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Abstract
This study computes and analyzes the environmental and economic efficiencies of 31 Asia-Pacific countries and regions in 2007, using the slack-based measurement (SBM) data envelopment analysis (DEA) approach. Four economies, Brunei, Macao, Samoa, and Singapore, are found to be environmentally efficient. Of this group, only Brunei and Samoa are found to be economically efficient. We subsequently examined an environmental Kuznets curve type relationship between the environmental efficiency and per capita income. The empirical results show that a U-shaped relationship exists and the turning point per capita income is 4,239 US dollar.

Keywords: data envelopment analysis; environmental efficiency; environmental Kuznets curve
JEL Classification Codes: Q54, O44, O13

INTRODUCTION

The Kyoto Protocol, the first step toward climate change mitigation, expired in 2012. Before launching the post-Kyoto scheme that would remain unclear and uncertain, we should analyze the extent to which countries achieve low carbon economies.

The Asia-Pacific economy, which includes the rapidly growing China and India, is one of the main sources of carbon dioxide emissions, which cause global warming. China surpassed the United

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States as the world's largest carbon dioxide emitter in 2007. In 2010, China accounted for 24% of all global fuel-related carbon dioxide emissions (International Energy Agency, 2012). India and Japan are third and fifth, at 5.4 and 3.8%, respectively. Obviously, reducing carbon dioxide emissions is one of the most significant issues in the Asia-Pacific economy; however, it is unacceptable if it results in declining economic growth.

Efficiency studies have focused on whether it is possible to reduce carbon emissions without impeding economic output by improving efficiency. Data envelopment analysis (DEA), originally proposed by Charnes et al. (1978), has been applied for this purpose. DEA is a powerful tool to measure the relative efficiency of decision-making units (DMUs), such as countries, regions, sectors, and firms. It includes the following three features: First, because DEA is a nonparametric linear programming methodology used to measure the efficiency of multiple DMUs, it does not require any functional form. Second, it can compute efficiency of multiple inputs and outputs. Third, it provides information on the extent to which the inefficient DMU saves inputs and increases outputs.

A number of studies have measured environmental efficiency by using DEA[1]. Zaim and Taskin (2000), Lozano and Gutiérrez (2008), and Sözen and Alp (2009) evaluate the environmental efficiency of developed countries, taking greenhouse gas emissions into consideration. In this way, data availability for developed countries has facilitated many studies. Environmental efficiency studies on the Asia-Pacific economy are as follows. Honma and Hu (2009) evaluate the environmental efficiency of Japanese regions with respect to air pollution emissions and waste. Ke and Hu (2011) measure the environmental productivity of carbon dioxide emissions for 15 Pacific Rim economies in the Asia-Pacific Economic Cooperation (APEC). Hu and Wang (2006) propose the total-factor energy efficiency (TFEE), which is defined as the ratio of the target energy input, as suggested by the DEA, to the actual energy input, and

1 Song et al. (2012) provide a recent survey of environmental efficiency assessment based on DEA

measure the regional energy efficiency of China. The TFEE index has been applied to APEC economies (Hu and Kao, 2007), Japan (Honma and Hu, 2008; 2013), and Taiwan (Hu et al.,2013). Managi and Jena (2008) evaluated the environmental productivity of Indian regions. Färe et al. (2001) estimate a total factor productivity of 17 APEC economies and decompose efficiency change and technical change, not including environmental variables.

Although the ordinary DEA model has broad applications, it has two drawbacks. First, although it specifies efficient DMUs, it cannot provide further details about efficient DMUs with a full unity score. Second, the scores censored at unity for efficient DMUs are embarrassing for a second stage analysis. To regress efficiency scores on variables to investigate the determinants of efficiency, analysts should use the Tobit regression model. However, because detailed information of efficient DMUs is not available in the Tobit model, its results may be inaccurate.

To overcome the drawbacks, a method to identify efficient DMUs has been developed in DEA studies. We employ the slack-based measurement (SBM) super efficiency model[2] proposed in Tone (2002), which extends the SBM model in Tone (2001).

Some environmental efficiency studies investigate a relationship between the efficiency and per capita income, which is suggested in the environmental Kuznets curve (EKC) hypothesis, in the second-stage analysis. Its significance has been noted since it was indicated by Grossman and Krueger (1991) and Shafik and Bandyopadhyay (1992) in environmental economics literature, [3]. The EKC hypothesis states that environmental degradation rises and, after the turning point income is achieved, declines with increasing income per capita. Several empirical studies have explored the validity of the EKC hypothesis. In relation to efficiency studies, Zaim and Taskin (2000) note that an N-shaped curve with a cubic income term between environmental efficiency and per capita income exists in OECD countries. On the other hand, Hu and Kao (2007) indicate that a

[2] Super efficiency of which score is allowed to be larger than unity is firstly proposed by Andersen and Petersen (1993).

[3] See, Dinda (2004), Stern (2004), and Kijima et al.(2010).

U-shaped relationship exists between per capita energy savings targets and per capita income in the Asia-Pacific economy. Managi and Jena (2008) find that a U-shaped relationship exists between environmental productivity and per capita income in India.

This paper aims to evaluate the environmental efficiency of the Asia-Pacific region by using the SBM super-efficiency DEA model and examine the relationship between environmental and economic efficiencies.

METHODOROGY

We briefly present the non-radial, non-oriented, constant returns to scale (CRS) SBM DEA model proposed in Tone (2002). Suppose that there are *n* DMUs. DMU *j* (*j* = 1, ..., *n*) produces *k* outputs $\mathbf{y}_j = (y_{1j}, \cdots, y_{kj})$ using *m* inputs $\mathbf{x}_j = (x_{1j,\dots} x_{mj})$. Then, the input matrices and output matrices are given as $\mathbf{X} = (x_{ij}) \in \mathbf{R}^{m \times n}$ and $\mathbf{Y} = (y_{ij}) \in \mathbf{R}^{k \times n}$. The non-radial, non-oriented SBM efficiency of DMU *o* is defined in Tone (2001) as follows:

$$\text{minimize} \quad \theta = \frac{1 - \frac{1}{m} \sum_{i=1}^{m} \frac{s_i^-}{x_{io}}}{1 + \frac{1}{k} \sum_{i=1}^{k} \frac{s_i^+}{y_{io}}}$$

$$\text{subject to} \quad \mathbf{x}_o = X\boldsymbol{\lambda} + \mathbf{s}^-,$$

$$\mathbf{y}_i = Y\boldsymbol{\lambda} - \mathbf{s}^+,$$

$$\mathbf{s}^- \geq \mathbf{0},$$

$$\mathbf{s}^+ \geq \mathbf{0},$$

$$\boldsymbol{\lambda} \geq \mathbf{0}, \qquad (1)$$

where $\mathbf{s}^- \in R^m$ and $\mathbf{s}^+ \in R^k$ present *input excesses* and *output shortfalls*, respectively, which are called *slacks*. θ^* takes the value between zero and unity. DMU o is efficient if and only if the optimal solution θ^* equals unity. This is equivalent to $\mathbf{s}^{-*} = 0$ and $\mathbf{s}^{+*} = 0$, which means no input excesses and no output shortfalls exist.

To discriminate efficient DMUs with $\theta^* = 1$, Tone (2002) proposes the following super SBM model. Assuming DMU o is efficient ($\theta^* = 1$), super SBM efficiency is defined as

minimize
$$\rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\bar{x}_i}{x_{io}}}{\frac{1}{k}\sum_{i=1}^{k}\frac{\bar{y}_i}{y_{io}}}$$

subject to

$$\bar{\mathbf{x}} \geq \sum_{j=1, j\neq o}^{n} \lambda_j \mathbf{x}_j$$

$$\bar{\mathbf{y}} \leq \sum_{j=1, j\neq o}^{n} \lambda_j \mathbf{y}_j,$$

$$\bar{\mathbf{x}} \geq \mathbf{x}_o,$$

$$\bar{\mathbf{y}} \leq \mathbf{y}_o,$$

$$\bar{\mathbf{y}} \geq 0,$$

$$\boldsymbol{\lambda} \geq \mathbf{0}. \tag{2}$$

The super SBM efficiency score ρ^* takes the value larger than or equal to unity. The value of ρ^* presents the extent to which the DMU outperforms others.

DATA

The study uses a cross-country data set of the Asia-Pacific economy in 2007. There are three inputs and one output. The three inputs are the number of employed workers, capital stock, and carbon dioxide emissions. Following a traditional treatment of pollutants in environmental economics (López, 1994), carbon dioxide is treated as a cost of production. Gross domestic product (GDP) is the sole output. All inputs and output data are taken from the Extended Penn World Table 4.0 and monetary values are in 2005 US dollars. Table 1 provides the descriptive statistics for the inputs and output.

The countries studied with the abbreviations that figures use are as follows: Australia (AUS), Bangladesh (BGD), Bhutan (BTN), Brunei (BRN), Cambodia (KHM), China (CHN), Fiji (FJI), Hong Kong (HKG), India (IND), Indonesia (IDN), Japan (JPN), Laos (LAO), Macao (MAC), Malaysia (MYS), Maldives (MDV), Mongolia (MNG), Nepal (NPL), New Zealand (NZL), Pakistan (PAK), Papua New Guinea (PNG), Philippines (PHL), Samoa (WSM), Singapore (SGP), Solomon Islands (SLB), South Korea (KOR), Sri Lanka (LKA), Taiwan (TWN), Thailand (THA), Tonga (TON), Vanuatu (VUT), and Vietnam (VNM).

Table 1 Descriptive statistics for inputs and output

	Labor (1,000 persons)	Capital stock (million dollars)	Carbon dioxide (million tons)	GDP (million dollars)
Max	766,807	17,081,197	1,852,142	7,719,286
Min	42	948	22	789
Mean	56,227	1,406,333	107,429	703,054
SD	152,047	3,405,833	333,114	1,594,966

ENVIRONMENTAL AND ECONOMIC EFFICIENCY IN ASIA-PACIFIC ECONOMIES

Solving the SBM DEA model, the environmental efficiency is calculated using labor, capital stock, and carbon dioxide emissions as inputs. The economic efficiency is calculated using labor and capital stock as inputs.

Table 2 shows the environmental and economic efficiencies in the Asia-Pacific economies. Note that the two efficiency values cannot be compared because the inputs in each model are different. Generally, in DEA, an efficiency value tends to increase with the number of outputs and inputs. Economies whose scores are greater than unity perform efficiently. Moreover, the score shows the extent to which an economy outperforms other economies. According to the data, Brunei, Macao, Samoa, and Singapore are environmentally efficient. These economies cannot further reduce carbon dioxide emissions and other inputs without reducing GDP. With regard to Table 2 Environmental and economic efficiencies in the Asia-Pacific region

Country/Region	Environmental efficiency	Rank	Economic efficiency	Rank
Australia	0.580	7	0.670	5
Bangladesh	0.338	24	0.303	26
Bhutan	0.265	28	0.215	31
Brunei	1.134	3	1.201	1
Cambodia	0.553	10	0.494	12
China	0.255	30	0.291	27
Fiji	0.355	22	0.380	20
Hong Kong	0.601	5	0.590	8
India	0.347	23	0.383	19
Indonesia	0.315	25	0.338	22
Japan	0.533	12	0.580	9
Laos	0.488	14	0.385	18
Macao	1.774	1	0.833	3
Malaysia	0.357	21	0.406	17
Maldives	0.236	31	0.249	30
Mongolia	0.282	27	0.332	24
Nepal	0.406	20	0.273	29
New Zealand	0.560	9	0.613	7
Pakistan	0.428	17	0.472	15
Papua New Guinea	0.509	13	0.510	11
Philippines	0.464	16	0.485	13
Samoa	1.156	2	1.147	2
Singapore	1.012	4	0.712	4
Solomon Islands	0.546	11	0.547	10
South Korea	0.411	19	0.454	16
Sri Lanka	0.419	18	0.371	21
Taiwan	0.579	8	0.660	6
Thailand	0.288	26	0.316	25
Tonga	0.472	15	0.480	14
Vanuatu	0.582	6	0.337	23
Vietnam	0.261	29	0.278	28

economic efficiency, only Brunei and Samoa operate efficiently. Whereas Macao is the most environmentally efficient, Brunei is the most economically efficient. There is concern that the two largest developing countries, China and India, have lower scores 0.255 and 0.347, respectively, in both efficiency indices.

Except for Vanuatu and Nepal, ranks of the economies are similar between the two indices. The Spearman's rank correlation coefficient between the two ranks is 0.8903. Although Vanuatu ranks sixth in environmental efficiency, it drops to 23rd in economic efficiency. Similarly, Nepal ranks 20th in environmental efficiency and drops to 29th in economic efficiency.

RELATIOHSHIP BETWEEN ENVIRONMENTAL AND ECONOMIC EFFICIENCIES

Figures 1 and 2 present the relationships between the environmental and economic efficiencies indices and per capita income. They show that Samoa (WSM in the figures) occupies a unique position of having a combination of a middle income level of per capita income and higher efficiency values. Among middle income economies, only Samoa achieves efficiency values above unity.

Next, we investigate the relationship between environmental efficiency and per capita income by using the ordinary least squares (OLS) method. For this purpose, the following equation is estimated:

$$\ln(EnvEff_j + 1) = \beta_1 + \beta_2 \ln GDPpc_j + \beta_3 (\ln GDPpc_j)^2 + \varepsilon_j$$

Because a simple log transformation of the environmental efficiency values involves negative values, the environmental efficiency values are converted into efficiency plus unity. $GDPpc_j$ is GDP per capita, and ε_j is the random error term. The U-shaped relationship requires β_2<0 and β_3>0.

Figure 1 Relationship between environmental efficiency and income

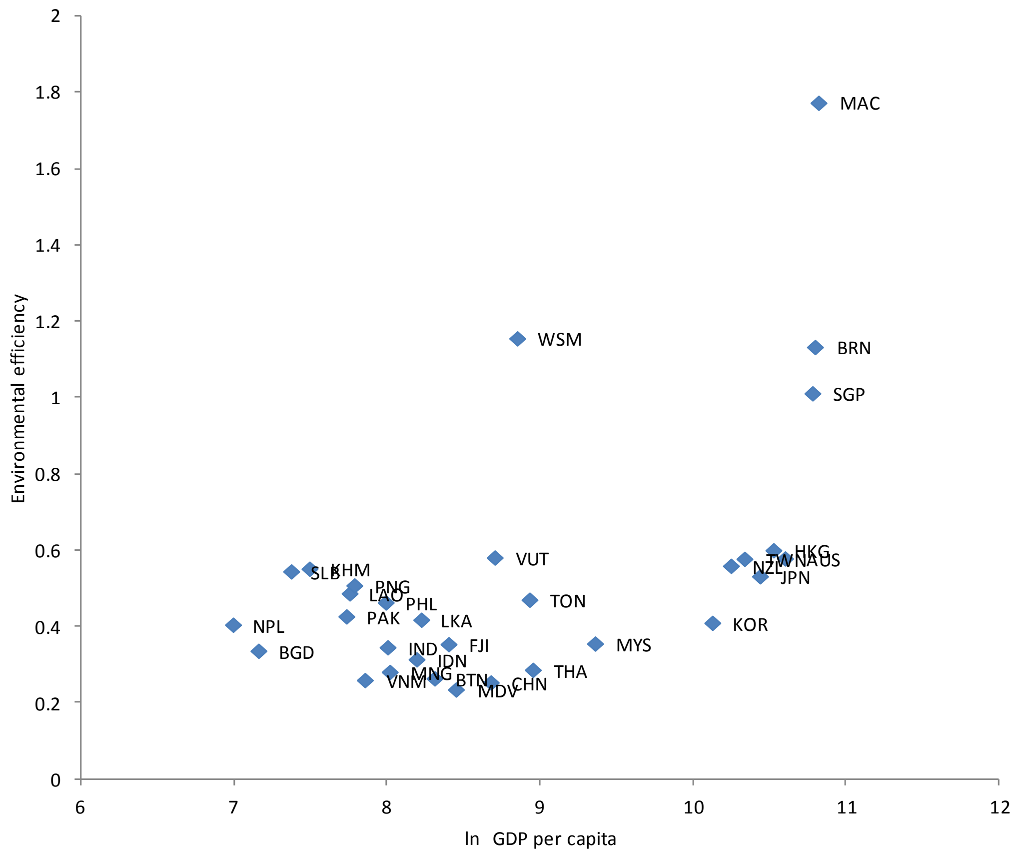

Figure 2 Relationship between economic efficiency and income

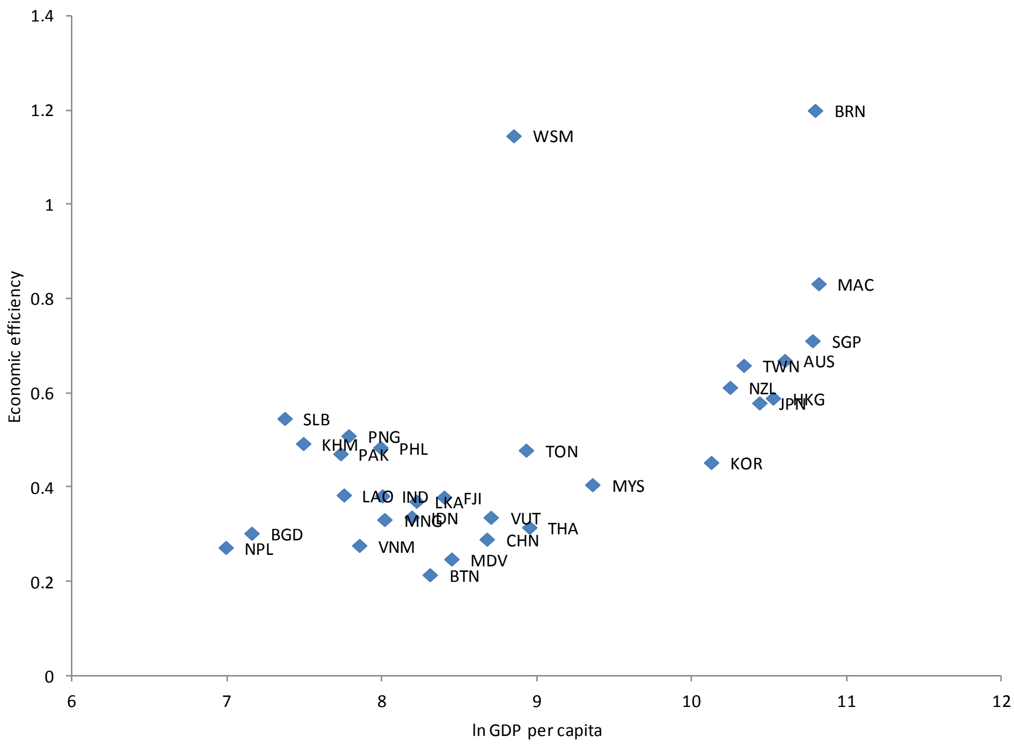

Table 3 Results of OLS

Variable	Coefficient
Intercept	4.316*
	(2.426)
ln GDPpc	-0.958*
	(-2.413)
(ln GDPpc)^2	0.057*
	(2.628)
Adjusted R^2	0.414

t statistics are given in parentheses. * Significan at 5% level.

Table 3 shows the results of the OLS analyses performed on the environmental efficiency scores[4]. The estimated coefficients for *ln GDPpc* and $(ln\ GDPpc)^2$ are significantly negative and positive as predicted, respectively. We find that a U-shaped relationship between the environmental efficiency and per capita income exists. Solving $GDPpc = \exp(-\beta_2 / 2\beta_3)$, we obtain the turning point income level, 4,239 dollar.

CONCLUDING REMARKS

In this study, we measure environmental and economic efficiencies and provide measures to reduce carbon dioxide emissions for 31 economies in the Asia-Pacific region. Furthermore, we investigate the relationship between environmental efficiency and per capita income. The empirical result presents a U-shaped relationship between the environmental efficiency and per capita income exists. The turning income level is 4,239 US dollar. Further studies need to enlarge a panel dataset and to incorporate other pollutants such as sulfur dioxide, nitrogen dioxide and suspended particulate matter (SPM).

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[4] We examined models that added the cubic term of GDP per capita and control variables. Their results are omitted because they are insignificant.

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