates that the EU_{TE} increases as GDP per capita improves, and then it declines. A further increase in the efficiency of energy use does not occur until the GDP per capita reaches 20,000 US dollars. It is found that only a third of the income level in the sample are above this level. That is, the relationship between EU_{TE} and economic development for the remaining two-thirds of the countries is in the position of increasing GDP per capita with a decline to EU_{TE}.

As with EU_{PTE}, various forms of GDP per capita (*GDP*), population density (*Den*), and openness of trade (*Open*) also have a significant impact on EU_{PTE}. The higher the degree of trade openness and the higher population density, the better the EU_{PTE} is. This phenomenon mainly benefits from the positive effect of transition and interaction between the countries through more open trade. A situation similar to the relationship estimated for the EU_{PTE} and economic development occurs: the N-shaped form of (6-3), shown in Fig. 4, performs relatively better in all three functional specifications. The first turning point is far below the boundary that can be pictured, and the second turning-point is at GDP per capita of 61,000 US dollars. This is a much greater income level than exists in any country. This also implies that the EU_{PTE} has not been enhanced by economic development in any country.

In addition, various forms of GDP per capita (*GDP*), the industry value to the share of GDP (*Indus*), and openness of trade (*Open*) have significant impact on the EU_{SE}. The higher the ratio of the industry value to the share of GDP, the farther away the production scale is from the constant return to scale, and the EU_{SE} is then declining. It reveals that the best estimated specification for the relationship between economic development and EU_{SE} is the cubic, inverse-N-shaped form from (6-3), shown in Fig. 4. Most countries are in the range of simultaneous increase of GDP per capita and EU_{SE}. That is, for most of countries, an increase in GDP per capita brings EU_{SE} toward optimal production scale.

In the use of energy, all three curves, EU_{TE}, EU_{PTE}, and EU_{SE}, are measured based on meta-frontiers of ranking all 57 countries from 1990 to 2005. These curves represent the highest EU_{TE}, EU_{PTE}, and EU_{SE} that all DMU currently achieve. The overall results indicate that most countries have paid more attention to increasing the EU_{SE} to gain more output than that to the improvement of EU_{PTE} or EU_{TE}. That is, as their economies develop, most countries do not take advantage of either the EU_{PTE} or EU_{TE} through better technology. In order to reduce CO_2 and maintain a certain level of economic development, a potential policy has to redirect attention to advancing the EU_{PTE}.

4.2. The interaction between CO_2 emission control efficiency and economic development

The results presented in Table 3 show the estimated relationship between economic development and CEC_{TE}, CEC_{PTE}, and CEC_{SE}, respectively. It shows that the various forms of GDP per capita (*GDP*), the industry value to the share of GDP (*Indus*), and population density (*Den*) have a significant impact on the CEC_{TE}. The higher the ratio of the industry value to the share of GDP, the higher efficiency the value of CEC_{TE} is. This indicates that an increase in GDP per capita does not lead the CO_2 emission control in an efficient direction. All the test statistics demonstrate that the cubic form of (7-3) performs best among the three types of specifications. The first turning-point is not shown in Fig. 5 due to the

Table 2
Estimated results of energy use efficiency and economic development.[a,b]

Variable	Global technical efficiency of energy use and economic development[c]			Pure technical efficiency of energy use and economic development[c]			Scale efficiency of energy use and economic development[c]		
	Linear (6-1)	Quadratic (6-2)	Cubic (6-3)	Linear (6-1)	Quadratic (6-2)	Cubic (6-3)	Linear (6-1)	Quadratic (6-2)	Cubic (6-3)
lnGDP	−0.1287***	−0.0521	1.7019**	−0.2241***	−0.1852	2.8238***	0.1155***	0.2241***	−0.6184*
	(−5.720)	(−0.487)	(2.286)	(−9.165)	(−1.593)	(3.510)	(11.053)	(4.523)	(−1.794)
$(\text{lnGDP})^2$	–	−0.0049	−0.2196**	–	−0.0025	−0.3708***	–	−0.0069**	0.0961**
	–	(−0.732)	(−2.429)	–	(−0.342)	(−3.794)	–	(−2.242)	(2.296)
$(\text{lnGDP})^3$	–	–	0.0086**	–	–	0.0146***	–	–	−0.0041**
	–	–	(2.381)	–	–	(3.779)	–	–	(−2.470)
Indus	−0.00004	−0.0001	−0.0002	0.0007	0.0007	0.0005	−0.0010***	−0.0011***	−0.0010***
	(−0.058)	(−0.076)	(−0.244)	(0.953)	(0.944)	(0.683)	(−3.025)	(−3.088)	(−2.916)
Den	0.0020***	0.0020***	0.0017***	0.0021***	0.0020***	0.0016***	0.0001	−0.0001	−0.00002
	(4.789)	(4.659)	(3.960)	(4.518)	(4.438)	(3.431)	(0.453)	(−0.730)	(−0.115)
Open	0.0577***	0.0595***	0.0599***	0.0395**	0.0404**	0.0412**	0.0125	0.0152*	0.0149*
	(3.164)	(3.233)	(3.264)	(1.996)	(2.022)	(2.073)	(1.482)	(1.776)	(1.760)
Constant	1.4977***	1.2162***	−3.410*	2.350***	2.2074***	−5.7293***	−0.0297	−0.4289**	1.7936*
	(7.914)	(2.838)	(−1.714)	(11.431)	(4.740)	(−2.664)	(−0.339)	(−2.161)	(1.947)
Adj-R^2	0.8913	0.8912	0.9016	0.8783	0.8782	0.8803	0.8617	0.8624	0.8634
F value	99.34***	93.05***	92.46***	83.24***	82.05***	82.55***	71.98***	71.46***	71.07***
Hausman χ^2	134.94***	124.47***	39.25***	196.47***	173.43***	46.89***	79.78***	55.76***	31.28***

[a] Numbers in parentheses are *t* values of corresponding estimated coefficients.
[b] Numbers for all estimated coefficients and test statistics with one, two, and three asterisks indicate the coefficient are significantly different from zero at 10%, 5%, and 1% significant level respectively.
[c] Number under each equation is the corresponding equation specified in the text.

Table 3
Estimated results of CO_2 emission control efficiency and economic development.[a,b]

Variable	Global technical efficiency of CO_2 emission control and economic development[c]			Pure technical efficiency of CO_2 emission control and economic development[c]			Scale efficiency of CO_2 emission control and economic development[c]		
	Linear (7-1)	Quadratic (7-2)	Cubic (7-3)	Linear (7-1)	Quadratic (7-2)	Cubic (7-3)	Linear (7-1)	Quadratic (7-2)	Cubic (7-3)
lnGDP	-0.0215	-0.0824	1.0363*	−0.0025	−0.0312	0.6694**	−0.0198**	−0.1029**	0.8559***
	(−1.278)	(−1.029)	(1.859)	(−0.125)	(−0.319)	(1.978)	(−2.207)	(−2.508)	(2.896)
$(lnGDP)^2$	–	0.0039	−0.1330**	–	0.0018	−0.0839**	–	0.0056**	−0.1122***
	–	(0.777)	(−1.964)	–	(0.229)	(−2.009)	–	(2.090)	(−3.127)
$(lnGDP)^3$	–	–	0.0055**	–	–	0.0034**	–	–	0.0046***
	–	–	(2.027)	–	–	(2.034)	–	–	(3.292)
Indus	0.0013**	0.0013**	0.0013**	0.0013*	0.0013*	0.0012*	0.0001	0.0001	0.0001
	(2.374)	(2.392)	(2.248)	(1.867)	(1.873)	(1.796)	(0.434)	(0.487)	(0.257)
Den	−0.0008***	−0.0008***	−0.0009***	−0.0001	−0.0001	−0.0002	−0.0008***	−0.0008***	−0.0009***
	(−2.670)	(−2.552)	(−2.971)	(−0.356)	(−0.315)	(−0.556)	(−5.159)	(−4.870)	(−5.550)
Open	−0.0129	−0.0144	−0.0141	−0.0070	−0.0076	−0.0075	−0.0140*	−0.0161**	−0.0158**
	(−0.946)	(−1.042)	(−1.026)	(−0.419)	(−0.456)	(−0.447)	(−1.926)	(−2.196)	(−2.180)
Constant	0.7017***	0.9252***	−2.0254	0.5531***	0.6585	−1.1895	1.1283***	1.4483***	−1.0912
	(4.955)	(2.886)	(−1.359)	(3.189)	(1.676)	(−0.650)	(14.934)	(8.486)	(−1.382)
Adj-R^2	0.7102	0.7102	0.7113	0.8515	0.8514	0.8516	0.9684	0.9685	0.9689
F value	28.92***	28.53***	28.33***	66.33***	65.39***	64.56***	350.55***	347.49***	347.44***
Hausman χ^2	17.40***	17.14***	19.17***	12.27**	12.84**	13.16***	11.18**	13.54**	18.27***

[a] Numbers in parentheses are *t* values of corresponding estimated coefficients.
[b] Numbers for all estimated coefficients and test statistics with one, two, and three asterisks indicate the coefficient are significantly different from zero at 10%, 5%, and 1% significant level respectively.
[c] Number under each equation is the corresponding equation specified in the text.

relatively small range of the sample level of GDP per capita. The income levels of a third of the countries are far above the second turning point, with a GDP per capita of 17,000 US dollars in the sample. That is, the other two-thirds of the countries are in the range of concurrent increasing GDP per capita and improvement of CEC_{TE}.

Regarding the CEC_{PTE}, various forms of economic development variables (*GDP*) and the industry value to the share of GDP (*Indus*) are the major factors influencing this type of efficiency. Similar to the CEC_{TE}, the cubic form estimated by (7-3) performs best among all specifications. Due to the reserved efficiency value defined for energy emission control, an inverse-N-shaped relationship, shown in Fig. 5, is then attained. The corresponding estimated second turning point occurs at a GDP per capita of 11,000 US dollars, which is lower than that for CEC_{TE}. About 63.14% of the countries benefit from the pure technical efficient control of energy emission. This includes most of the developing countries and some of the developed countries. It also indicates that, for an economy at

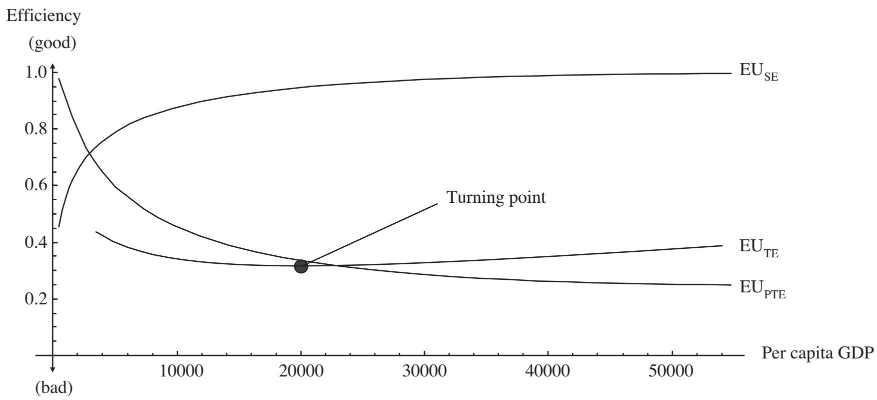

Fig. 4. Relationship of GDP per capita and energy use efficiency.

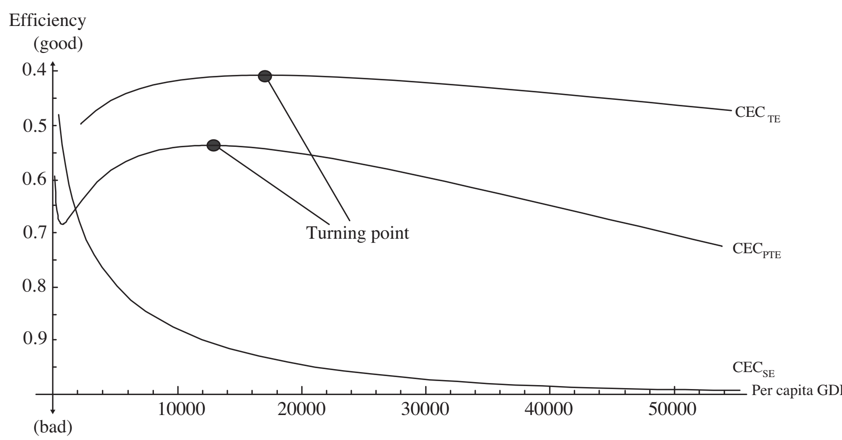

Fig. 5. Relationship of CO_2 emission control efficiency and GDP per capita.

an early stage of development, the CEC_{PTE} will naturally benefit from its small economic scale. However, the CEC_{PTE} will then confront the environmental regulations, institutional designs, and various enforcement difficulties when the economy approaches the levels of a developed country.

Finally, the CEC_{SE} is mainly affected by various forms of GDP per capita (*GDP*), population density (*Den*), and openness of trade (*Open*). The higher the density of population or openness of trade, the lower the value of CEC_{SE} is. This corresponds to a more efficient control of CO_2 emission. The cubic form specification of (7-3) has the best outcome of all the functional forms indentified above. Similarly, an inverse-N-shaped relationship, shown as Fig. 5, between CEC_{SE} and economic development is portrayed. The relationship reveals that, for all countries, CEC_{SE} moves away from the ideal level as GDP per capita increases. Similarly, the curves of CEC_{TE}, CEC_{PTE}, and CEC_{SE} are obtained from meta-frontiers from ranking all 57 countries over 16 years. These curves represent the best CEC_{TE}, CEC_{PTE}, and CEC_{SE} currently achieved.

4.3. Interrelationship among economic development, energy use efficiency, and CO_2 emission control efficiency

With the estimated relationships between economic development and EU_{TE}, EU_{PTE}, EU_{SE}, CEC_{TE}, CEC_{PTE}, and CEC_{SE} described above, the interaction between economic development, the energy use efficiency and CO_2 emission control efficiency – either TE, PTE, or SE – can be indirectly inferred from the four quadrants shown in Figs. 6–8. The interaction among these three provide us with the information to know whether different aspects of energy use efficiency and CO_2 emission control efficiency are compatible or substitutable along the economic development. Such information will guide decision makers to a better choice of policy focus since

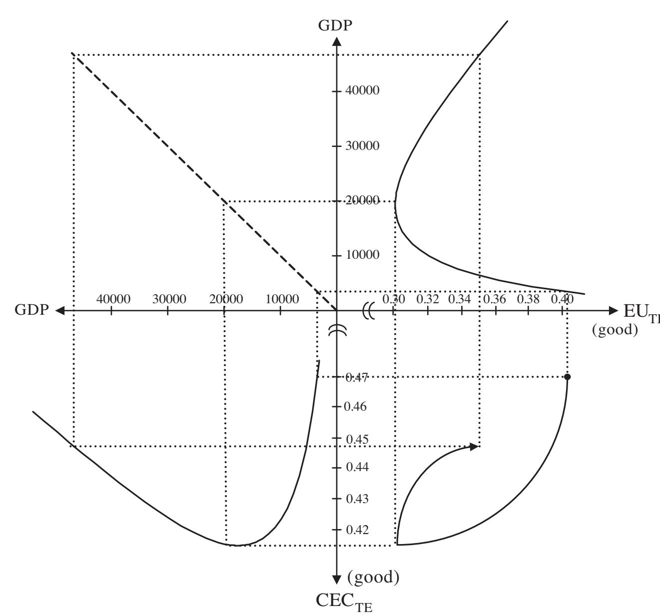

Fig. 6. The relationship among EU_{TE}, CEC_{TE}, and GDP per capita.

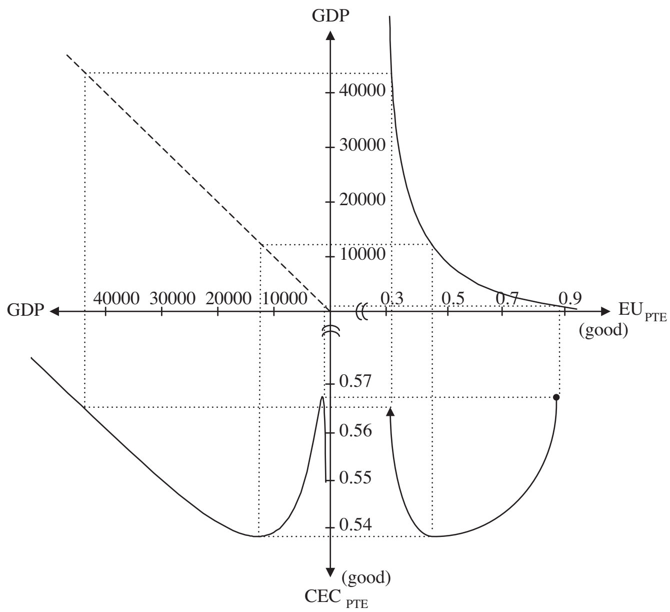

Fig. 7. The relationship among EU_{PTE}, CEC_{PTE}, and GDP per capita.

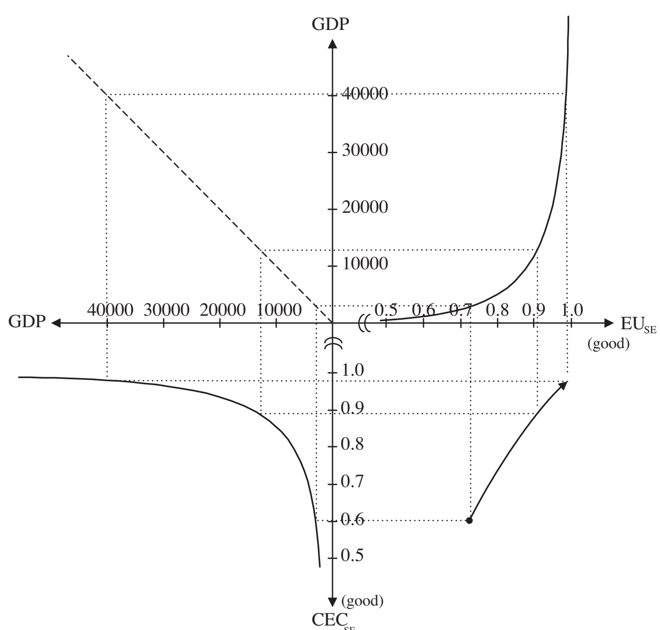

Fig. 8. The relationship among EU_{SE}, CEC_{SE}, and GDP per capita.

the use of energy and reduction of CO_2 emission are inescapable, and development of the economy is essential.

The first and the third quadrants in Fig. 6 show the curves of EU_{TE} and CEC_{TE} from Figs. 4 and 5, respectively. The second quadrant shows a 45° angle for transposing the GDP per capita from the vertical to horizontal axis. The fourth quadrant is the indirectly inferred relationship between EU_{TE} and CEC_{TE}. It shows that increasing EU_{TE} will sacrifice the CEC_{TE} up to GDP per capita of 20,000 US dollars. The reverse situation occurs after that. We should look deeply for what the possible sources of the substitution and comparability of these PTE of energy use and CO_2 emission control may be.

Similar procedures are applied to construct Fig. 7 to obtain the interaction between EU_{PTE} and CEC_{PTE}. It can be observed from the fourth quadrant of Fig. 7 that a trade-off exists between EU_{PTE} and CEC_{PTE} before GDP per capita reaches 11,000 dollars. Beyond this level of GDP per capita, both of these efficiency indices simultaneously decline. That is, there is no advantage to EU_{PTE} or CEC_{PTE} while the economy is further developed.

Fig. 8 presents the interaction between EU_{SE} and CEC_{SE}. It is shown that EU_{SE} and CEC_{SE} simultaneously exhibit a complementary relationship throughout the development of the economy. This indicates that it is hard to achieve an efficient status concurrently along these two indices while developing the economy.

5. Concluding remarks

This study's primary purpose is to explore a possible interrelationship among economic development, energy use efficiency, and CO_2 emission control efficiency. It further deconstructs the global technical efficiency of energy use and global efficiency of CO_2 emission control into their pure technical efficiency and scale efficiency, respectively. The interrelationship among global technical efficiency, pure technical efficiency, scale efficiency, and economic development, both for energy use and CO_2 emission control, can thus be identified. Fifty-seven countries, including all the emission reduction commitment countries in the Kyoto Protocol, are analysed from 1990 to 2005.

The results show that for the energy use efficiency, CO_2 emission control efficiency, or any sub-indices of their related efficiency, economic development, represented by GDP per capita, is a significant factor. It is thus essential to note the relationship between any of the efficiency indices and economic development in order to observe the change in these efficiencies along the development of economy.

As the development of their economies proceeds, most countries take advantage of neither the pure technical efficiency of energy use nor the global technical efficiency of energy use through better technology. In order to achieve the objective of CO_2 emission reduction and to maintain a certain level of economic development, potential policies have to redirect their focus from changing the scale efficiency of energy use to advancing the pure technical efficiency of energy use.

For the efficiency of CO_2 emission control, most of the countries in the sample are located in the declining efficiency of global technical efficiency of CO_2 emission control. It suggests that countries at very early stages of development will naturally benefit from the pure technical efficiency of CO_2 emission control due to the small scale of their economies. However, this efficiency will then confront the environmental regulations, institutional designs, and various enforcement difficulties when the economy approaches developed country levels at a per capita GDP near 17,000 dollars. This results in the declining CO_2 emission control efficiency for large scale emissions, accompanied by large scale production.

Finally, the interrelationship among economic development, energy use efficiency, and CO_2 emission control efficiency indicate that the increasing global technical efficiency of CO_2 emission control has to be accompanied by the sacrifice of the global technical efficiency of energy use at the early stage of economic development. However, further economic development will make both the global technical energy use efficiency and global technical CO_2 emission control efficiency less efficient. If the use of energy is an inescapable product of economic growth, so is the emission of greenhouse gases from the use of energy; thus, for developed countries, the enhancement of the pure technical efficiency in the energy use and the scale efficiency of CO_2 emission control are important tasks to pursue. On the contrary, developing countries have to seek the improvement of the pure technical efficiency of CO_2 emission control and scale efficiency of energy use.

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