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Energy Policy 34 (2006) 3206–3217

ENERGY POLICY

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Total-factor energy efficiency of regions in China

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Abstract

This paper analyzes energy efficiencies of 29 administrative regions in China for the period 1995–2002 with a newly introduced index. Most existing studies of regional productivity and efficiency neglect energy inputs. We use the data envelopment analysis (DEA) to find the target energy input of each region in China at each particular year. The index of total-factor energy efficiency (TFEE) then divides the target energy input by the actual energy input. In our DEA model, labor, capital stock, energy consumption, and total sown area of farm crops used as a proxy of biomass energy are the four inputs and real GDP is the single output. The conventional energy productivity ratio regarded as a partial-factor energy efficiency index is computed for comparison in contrast to TFEE; our index is found fitting better to the real case. According to the TFEE index rankings, the central area of China has the worst energy efficiency and its total adjustmentof energy consumption amount is over half of China's total. Regional TFEE in China generally improved during the research period except for the western area. A U-shape relation between the area's TFEE and per capita income in the areas of China is found, confirming the scenario that energy efficiency eventually improves with economic growth.

Keywords: Data envelopment analysis; Total-factor energy efficiency (TFEE); China economy

1. Introduction

China's economy has grown aggressively in the past two decades and is still expanding at a 9.5% annual rate in the fourth quarter of 2004 (Business Asia, 2005). At the same time, its energy supply is under a severe supply constraint following such roaring development, as demand for electric power in the country increased by 69% from 2000 to 2004. Much of the fixed asset investments have moved into energy-intensive industries, yet there is nearly a one-third shortage of electricity consumption in China.

China is the second largest energy-consuming economy in the world. One forecast (Kadoshin and Nishiyama, 2000) shows that by 2010, China will consume three times its 1992 energy input. That is, China's share of the world's total energy consumption will grow from 8.6% in 1992 to 15.9% in 2010. Along with this fast demand for energy, the efficiency of energy use should be of concern especially under China's energy policy. Various plans are being carried out to increase investment and to speed up construction in order to establish a sufficient energy supply. However, the efficiency of energy consumption needs to be promoted simultaneously such that redundant energy consumption is eliminated.

Energy alone cannot produce just any output. Energy must be put together with other inputs in order to produce outputs. Therefore, a multiple-input model should be applied to correctly assess the energy efficiency in a region. In our study the regional targets of energy inputs can be found through the data envelopment analysis (DEA). The out-of-date technology level and the inefficient production process generate a redundant portion of energy consumption which needs to be further adjusted. The amount of total adjustments, including slack and radial adjustments, is computed by

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doi:10.1016/j.enpol.2005.06.015

DEA. The target level of energy use, called target energy input, is obtained when the amount of total adjustments is reduced from the actual energy use amount. A new index of energy efficiency, named total-factor energy efficiency (TFEE), is constructed as the ratio of the target energy input that is suggested from DEA to the actual energy inputs in a region.

Energy efficiency improvement relies on total-factor productivity improvement (Boyd and Pang, 2000). The TFEE index incorporates energies, labor, and capital stock as multiple inputs so as to produce economic output (GDP[2]). In contrast, a traditional energy efficiency index only takes energy into account as a single input (Patterson, 1996) to produce GDP output while neglecting other key inputs such as capital and labor. DEA can be easily applied to a multiple input–output framework to compute the index of TFEE. An empirical analysis of regional energy efficiency in China presents results from a real case application of the new index.

Sustainable development has to be considered with an energy policy (Gibbs, 2000) since energy supply is inevitable for economic growth. The concept should be introduced by covering areas on a local or regional level and then extending to the national level (Gibbs, 1998). Our study concentrates specifically on the regional level of energy efficiency in China where further improvements can be planned and executed accordingly. China is now in a transition period, having started from a high resource-consuming and low-efficiency economic development pattern (Yang, 2002; World Bank, 2001; Fleisher and Chen, 1997). It is of particular importance to improve energy efficiency in the various regions within China in order to sustain its economic growth.

This paper is organized as follows. Section 2 provides administrative data and descriptive statistics at the regional level in China. Section 3 reviews DEA methodology and describes how the index of TFEE is constructed on the basis of DEA. An empirical study for the energy efficiency of regions in China based on TFEE is given in Section 4. Section 4 also compares the TFEE result with the commonly used partial-factor energy efficiency (PFEE) result—the energy productivity ratio (Patterson, 1996). Section 5 concludes our research findings.

2. Regional data and descriptive statistics

From the perspective of China's development and political factors, its provinces, autonomous regions, and municipalities are usually divided into three major areas: the east, central, and west as shown in Fig. 1.

East Area (12 Regions)						Central Area (9 Regions)				West Area (8 Regions)			
1	Beijing	6	Jiangsu	11	Guangxi	13	Shanxi	18	Jiangxi	22	Sichuan	27	Qinghai
2	Tianjin	7	Zhejiang	12	Hainan	14	Inner Mongolia	19	Hennan	23	Guizhou	28	Ningxia
3	Hebei	8	Fujian			15	Jilin	20	Hubei	24	Yunnan	29	Xinjiang
4	Liaoning	9	Shandong			16	Heilongjiang	21	Hunan	25	Shaanxi		
5	Shanghai	10	Guangdong			17	Anhui			26	Gansu		

Fig. 1. The administrative regions and three major areas in China.

The east area is constituted by 12 regions that stretch from the province of Liaoning to Guangxi, including the coastal provinces of Shandong, Hebei, Jiangsu, Zhejiang, Fujian, Guandong, and Hainan, and the three municipalities of Beijing, Tianjin, and Shanghai. The east area is well known and has experienced the most rapid economic growth in China and its GDP output is around half of China's total. The east area has also attracted the most foreign investment, technology, and managerial know-how. The central area consists of nine regions that are all inland provinces: Heilongjiang, Jilin, Inner Mongolia, Henan, Shanxi, Anhui, Hubei, Hunan, and Jiangxi. This area has a large population and is a home base for farming. Foreign investment in this area is less and technology lags do exist. The west area covers more than half of the territory in China including the provinces of Gansu, Guizhou, Ningxia, Qinghai, Shaanxi, Tibet, Yunnan, Xinjiang, Sichuan, and the municipality Chongqing. Compared to the other two areas, this area has low population density and is the least developed area in China.

Since Chongqing was promoted to be the fourth municipality in China only in 1997, this municipality is still combined with the Sichuan province and they together are regarded as one region in this research. The energy input data of Tibet were not available for this research. Thus, a total of eight regions in the west area are included in this study. The three areas are abbreviated as E, C, and W for the east, central, and west areas, respectively. A total of 29 regions are this study's targets to be analyzed for their energy efficiency.

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[2] GDP represents gross domestic product.

2.1. Data sources

A panel dataset of 29 regions from 1995[3] to 2002 is collected for analysis. Data of labor employment and GDP are both collected from the China Statistical Yearbook. Data of capital stock are not available in any statistical yearbooks of China. In this study every regional capital stock in a specific year is calculated by the authors according to the formula (Li, 2003):

$$\begin{aligned}&\text{Capital stock in the current year}\\&\quad= \text{capital stock (previous year)}\\&\qquad+ \text{capital formation (current year)}\\&\qquad- \text{capital depreciation (current year).}\end{aligned} \tag{1}$$

The 1995 regional capital stocks in 1978 prices are obtained from Li (2003). All monetary inputs and outputs such as the GDP and capital stock are transformed into 1995 prices with GDP deflators.

Regional energy consumption levels are collected from the China Energy Statistical Yearbook. These energy datasets contain only the conventional energy consumption—mainly coal, petroleum, and natural gas. Those energy resources with a low calorific value are excluded, most of which are renewable energies. Biomass energy is almost 100% of this renewable energy source in China (Chang et al., 2003). There are also other renewable sources such as solar, wind, geothermal, and oceanic energies, but all are consumed at very low levels (International Energy Agency (IEA), 2004). Biomass energy is one of the main sources for non-commercial energy use in China's rural areas, constituting 38.7% of China's total energy consumption in 1970, but then later dropping to 19.9% of China's total in 2000 (Chang et al., 2003). Few data sources of biomass energy consumption could be found, and those had been offered were incomplete for this study and relied on estimations (Sinton and Fridley, 2002).

Biomass energy still counts for around 20% of the total energy consumption in China as of 2000. China Rural Energy Statistical Yearbook once provided regional data of biomass energy consumption, but only up to 1999. Since biomass energy is mainly composed of straw, stalk, crop residue, and fuel wood (Chang et al., 2003), the total sown area of farm crops of the regions is selected as a proxy of the biomass energy consumption in this study.[4] The data of regional total sown area of farm crops (abbreviated as 'farm area' hereafter) are available in the China Statistical Yearbook for each sample year. A very high positive correlation coefficient of 0.841 is found between total biomass energy consumption level and farm area of regions in China during our 1995–1996 data collection. The factor farm area of regions is hence an appropriate proxy of the biomass portion of energy input in this study. The data are therefore complete for an analysis of energy efficiency in regions of China.

2.2. Descriptive statistics of the regions in China

The descriptive statistics of China's regions for their GDP performances in terms of production output, labor employment, capital stock, and energy consumption, including farm area as production inputs in our energy efficiency analysis, are first given in Table 1. As the data in this table show, the east area, frequently called the coastal area, includes regions that show the fastest development progress in China. Mean GDP output in this area is 3.77 trillion RMB,[5] which is much higher than 1.75 trillion RMB of the central area and 0.88 trillion RMB of the west area during the sample years. The standard deviation of GDP output shows the same tendency and matches the economic growth pattern among these areas. The east area has a standard deviation of 210.4 billion RMB, which is also much higher than the other two areas, which are 72.7 billion RMB in the central area and 31.3 billion RMB in the west area. The fast-developing east area receives the largest investment—three times that of the central area and five times the west area.

The situation of energy consumption appears to be the same as that of the GDP result. The east area, as its economic growth shows, consumes the largest portion of energy amount in China. As shown in Table 1, the east area consumed 69.5 billion metric tons of standard coal equivalent (Btce) on an average from 1995 to 2002. This is much higher than 28.1 Btce consumed by the west area and 46.2 Btce consumed by the central area. While analyzing deviations of energy consumption among these areas, we find that the east area increased its energy consumption the fastest from 1995 to 2002 versus the central and west areas. As aforementioned, the central area is the home base of farming, and it consumes the largest level of biomass energy. The east area consumes the second biggest amount and the west area has the lowest level in accordance with farm area data shown in Table 1.

A correlation matrix is shown in Table 2, whereby a high correlation exists between these inputs and output. The correlation coefficient between the energy input and GDP output is 0.801 ($P<0.005$). A positive correlation coefficient of 0.539 is found between the farm area input and GDP output as well. These results all show

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[3] Complete panel data of these variables started from 1995.

[4] We have tried to use the forest area as a proxy of fuel wood as one of the biomass energy sources. However, the sign of the correlation coefficient between real GDP and forest area is negative, hence violating the 'isotonicity' requirement between an input and an output.

[5] The RMB is an abbreviation of Ren-Min-Bi, meaning 'people's currency' in Chinese. The RMB is the official currency of the People's Republic of China.

Table 1
Summary statistics of input and output factors by region (1995–2002)

ID	Region		Input Factors								Output factors	
			Labor employment (10,000 persons)		Capital stock (100 million RMB)		Energy consumption (Mtce)		Total sown area of farm crops (1000 ha)		Gross domestic product (100 million RMB)	
			Mean	STDev	Mean	STDev	Mean	STDev	Mean	STDev	Mean	STDev
1	Beijing	E	661.25	59.18	19,431.65	3662.31	3992.63	333.17	484.43	80.45	1602.58	153.59
2	Tianjin	E	442.24	40.20	11,107.28	2020.18	2657.50	222.80	557.13	20.87	1061.09	82.69
3	Hebei	E	3397.53	21.04	13,978.40	4551.14	9670.38	926.31	8944.05	123.98	3295.88	215.68
4	Liaoning	E	1907.96	121.90	56,457.27	7,175.74	9924.25	650.52	3693.11	126.81	3008.53	132.15
5	Shanghai	E	721.56	48.05	33,191.94	6886.27	5189.75	576.34	529.55	30.49	2873.36	228.68
6	Jiangsu	E	3642.55	104.45	40,401.86	8944.46	8441.63	565.02	7923.98	98.49	5655.75	294.58
7	Zhejiang	E	2717.79	59.95	23,761.19	6167.38	5633.00	942.97	3689.34	358.03	3965.71	291.14
8	Fujian	E	1635.88	44.58	10,940.81	3611.55	2776.88	402.65	2835.19	104.47	2525.74	177.48
9	Shandong	E	4682.25	34.71	30,967.33	8605.29	9297.88	856.50	11,079.03	144.98	5606.69	321.22
10	Guangdong	E	3806.29	112.26	28,601.31	7684.30	8892.13	1358.10	5292.34	203.30	6254.00	356.32
11	Guangxi	E	2483.00	61.21	6172.15	1395.27	2580.25	197.51	6173.84	198.20	1510.36	136.10
12	Hainan	E	333.64	7.43	2976.39	520.71	429.50	87.00	898.21	28.73	347.94	7.99
13	Shanxi	C	1442.70	28.95	8887.96	1631.26	7426.63	1030.32	3911.38	121.28	1,155.07	64.82
14	Inner Mongolia	C	911.20	327.73	6564.68	1320.36	3481.75	651.83	5727.68	357.67	925.19	48.86
15	Jilin	C	1152.95	86.39	7810.24	1580.51	3991.50	285.72	4304.51	345.87	1221.38	48.40
16	Heilongjiang	C	1637.79	50.48	11,588.03	2242.60	6059.88	175.20	9274.30	457.75	2178.37	82.54
17	Anhui	C	3323.05	64.27	11,235.34	2649.00	4,710.75	373.81	8635.93	256.74	2,102.41	80.19
18	Jiangxi	C	1996.03	63.20	8456.92	1847.88	2248.63	183.14	5777.39	244.08	1380.92	65.91
19	Hennan	C	5172.75	333.13	18,718.26	4528.35	7398.13	783.89	12,690.29	465.98	3377.12	170.38
20	Hubei	C	2,594.09	111.68	15,382.57	3992.74	6,103.75	300.12	7580.59	155.35	2790.39	174.26
21	Hunan	C	3504.71	50.32	9905.99	2598.71	4803.25	532.53	7933.06	83.34	2437.29	104.82
22	Sichuan	W	6180.41	131.67	14,503.10	4351.39	9852.44	450.88	13,118.30	168.69	3814.44	132.03
23	Guizhou	W	1976.33	80.42	4169.23	989.50	4049.88	441.30	4517.35	174.14	659.48	21.96
24	Yunnan	W	2270.11	49.94	6833.66	1676.02	3265.75	410.90	5441.01	365.69	1322.75	61.22
25	Shaanxi	W	1806.74	29.23	10,080.84	1784.45	3145.13	357.55	4535.93	199.66	1096.54	55.13
26	Gansu	W	1190.28	26.59	5588.69	1047.75	2832.63	157.32	3743.80	50.83	651.46	40.80
27	Qinghai	W	237.13	5.80	1797.95	333.37	824.88	131.36	552.01	27.09	175.98	10.89
28	Ningxia	W	265.48	12.47	1963.38	342.72	838.75	50.58	1014.99	58.95	178.71	6.38
29	Xinjiang	W	680.58	11.12	6831.47	1406.17	3276.63	232.13	3281.93	159.15	877.31	40.75
	Sum		62,774.23	446.37	428,305.91	94,995.22	143,796.06	10,986.60	134,754.26	54,336.87	64,052.43	3,002.45
	East		26,431.93	3884.69	277,987.58	60,805.13	69,485.75	6670.12	52,100.18	806.64	37,707.63	2,104.51
	Central		21,735.26	1560.11	98,550.00	22,369.30	46,224.25	2861.73	65,835.11	1,417.98	17,568.14	727.12
	West		14,607.04	2083.07	51,768.32	11,912.26	28,086.06	1747.12	36,205.31	735.26	8,776.66	312.93

Notes: (1) All monetary values are 1995 prices. (2) Source: China Energy Statistical Yearbook, 1991–1996, 1997–1999, 2000–2002, China Statistical Yearbook, 1995–2002.(3) E: east area, C: central area, and W: west area. (4) Data for the administration region Chongqing is regarded as a part of Sichuan in this paper since it was promoted as one of the municipalities in China only from 1997. (5) Data of energy consumption in Tibet is not included since it was not available in the sample period.

Table 2
Correlation matrix for inputs and output (1995–2002)

	GDP	Labor	Capital	Energy	Farm area
GDP	1.000				
Labor	0.739	1.000			
Capital	0.716	0.324	1.000		
Energy	0.801	0.718	0.701	1.000	
Farm area	0.539	0.887	0.148	0.628	1.000

Notes: (1) Farm area: total sown area of farm crops as explained in text.

'isotonicity' of the four inputs and the one output in our DEA model. The energy input efficiency shall be analyzed in this study in order to understand individual energy efficiency states among all regions of China.

3. Total-factor energy efficiency (TFEE)

We employ an economic production function that is constructed by DEA in order to analyze regional energy efficiencies in China based on the viewpoint of total-factor productivity. Energy, including farm area as a proxy, is considered in conjunction with conventional inputs labor and capital stock, which are normally used in an economic productivity analysis as the total inputs to produce economic output (GDP). For an economy or a region, it is preferable that the local GDP increases and that energy consumption is saved in order to reach production efficiency. Therefore, the goal for GDP growth and efficiency of energy consumption should be put together in order to sustain economic development.

An efficiency frontier is established by DEA composed of those regions with the best production efficiency with energy input considered. The energy efficiency is measured in each region for how far apart they are from this efficiency frontier. The methodology of DEA is first reviewed in Section 3.1. How the total adjustments are computed as gaps between efficiency of each region and that on the frontier is explained in detail in Section 3.2. The TFEE index is therefore constructed accordingly in Sections 3.3 and 3.4. We use the software Deap 2.1, kindly provided by Coelli (1996), to solve the linear programming problems.

3.1. Methodology of DEA

DEA is known as a mathematical procedure using a linear programming technique to assess the efficiencies of decision-making units (DMU) that refer to a set of firms (Coelli, 1996) and a set of regions in this study. All DMUs take an identical variety of inputs to produce an identical variety of outputs (Ramanathan, 1999); but through distinct production processes and technologies decided and used in each DMU, the input and output levels and their production efficiency are eventually decided upon. A non-parametric piecewise frontier composed of DMUs, which owns the optimal efficiency over the datasets, is constructed by DEA for comparative efficiency measurement. Those DMUs which are located at the efficiency frontier have their maximum outputs generated among all DMUs by taking the minimum level of inputs, are efficient DMUs, and own the best efficiency among all DMUs.

DEA does not need to specify either the production functional form or weights on different inputs and outputs. It produces detailed information on the efficiency of the unit, not only relative to the efficiency frontier, but also to specific efficient units which can be identified as role models or comparators (Hawdon, 2003). Comprehensive reviews of the development of efficiency measurement can be found in Lovell and Schmidt (1993). There are K inputs and M outputs for each of these N DMUs. The envelopment of the ith DMU can be derived from the following linear programming problem:

$$\begin{aligned} &\mathrm{Min}_{\theta,\lambda}\ \theta \\ &\text{such that} \quad -y_i + Y\lambda \geqslant 0, \\ &\qquad\qquad\quad \theta_{x_i} - X\lambda \geqslant 0, \\ &\qquad\qquad\quad \lambda \geqslant 0, \end{aligned} \tag{2}$$

where θ is a scalar and λ is an $N\times 1$ vector of constants, and whereby the value of θ obtained is the efficiency score for the ith DMU. This satisfies $\theta \leqslant 1$ with a value of 1, indicating a point on the frontier and hence a technically efficient DMU (Coelli et al., 1998). The above procedure constructs a piecewise linear approximation to the frontier by minimizing the quantities of the K inputs required to meet the output levels of the ith DMU. The weight λ serves to form a convex combination of observed inputs and outputs. The efficiency score θ measures the maximal radial expansion of the outputs given the level of inputs. It is an input-orientated measurement of efficiency.

Eq. (2) is known as the constant returns to scale (CRS) DEA model (Charnes et al., 1978). This model finds the overall technical efficiency (OTE) of each DMU. The variable returns to scale (VRS) DEA model (Banker et al., 1984) further decomposes the OTE into pure technical efficiency (PTE) and scale efficiency (SE). That is, OTE = PTE × SE. In order to pursue OTE with energy inputs, our study adopts the CRS DEA model. Both output-oriented and input-oriented CRS DEA models generate exactly the same efficiency scores, target inputs, and target outputs. However, the results of a VRS DEA model can be drastically changed by shifting the DEA model from output orientation to input orientation.

3.2. Slack and radial adjustments of energy input

DEA identifies the most efficient point on the frontier as a target for those inefficient DMUs to achieve through a sequence of linear programming computation (Coelli, 1996). For the ith DMU, the distance from an inefficient point where it is located to the projected point on the frontier by radial adjusting the level of inputs, $(1-\theta)x_i$, is called 'radial adjustment'. Moreover, the mostly seen piecewise linear form of the non-parametric frontier causes the second stage to shift from the projected point to a point at the practical minimum level of the inputs on the frontier. The distance of shifting along with the frontier in between is called 'slack'.

How a point with a practical minimum level for inputs on the frontier can be identified in DEA is illustrated in Fig. 2. The maximum level Y output by the DMUs located on the frontier is normalized to unity and generated from the energy input and other inputs which are also normalized by dividing Y. Point B is the actual input set and point B′ is the projected point on the frontier for DMU B as the target in order to improve its efficiency accordingly by reducing the radial adjustment BB′. However, as mentioned, the practical frontier is a piecewise linear format that requires the second-stage adjustment to determine a practical minimum point for inputs. In Fig. 2, point A′ is the projected point on the frontier for another DMU A as the target to reach by reducing the radial adjustment AA′. However, the input level at point A′ could be further reduced to input level at point C while maintaining the same output level. The amount CA′ that shall further be adjusted for

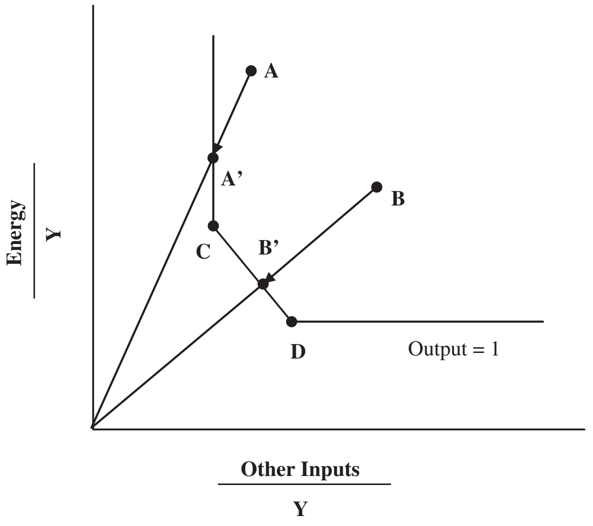

Fig. 2. Radial adjustment and slack identified in an input-oriented CRS DEA.

the input level at point A′ along with the frontier is called ‘slack’.

The summation amount of slack (CA′) and radial adjustment (AA′) for inputs is called the amount of total adjustments (CA), meaning that it is the total amount for inputs which should be adjusted by a DMU so as to reach its optimal production efficiency. The adjustments require both a promotion of technology level and an improvement of production process so that OTE is optimized. The amount of total adjustments therefore decreases and the output level is maximized so that the DMU operates at the frontier position of production efficiency. The practice minimum input level is called the target input level for a DMU.

When incorporating energy as an input into an economy’s production in a region, the target level of energy input is named ‘target energy input’, which represents a practical minimum level of energy input to be taken as a target in a region in order to perform at the optimal efficiency of energy consumption. The level of target energy input is identified through DEA in conjunction with other inputs so as to produce economic output. An energy-efficient region, therefore, explains that it has operated at the maximum economic output by taking the minimum level of energy consumption based on the viewpoint of total-factor productivity and with OTE optimized. The amount of total adjustments for energy consumption is obtained from the gap between target and actual energy inputs and shall be reduced from its actual energy input level in the region.

3.3. Regional total-factor energy efficiency

The amount of total adjustments in energy input is regarded as the inefficient portion of actual energy consumption in a region. The more the amount of total adjustments, the less efficient the energy consumed in the region. Thus, if there does not exist an amount of total adjustments of energy input (equal to zero), then the region is utilizing energy at the ‘target energy input’ level, which is the optimal efficiency of energy consumption when its output is maximized. Therefore, energy efficiency in a region is defined in Eq. (3) as below, which is named total-factor energy efficiency (TFEE) for region i at time t since the index is established based on the viewpoint of total factor productivity:

$$\text{TFEE}\,(i,t) = \frac{\text{Target Energy Input}\,(i,t)}{\text{Actual Energy Input}\,(i,t)}, \tag{3}$$

which implies in the ith region and in the tth year.

As Eq. (3) shows, the index TFEE represents the efficiency level of energy consumption in a region. As the target energy input is the best practical minimum level of energy input in a region, the actual energy input is therefore always larger than or equal to this target energy input. This makes the index TFEE score to always be between zero and unity. When the actual energy input level of a DMU is equal to the suggested target energy input level, a TFEE score of unity is achieved. Conversely, if the actual energy input level is far away from the suggested target energy input level, then the index approaches zero, which represents low efficiency. This index is shown in percentile format in this study for easier reading.

3.4. Total-factor energy efficiency in an area

Index TFEE is also employed to analyze energy efficiency in an area. Assume area a covers r regions. Area a’s TFEE at time t is defined in Eq. (4):

$$\text{TFEE}\,(a,t) = \frac{\Sigma_{r\in a}\ \text{Target Energy Input}\,(r,t)}{\Sigma_{r\in a}\ \text{Actual Energy Input}\,(r,t)}, \tag{4}$$

which implies that the rth region belongs to area a.

Eq. (4) shows that the TFEE in an area is calculated by dividing the summation of target energy inputs by the total actual energy inputs of the area. This is a summation of actual energy input consumed in regions of the area. We calculate TFEE of an area in China in Section 4.3 in order to find its relation with per capita income of regions in China.

4. Empirical study of TFEE in regions of China

4.1. Regional total adjustments of energy input

Regions in the east area—the fast-developing area—have an amount of total adjustments of their energy input at 15.96 Btce in 1995 and then it decreased to 13.49 Btce in 2002. The amount remained at around one-third of China's total and fell slowly during the research period. Liaoning (4) and Hebei (3) are the two major regions generating around two-thirds of the area's total. Shandong (9) reduced its 1995 adjustments' amount to half in 2002 with continuous improvement. Shanghai (5), Fujian (8), and Guangdong (10) are the three regions in the area having no energy adjustments' amount in all years of the research period. Guangxi (11) and Hainan (12) have zero adjustments in 1995, but the amount rose in the later years. All detailed data are shown in Table 3.

Regions in the central area own the largest portion of the total adjustments' amount of energy use in China, which were 22.9 Btce (47.69% of China's total) in 1995 and 16.7 Btce (41.83% of China's total) in 2002. The adjustments' amount actually dropped rapidly during the research period, but was still above 40% of China's total. All regions in this area had non-zero adjustments among all the years of the research period except for Inner Mongolia (14) and Hunan (21) in the later years. Shanxi (13) created the largest energy adjustments' amount in this area, which was around one-third of the area's total in 1995 and then it rose up to half of the area's total in 2002. Heilongjiang (16), Hubei (20), Jilin (15), and Hennan (19) are the four regions that generated high amounts of adjustments in the area. Their amounts totaled one-third of the area's adjustments' amount in 1995 and were half of the area's total in 2002. The detailed data are shown in Table 3.

The west area contains the lowest level of total energy adjustments. Its adjustments' amount began at 9.15 Btce, increased up to 10.51 Btce in 1998, and then decreased to 9.72 Btce in 2002, remaining relatively flat as shown in Table 3. Sichuan (22) is the only region to have no adjustments among all the years of the research period. Gansu (26), Shannxi (25), and Xinjiang (29) are three regions that had higher levels of energy adjustments' amount at about two-thirds of the area's total. Guizhou (23) is the only region having its adjustments' amount increased during the period.

The total adjustments' amount of the energy input significantly decreased during 1995–2002 for all areas in China, and the results are shown in Fig. 3. It shows a total of 48.01 Btce in 1995 and then it dropped to 39.89 Btce in 2002. The major reduction comes from regions in the east area as well as the central area, though regions in the central area still constitute over 40% of China's total energy adjustments. Regions in the west area contain the least portion of China's total, but it is worth noting that their adjustments' amount slightly increased.

4.2. Regional TFEE

Table 4 shows the regional result during 1995–2002 based on the TFEE index. The TFEE score is computed for a comparison of energy efficiency among regions. The ratio of the actual energy input to the target energy input is analyzed instead of using an absolute amount for comparison. A total of four regions in China are found to always have optimal efficiency during the research period. Three of these regions are located in the east area: Shanghai (5), Fujian (8), and Guangdong (10). The one region left is Sichuan (22), located in the west area.

These four regions, having the optimal efficiency result in our analysis, actually constitute the efficiency frontier of energy consumption among all regions of China. They have the best technology level and production processes so that their inputs and output are operating at the optimal level. The other regions in China which are not yet at the frontier efficiency position can, therefore, base themselves on these frontier regions as targets to adjust their technology levels and production processes accordingly. A target is hence identified by TFEE analysis based on DEA so that feasible steps for improvement of the OTE do exist. This is one of the benefits from TFEE analysis in a comparative study of energy efficiency.

As shown in Table 4, regions in the east area have the highest TFEE rank over all areas in China. In contrast, regions in the central area have the worst rank of efficiency. Regions in the west area have the second best rank for TFEE. The TFEE scores are in average 77.6%, 55.7%, and 64.4% over the research period for the east, central, and west areas, respectively. The central area was predicted to be the second best energy-efficient area before performing this empirical study. It does have the second largest amount of investments and labor employment, it consumes the second largest level of energy, and it contributes the second largest GDP output in China. However, its efficiency level does not perform the same as with the rank of inputs and output, while it does have the worst TFEE.

4.3. Energy efficiency vs. regional development

A U-shape relation is found to exist between the area's TFEE and per capita income in China. The east area has the highest level of per capita income and also the highest score of an area's TFEE among the three areas. The central area has the second highest level of per capita income, but the worst score of an area's TFEE. The west area has the lowest level of per capita income, but is the second best in TFEE. The per capita income actually represents the economic development level in the region or the area. The U-shape relation is illustrated in Fig. 4.

The discovered U-shape relation between TFEE and per capita income in an area, therefore, explains that an improvement of energy efficiency is followed by economic growth in an area, though it declines in the

Table 3
Total adjustments amount of energy use by region (1995–2002)

ID	Region		1995	1996	1997	1998	1999	2000	2001	2002
1	E	Beijing	1094.53	1104.27	1352.68	1336.31	1263.44	1286.48	1015.54	893.98
2	E	Tianjin	1065.11	862.70	849.51	901.04	804.54	930.04	874.57	726.68
3	E	Hebei	4163.53	3939.70	3970.14	3918.68	3875.62	5234.86	3744.19	4330.84
4	E	Liaoning	4861.31	4835.12	4804.35	4429.55	4353.00	5395.54	5025.00	4674.92
5	E	Shanghai	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	E	Jiangsu	1380.76	1336.77	1407.30	1628.80	1275.31	1213.20	887.79	643.60
7	E	Zhejiang	300.77	267.72	407.36	523.66	500.49	453.79	244.08	0.02
8	E	Fujian	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	E	Shandong	3097.46	3192.84	3386.02	3383.65	2873.38	1733.27	1874.18	1963.33
10	E	Guangdong	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	E	Guangxi	0.00	0.00	0.00	144.91	148.98	254.73	165.16	142.77
12	E	Hainan	0.00	0.00	43.57	67.09	63.07	90.75	114.03	109.68
13	C	Shanxi	7101.27	5530.22	5718.63	5353.53	5221.58	5441.85	6111.53	7198.79
14	C	Inner Mongolia	1638.16	1794.48	2396.75	2123.93	2764.61	2453.90	2487.75	0.00
15	C	Jilin	2777.67	2779.12	3032.67	2526.71	2278.99	2164.73	1893.43	2115.88
16	C	Heilongjiang	3306.50	2990.52	3605.66	3768.90	3794.19	3720.32	2522.89	2130.47
17	C	Anhui	1088.29	1229.93	1128.05	1188.91	1137.28	1766.90	1222.61	1208.48
18	C	Jiangxi	981.60	729.64	682.28	593.77	588.93	670.12	643.48	638.50
19	C	Hennan	2257.33	2037.60	1887.76	2131.44	2018.51	2637.65	1828.89	1792.59
20	C	Hubei	2994.68	2995.86	2893.44	2829.05	2632.96	2935.00	1323.62	1599.69
21	C	Hunan	752.89	589.36	232.20	113.95	0.00	0.00	0.00	0.00
22	W	Sichuan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	W	Guizhou	1610.57	2110.22	2384.96	2629.90	2251.12	2560.81	2710.67	2615.53
24	W	Yunnan	757.67	667.57	910.47	761.95	700.91	1087.97	815.62	928.05
25	W	Shaanxi	1994.61	2400.16	1919.72	1801.29	1427.53	1382.74	1554.33	1721.28
26	W	Gansu	2093.02	2018.59	1775.31	1806.03	1914.44	2144.81	1631.17	1583.77
27	W	Qinghai	469.33	476.00	485.12	560.22	715.36	645.59	638.22	680.50
28	W	Ningxia	533.22	565.65	573.56	643.56	636.07	669.05	592.73	577.14
29	W	Xinjiang	1690.38	2072.03	2036.59	2304.41	1965.99	1937.36	2029.38	1610.38
		Summary	48,010.66	46,526.06	47,884.10	47,471.22	45,206.28	48,811.47	41,950.82	39,886.84
		East	15963.47	15,539.13	16,220.93	16,333.69	15,157.81	16,592.66	13,944.51	13,485.80
		Central	22898.39	20,676.71	21,577.44	20,630.18	20,437.05	21,790.47	18,034.20	16,684.41
		West	9148.80	10,310.22	10,085.73	10,507.35	96,11.43	10,428.33	9972.11	97,16.64

Notes: (1) The unit is 10,000 tce. (2) E: east area, C: central area, and W: west area. (3) Data for the administration region Chongqing is regarded as a part of Sichuan in this paper since it was promoted as one of the municipalities in China only from 1997. (4) Data of energy consumption in Tibet is not included since it was not available in the sample period.

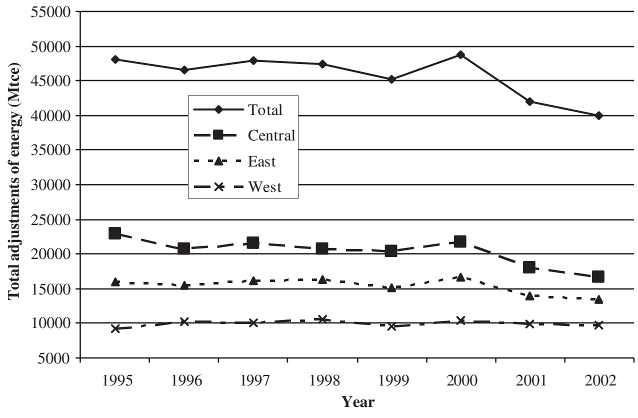

Fig. 3. Slack and radial adjustment of energy by area and year (1995–2002).

beginning period. This discovery matches the real condition of regional development in China. As shown in Table 4, most regions and areas in China have their improved TFEE followed up with economic growth in the period from 1995 to 2002 since China showed dramatic economic growth during this period. The east and central areas both improved during the sample's period. Especially, the central area had significant improvement in the period, although its average level is the lowest rank among all areas. The west area just started its development in recent years and therefore its TFEE score degraded in the beginning of the research period, and kept flat in the later years. However, there are no significant changes on the TFEE of regions in the west area.

4.4. *Comparison of total-factor and partial-factor energy efficiencies*

The commonly used indicator of energy efficiency, the index of energy productivity ratio (Patterson, 1996), is also computed for comparison with TFEE. In contrast

Table 4
Total-factor energy efficiency by region (1995–2002)

ID	Region		1995	1996	1997	1998	1999	2000	2001	2002
1	E	Beijing	68.9	69.9	64.7	65.8	68.3	69.5	76.5	80.1
2	E	Tianjin	58.5	65.5	65.5	63.1	68.5	66.7	70.0	76.0
3	E	Hebei	53.7	55.9	56.0	57.2	58.7	47.1	64.0	62.6
4	E	Liaoning	49.7	50.3	49.3	51.4	53.6	49.9	52.8	55.9
5	E	Shanghai	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
6	E	Jiangsu	82.8	83.5	82.4	79.9	84.4	85.9	90.0	93.3
7	E	Zhejiang	93.4	94.5	92.0	90.0	90.8	92.4	96.3	100.0
8	E	Fujian	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
9	E	Shandong	64.7	65.2	63.0	62.5	68.3	78.9	81.2	82.2
10	E	Guangdong	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
11	E	Guangxi	100.0	100.0	100.0	94.1	94.0	90.5	93.8	95.2
12	E	Hainan	100.0	100.0	88.8	83.5	85.4	81.1	78.1	80.4
13	C	Shanxi	15.6	19.2	18.1	19.2	19.7	19.2	23.3	22.9
14	C	Inner Mongolia	37.8	36.4	29.0	30.4	27.3	30.7	38.9	100.0
15	C	Jilin	32.4	33.4	30.0	32.6	38.3	40.8	51.0	51.4
16	C	Heilongjiang	44.3	49.0	44.0	36.9	37.4	39.7	58.2	64.5
17	C	Anhui	74.1	72.8	74.4	74.0	75.7	63.8	76.1	77.3
18	C	Jiangxi	59.0	66.1	68.0	70.7	72.4	69.8	72.4	75.4
19	C	Hennan	65.1	69.4	71.9	70.6	72.6	66.5	77.8	79.2
20	C	Hubei	47.0	50.1	52.6	53.2	56.0	53.2	78.1	76.2
21	C	Hunan	86.1	89.2	95.2	97.7	100.0	100.0	100.0	100.0
22	W	Sichuan	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
23	W	Guizhou	49.4	42.8	39.8	39.1	44.0	40.8	38.9	41.5
24	W	Yunnan	71.3	75.9	73.4	77.3	78.7	66.1	76.6	76.4
25	W	Shaanxi	36.4	31.9	38.3	40.4	46.5	49.4	52.3	53.6
26	W	Gansu	23.6	28.0	31.2	32.8	34.4	28.8	43.8	47.5
27	W	Qinghai	31.8	31.8	31.4	24.2	23.8	26.6	31.4	33.2
28	W	Ningxia	29.7	29.4	28.7	22.2	25.0	23.0	33.4	36.6
29	W	Xinjiang	40.3	35.7	36.9	29.7	38.8	41.6	42.0	55.5
		Total	64.1	65.8	65.2	65.6	67.7	66.4	72.7	76.0
		East	74.6	76.0	75.1	75.1	77.6	76.8	81.7	83.6
		Central	49.4	53.5	52.4	53.3	53.9	52.0	62.7	68.2
		West	64.1	61.7	62.8	62.8	65.6	63.1	65.9	69.1

Notes: (1) The unit is percentage. (2) E: east area, C: central area, and W: west area. (3) Data for the administration region Chongqing is regarded as a part of Sichuan in this paper since it was promoted as one of the municipalities in China only from 1997. (4) Data of energy consumption in Tibet is not included since it was not available in the sample period. (5) Scores with a gray shadow covered are those regions reaching the optimal efficiency with a unity (100%) TFEE score.

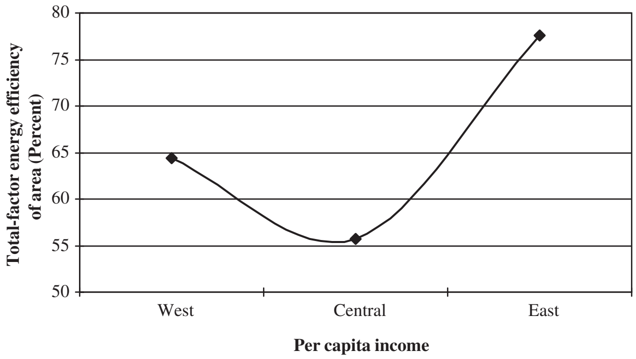

Fig. 4. The U-shape relation existing between total-factor energy efficiency of an area and per capita income of an area in China.

to the concept of TFEE, the commonly used index of energy productivity ratio can be regarded as a partial-factor energy efficiency (PFEE) index since energy is the only input factor considered in the index. The index PFEE computes the efficiency ratio by directly dividing GDP output by energy input as an indicator of energy efficiency. In contrast, the index TFEE incorporates the key inputs, labor and capital stock, together with the energy input, including the farm area proxy, to form a multiple-inputs model to assess energy efficiency on the basis of a total-factors effect.

Table 5 shows the PFEE score of the three main areas and that of China's total. The east area drops the most, over 10%, from 62.46% in 1995 to 51.45% in 2002. The west area drops the least at just 3% from 28.68% in 1995 to 25.51% in 2002. The central area's efficiency increased in period from 1995 to 1998, but then dropped in the period from 1999 to 2002: the lowest ratio is 36.44% in 2002. The PFEE score of China's total dropped from 45.31% in 1995 to 39.64% in 2002. As can be seen from these results, energy efficiency among

Table 5
Regional partial factor energy efficiency–the energy productivity ratio (1995–2002)

ID	Region		1995	1996	1997	1998	1999	2000	2001	2002
1	Beijing	E	39.7	40.2	39.6	40.0	39.6	39.4	41.2	41.1
2	Tianjin	E	35.8	40.2	42.3	42.5	41.2	39.3	39.4	39.1
3	Hebei	E	31.7	35.2	36.7	36.2	35.4	34.5	33.5	30.4
4	Liaoning	E	28.9	29.5	30.9	33.2	32.3	29.1	29.5	29.7
5	Shanghai	E	55.1	55.3	59.2	58.9	56.3	55.5	53.2	50.9
6	Jiangsu	E	64.1	67.4	70.1	69.0	68.5	66.8	66.9	63.7
7	Zhejiang	E	77.0	77.8	76.8	74.3	71.4	67.8	64.6	60.8
8	Fujian	E	94.8	96.9	99.3	100.5	93.0	89.2	84.0	77.3
9	Shandong	E	57.0	59.3	61.0	61.9	61.4	69.8	59.3	55.0
10	Guangdong	E	78.1	76.7	77.2	73.6	70.4	68.5	65.4	59.7
11	Guangxi	E	67.4	70.3	64.9	60.8	57.4	51.5	52.2	47.4
12	Hainan	E	120.2	102.9	88.2	83.9	79.4	72.4	65.6	62.2
13	Shanxi	C	13.0	17.4	17.8	18.8	16.8	16.4	14.0	12.4
14	Inner Mongolia	C	31.6	31.8	27.2	30.4	24.2	26.5	23.7	21.9
15	Jilin	C	27.5	29.2	28.0	32.3	32.8	33.4	32.9	29.7
16	Heilongjiang	C	33.9	37.3	35.3	36.9	34.7	35.3	36.9	37.3
17	Anhui	C	47.8	47.2	50.9	47.7	45.1	41.7	40.2	38.7
18	Jiangxi	C	52.1	64.2	67.5	71.1	66.8	60.5	58.4	54.3
19	Hennan	C	46.4	50.4	51.0	46.8	45.0	43.7	42.8	41.3
20	Hubei	C	42.3	45.1	47.4	47.7	46.8	45.7	48.1	42.7
21	Hunan	C	40.5	44.1	52.2	51.1	59.1	60.8	53.9	49.6
22	Sichuan	W	37.1	40.7	42.2	38.9	37.5	37.7	39.3	36.8
23	Guizhou	W	19.2	17.8	16.8	15.2	16.5	15.4	15.3	15.3
24	Yunnan	W	45.7	49.1	40.2	41.5	41.0	40.8	37.2	32.7
25	Shaanxi	W	31.7	30.4	35.8	35.6	40.5	40.7	35.4	31.6
26	Gansu	W	20.2	23.2	25.4	25.2	23.2	21.9	23.1	22.2
27	Qinghai	W	24.0	24.0	24.0	23.2	18.4	20.1	20.2	19.3
28	Ningxia	W	22.4	22.0	22.0	21.4	20.7	20.5	21.0	20.8
29	Xinjiang	W	29.2	25.8	27.3	26.5	26.4	27.6	26.6	25.4
	Average		45.3	46.6	46.8	46.4	44.9	43.9	42.2	39.6
	East		62.5	62.6	62.2	61.2	58.8	57.0	54.6	51.5
	Central		37.2	40.7	41.9	42.5	41.3	40.4	39.0	36.4
	West		28.7	29.1	29.2	28.4	28.0	28.1	27.2	25.5

Notes: (1) The unit is percentage. (2) E: east area, C: central area, and W: west area. (3) Data for the administration region Chongqing is regarded as a part of Sichuan in this paper since it was promoted as one of the municipalities in China only from 1997. (4) Data of energy consumption in Tibet is not included since it was not available in the sample period.

areas in China and that of China's total are dropping in the sample period.

The result is different from the result found from the TFEE score. First, all areas' PFEE scores are declining in the period, meaning that energy efficiency drops in all areas of China. The more developed the area is, such as the east area, the more the energy efficiency drops. In TFEE, the energy efficiency drops the most for an area in a developing stage but not in a developed stage. This is because in a developing stage, out-of-date technologies and inappropriate production processes need to be upgraded while more output is still generated. The upgraded technologies and more advanced production processes should have been launched when an area or a region enters a developed stage and a better efficiency level is therefore expected. Second, energy efficiency is proportional to an economy's developmental progress in an area. TFEE does not mean that a proportional relation exists between the state of economic development and energy efficiency, but a U-shape relation does, which fits better to the real condition.

The comparative result also shows that the substitution among inputs (labor, capital stock, and energy) to produce the output (GDP) is significant. The PFEE scores could be over-estimated if energy is taken as the single input in the production. A certain portion of GDP output is produced not only by the energy itself, but also by other inputs (labor and capital stock). Hence, a multiple-inputs framework is integral to correctly evaluate energy efficiency, with which the index TFEE is established.

5. Concluding remarks

The index of total-factor energy efficiency (TFEE) is first constructed in this study by taking the ratio of actual energy input to target energy input and this is conducted through DEA. The formula is constructed in Eq. (3). The multiple-inputs model is adopted for an assessment of energy efficiency since energy is not the only input to produce output and it has to be accompanied by other inputs to produce real economic outputs. On the other hand, a certain portion of GDP output is generated not only by energy input, but also by inputs of labor and capital stock. A substitution effect, whereby GDP output is generated from other inputs rather than energy input, is therefore well considered under such a multiple-inputs model. Index TFEE therefore evaluates energy efficiency in an appropriate approach.

A unity TFEE score identifies a DMU which operates optimally at the efficiency of energy consumption. The DMU with a unity TFEE score consumes the minimum level of energy input and generates the maximum economic output including other inputs considered. An efficiency frontier of energy consumption is constituted by these DMUs. For those DMUs which have a TFEE score of less than unity and are not yet at the frontier efficiency of energy consumption; they are capable of taking one of those DMUs located at the frontier as a target to adjust their technology levels and production processes according to efficiency improvement. The slack and radial adjustments provide adequate input targets for a DMU with a TFEE less than unity to achieve the optimal energy efficiency.

This paper reports the result of an empirical study of regional energy efficiency in China based on the index TFEE. The commonly used index of the energy productivity ratio (Patterson, 1996) as PFEE is calculated as well for comparison. The index PFEE observes only the partial effect between energy input and GDP output, but not the total-factor effects observed in TFEE based on the multiple-inputs model. As a result of comparison, index TFEE shows the advantage of assessing energy efficiency as being more practical than PFEE. A U-shape relation is found between the TFEE and per capita income in an area, which explains that an improvement in energy efficiency is followed by economic growth though it declines in the beginning period. As Table 4 shows, TFEE in most regions of China, especially for those located in the east and central areas, is improving during the research period. The more economic growth there is, the more is energy efficiency a concern and can improve. These results cannot be observed from a conventional PFEE index.

The developed area (east area) in China has the highest TFEE rank and the least developed area (west area) has the second best rank. However, the developing area (the central area) has the worst TFEE rank even though this area creates the second highest level of GDP output in China. Shanghai (5), Fujian (8), Guangdong (10), and Sichuan (22) are the four regions which constitute the efficiency frontier of energy consumption in our analysis. These regions are going to be targets and learning models for other regions which are not yet at the optimal level of energy efficiency so that they can improve their technology level and production processes accordingly.

It is noted that the index TFEE assesses the energy efficiency of each region in China based on China's own frontier, and not on the other economies' or countries'. This means that the feasible improvement steps do exist for those energy-inefficient regions to move onto the frontier. Similarities do exist on a variety of inputs, technology, and production processes among these regions, and the target is reachable and total adjustments are possibly reduced from the actual inputs in these regions by improving technology and production processes.

Because sustainable economic development relies upon efficient energy consumption, energy efficiency on a regional basis is the main focus in this study. Further improvement actions can be taken at the regional level and a more detailed analysis can be conducted by taking a reference for each region's root causes at a deeper level. Industrial structure, energy policies, energy consumption type, and treatments from local governments can be further incorporated together. A world energy efficiency frontier can be also established with the same method to overview China's efficiency rank of energy consumption globally, but it would require more data to be collected. As long as a good balance between economic growth and efficiency of energy consumption is reached, sustainable development with sufficient energy supply can be achieved.

Acknowledgements

We would like to express our appreciation for the valuable comments from an anonymous referee and an editor of this journal. The authors also thank Shih-Nang Chen, Cherng G. Ding, Kuo-Hsiung Lin, and seminar participants at the Shih-Hsin University for their useful suggestions and comments. Partial financial support from Taiwan's National Science Council (NSC 93-2415-H-009-001) is gratefully acknowledged. The usual disclaimer applies.

References

Banker, R.D., Charnes, A., Cooper, W.W., 1984. Some models for estimating technical and scale inefficiencies in data envelopment analysis. Management Science 30, 1078–1092.

Boyd, G.A., Pang, J.X., 2000. Estimating the linkage between energy efficiency and productivity. Energy Policy 28, 289–296.

Business Asia, 2005. Economic outlook: China. Business Asia 37 (6), 9.

Chang, J., Leung, D.Y.C., Wu, C.Z., Yuan, Z.H., 2003. A review on the energy production, consumption, and prospect of renewable energy in China. Renewable and Sustainable Energy Reviews 7, 453–468.

Charnes, A., Cooper, W.W., Rhodes, E., 1978. Measuring the efficiency of decision making units. European Journal of Operational Research 2, 429–444.

Coelli, T.J., 1996. A Guide to Deap Version 2.1: A Data Envelopment Analysis (Computer) Program. Department of Econometrics, University of New England, Armidale, Australia.

Coelli, T.J., Rao, D.S.P., Battese, G.E., 1998. An Introduction to Efficiency and Productivity Analysis. Kluwer Academic Publishers, Boston, MA.

Fleisher, B., Chen, J., 1997. The coast–noncoast income gap, productivity, and regional economic policy in China. Journal of Comparative Economics 25, 220–236.

Gibbs, D., 1998. Regional development agencies and sustainable development. Regional Studies 32, 365–368.

Gibbs, D., 2000. Ecological modernization, regional development and regional development agencies. Geoforum 31, 9–19.

Hawdon, D., 2003. Efficiency, performance and regulation of the international gas industry—a bootstrap DEA approach. Energy Policy 31, 1167–1178.

International Energy Agency (IEA), 2004. World Energy Outlook 2004. OECD/IEA, Paris.

Kadoshin, S., Nishiyama, T., 2000. The trend in current and near future energy consumption from a statistical perspective. Applied Energy 67, 289–296.

Li, K.W., 2003. China's capital and productivity measurement using financial resources. Center Discussion Paper No. 851, Economic Growth Center, Yale University.

Lovell, A.K., Schmidt, S.S., 1993. Production Frontiers and Productive Efficiency, the Measurement of Productive Efficiency: Techniques and Applications. Oxford University Press, New York.

Patterson, M.G., 1996. What is energy efficiency? Concepts, indicators, and methodological issues. Energy Policy 24, 377–390.

Ramanathan, R., 1999. A holistic approach to compare energy efficiencies of different transport modes. Energy Policy 28, 743–747.

Sinton, J.E., Fridley, D.G., 2002. A guide to China's energy statistics. Journal of Energy Literature 8, 22–35.

World Bank, 2001. China country brief. http://www.worldbank.org.

Yang, D.T., 2002. What has caused regional inequality in China? China Economic Review 13, 331–334.