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Ecological total-factor energy efficiency of regions in China

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ABSTRACT

Most existing energy efficiency indices are computed without taking into account undesirable outputs such as CO_2 and SO_2 emissions. This paper computes the ecological total-factor energy efficiency (ETFEE) of 30 regions in China for the period 2005–2009 through the slack-based model (SBM) with undesirable outputs. We calculate the ETFEE index by comparing the target energy input obtained from SBM with undesirable outputs to the actual energy input. Findings show that China's regional ETFEE still remains a low level of around 0.600 and regional energy efficiency is overestimated by more than 0.100 when not looking at environmental impacts. China's regional energy efficiency is extremely unbalanced: the east area ranks first with the highest ETFEE of above 0.700, the northeast and central areas follow, and the west area has the lowest ETFEE of less than 0.500. A monotone increasing relation exists between the area's ETFEE and China's per capita GDP. The truncated regression model shows that the ratio of R&D expenditure to GDP and the degree of foreign dependence have positive impacts, whereas the ratio of the secondary industry to GDP and the ratio of government subsidies for industrial pollution treatment to GDP have negative effects, on the ETFEE.

1. Introduction

China has created an economic growth miracle in the past 30 odd years, as its GDP has grown by almost 110 times from 1978 to 2010. In 2010, China surpassed Japan to rank second in the world with a GDP of 39.8 trillion RMB (National Bureau of Statistics of China, 2011). China in 2010 also became the world's biggest energy consumer with a whopping 20.3% share of global energy use (BP, 2011). Obviously, its economic growth is driven by huge energy consumption, which is not sustainable. It is very important for China to now improve energy efficiency without harming economic performance due to the following three reasons.

First, China's energy supply is becoming increasingly insufficient. Taking crude oil as example, its import dependence went from a low of 6% in 1993 to a high of 55.2% in 2011 (Ministry of Industry and Information Technology of the People's Republic of China, 2011). Coal imports increased rapidly as well from 2.18 million tons in 2000 to 125.84 million tons in 2009 (China Energy Statistical Yearbook, 2010). China's energy demand continues to grow and is showing signs of a shortage in the long term (Liu, 2011).

Second, there is a big gap between China and developed countries on energy consumption per unit of GDP. Although the gap is gradually narrowing, China's level is 4.5 times that of Japan and almost 2.8 times that of the U.S. in 2008. An important cause for such a gap is its low energy efficiency. China's transformation of its economic growth model and an upgrade to its industrial structure are becoming quite imperative.

Third, pollution is a severe constraint to economic growth in China. The economic loss caused by pollution has reached 1.4 trillion RMB, which accounted for 3.9% of GDP in 2008 (China Environmental and Economic Accounting Report, 2010). According to China's commitments in 2009, its CO_2 emissions per unit of GDP should decrease 40%–45% by 2020 compared to the level in 2005. However, total energy consumption will not fall due to continued stable economic growth. Energy efficiency improvement is the major solution to the energy problem and is a major goal that China is pursuing for the sake of current and future economic growth (Shi, 2007).

Energy efficiency plays an important role in economic development, attracting more and more academic evaluations that use two different methods: one is partial-factor energy efficiency, and the other is total-factor energy efficiency. Based on the partial-factor evaluation framework, the most popular indices include the energy intensity and energy productivity ratios. Energy intensity refers to the ratio of energy input to GDP, while energy productivity is the reciprocal of the energy input: the GDP ratio. Both indices only take energy into account as a single input to produce

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GDP while neglecting other key inputs such as capital and labor. There has been widespread criticism of using energy intensity for measuring energy efficiency (Patterson, 1996). The main problem with energy/GDP, as pointed out by Wilson et al. (1994), is that it does not measure the underlying technical energy efficiency, which can present misleading conclusions.

Proposing a total-factor framework, Hu and Wang (2006) initially put forward the TFEE (total-factor energy efficiency) index, which is constructed as the ratio of the target energy input suggested by DEA to the actual energy input. Hu and Kao (2007) calculated energy-saving target ratios for 17 APEC economies during 1991–2000 by the TFEE index and pointed out that China has the largest energy-saving target at up to almost half its current usage. They further found that the energy-saving target ratio has a positive relation with the percentage of the added value in the industry sector to GDP and a negative relation with that of the service sector. Hu et al. (2006) established an index containing a water adjustment target ratio based on the TFEE, discovering a *U*-shape relation between the total-factor water efficiency and per capita real income among areas in China with the central area having the worst water efficiency ranking.

Honma and Hu (2008) computed the regional TFEE in Japan for the period 1993–2003 and found that the inland regions and most regions along the Sea of Japan are efficient in energy use, whereas most of the inefficient prefectures that were developing mainly upon energy-intensive industries are located along the Pacific Belt Zone. Lee et al. (2011) computed the three major types of efficient electricity, coal, and gasoline oil savings for 27 regions in China during 2000–2003 by a total factor framework and presented that the east area contains most of the efficient regions with respect to the three major types of energy in every year during the research period. Zhang et al. (2011) employed TFEE to investigate energy efficiency in 23 developing countries during the period 1980–2005 and indicated that Botswana, Mexico, and Panama perform the best in terms of energy efficiency, whereas Kenya, Sri Lanka, Syria, and the Philippines perform the worst during the entire research period.

The TFEE is capable of measuring energy efficiency in a total-factor framework, but only takes GDP into account as the single output while neglecting undesirable outputs. However, GDP cannot be produced alone from the use of energy with other inputs, and environmental pollution is an undesirable and unavoidable by-product of GDP output. Global warming is a serious environmental problem in the world and has been a growing concern in recent years (e.g., Radhi, 2009; Cha et al., 2008; Fearnside, 2002). As such, a sustainable framework should be proposed to assess energy efficiency much more accurately, and environmental impacts should be incorporated — that is, not only the desirable GDP, but also the undesirable CO_2 and SO_2 should be taken as outputs. Following the sustainable framework, this paper puts forward a new index of energy efficiency and names it the ecological total-factor energy efficiency (ETFEE). The ETFEE is constructed as the ratio of the target energy input suggested from the SBM model with undesirable outputs to the actual energy input in a region.

The purposes of this paper are as follows. The first is to innovatively construct the index of ETFEE based on an SBM model with undesirable outputs. The second is to distinguish the difference between ecological total-factor energy efficiency and traditional total-factor energy efficiency and to comprehensively evaluate regional energy efficiency in China by using the ETFEE index. The third is to clarify the discrepancy of ETFEE among different areas (including east, central, west, and northeast areas) in China. The final purpose is to identify the influential factors of regional ETFEE.

This paper is organized as follows. Section 2 reviews the SBM and an undesirable output model based on SBM and then describes how the index of ETFEE is constructed. Section 3 presents the data source, variable definitions, and descriptive statistics. Section 4 provides an empirical study for the energy efficiency of regions in China based on ETFEE. The final section concludes the paper.

2. Methodology: Ecological total-factor energy efficiency (ETFEE)

Under the background of energy scarcity and environment pollution, it is preferable for a region to increase GDP while reducing pollution and energy consumption. This section proposes the ETFEE index on the viewpoint of sustainability, which is calculated by an undesirable model based on SBM. This model takes energy in conjunction with labor and capital stock as inputs, while taking not only GDP, but also undesirable CO_2 and SO_2 as outputs.

2.1. Slacks-based measure of efficiency (SBM)

Built upon the earlier work of Farrell (1957), DEA is a well established methodology to evaluate the relative efficiencies of a set of comparable entities by some specific mathematical programming models (Zhou et al., 2008). The SBM was introduced by Tone (2001) from the basic CCR-DEA (Charnes et al, 1978) and BCC-DEA (Banker et al., 1984) models. Cooper et al. (2007) pointed out that SBM has two important properties. First, the measure is invariant with respect to the unit of measurement of each input and output item. Second, the measure is monotone decreasing in each input and output slack. Moreover, the measure generally has no strict requirements with the input and output prices, does not impose any particular functional form on the data, and creates a more flexible piecewise linear function, and so it can be used to analyze the complex production process with multi-inputs and multi-outputs.

The fractional programming problem of the constant-returns to scale (CRS) SBM model is expressed as follows:

$$\begin{aligned}
&\min_{\lambda,s^+,s^-} \rho = \frac{1-(1/m)\sum_{i=1}^{m} s_i^- / x_{io}}{1+(1/n)\sum_{r=1}^{n} s_r^+ / y_{ro}} \\
&\text{subject to } x_o = X\lambda + S^- \\
&y_o = Y\lambda - S^+ \\
&\lambda \geq 0, s^- \geq 0,\ s^+ \geq 0, \qquad (1)
\end{aligned}$$

where each region has m inputs and n outputs; x_o, y_o, s_i^-, and s_r^+ represent the input, output, input slack, and the output slack for the oth region, respectively; X, Y, S^-, and S^+ are the corresponding matrices of the input, output, input slack, and output slack; and λ is a constant vector. The obtained value of ρ is the overall technical efficiency score for the oth DMU.

2.2. Undesirable output model: Based on SBM

Consider a production process in which desirable and undesirable outputs are jointly produced. Assume that $X \in R_+^m$, $Y^g \in R_+^{n_1}$, and $Y^b \in R_+^{n_2}$ are the vectors of inputs, desirable outputs, and undesirable outputs, respectively. The production technology can be described as:

$$T = \{(x, y^g, y^b) : x \text{ can produce}(y^g, y^b)\}. \qquad (2)$$

In order to reasonably model a production process in which both desirable and undesirable outputs are jointly produced, Färe et al. (1989) proposed two assumptions on the production technology. The first is that outputs are weakly disposable; i.e., if $(x, y^g, y^b) \in T$ and $0 \leq \theta \leq 1$, then $(x, \theta y^g, \theta y^b) \in T$. The second is that desirable and undesirable outputs are null-joint; i.e., if $(x, y^g, y^b) \in T$ and $y^b = 0$, then $y^g = 0$. The first assumption implies that the reduction of undesirable outputs is not free, and the proportional reduction in desirable and undesirable outputs at the same time is feasible. This second assumption implies that some undesirable outputs must also be produced when desirable outputs are produced.

The production possibility set that satisfies the above-mentioned assumptions can be expressed as follows:

$$P(x)=\{(y^g,y^b):X\geq x,\ y^g\leq Y^g\lambda,\ y^b\geq Y^b\lambda,\ \lambda\geq 0,\ X>0,\ Y^g>0,\ Y^b>0\},\tag{3}$$

where λ is a constant vector representing the weight of each DMU. The inequalities of the input and desirable output imply that the input and desirable output are strongly disposable. With the inequality of undesirable output considered, the desirable and undesirable outputs are weakly disposable. The inequalities of $Y^g>0$ and $Y^b>0$ fit the assumption that desirable and undesirable outputs are null-joint. Notice that the above definition corresponds to the constant returns to scale technology.

In accordance with the above-mentioned production technology, Cooper et al. (2007) proposed the CRS-SBM model with undesirable outputs to calculate the technical efficiency of a production system in which desirable and undesirable outputs are jointly produced. The fractional programming problem solved by the CRS-SBM model with undesirable outputs for region i is as follows:

$$\min_{\lambda,s^-,s^g,s^b}\rho=\frac{1-(1/m)\sum_{i=1}^{m}s_i^-/x_{io}}{1+(1/n_1+n_2)\left(\sum_{r=1}^{n_1}(s_r^g/y_{ro}^g)+\sum_{r=1}^{n_2}(s_r^b/y_{ro}^b)\right)}\tag{4}$$

$$\text{subject to } x_o=X\lambda+S^-\tag{5}$$

$$y_o^g=Y^g\lambda-S^g\tag{6}$$

$$y_o^b=Y^b\lambda+S^b\tag{7}$$

$$\lambda\geq 0,\ s^-\geq 0,\ s^g\geq 0,\ s^b\geq 0,\ X>0,\ Y>0,\tag{8}$$

where each region has m inputs, n_1 good outputs, and n_2 bad outputs; X, Y^g, and Y^b are the matrices of the input, good output, and bad output, respectively, while all of X, Y^g, and Y^b are strictly larger than zero; S^-, S^g, and S^b are the matrices of the input, good output, and bad output slacks, respectively; and λ is a constant vector.

Eq. (5) imposes strong disposability of inputs. Eq. (6) ensures the desirable output satisfies strong disposability. Eq. (7) depicts that undesirable outputs are weakly disposable. The inequalities $X>0$ and $Y>0$ imply that desirable and undesirable outputs are null-joint and the undesirable output is a byproduct of the desirable output. The computed value of ρ is the overall technical efficiency score for the oth region with the inclusion of undesirable outputs.

2.3. Regional ETFEE with undesirable outputs considered

Energy efficiency for region i at time t can be defined as below, which is called ecological total-factor energy efficiency (ETFEE) since it is established on the viewpoint of total factor productivity and sustainable development under the consideration of undesirable outputs.

$$\text{ETFEE}(i,t)=\frac{\text{Target energy input}(i,t)}{\text{Actual energy input}(i,t)}.\tag{9}$$

The target energy input for each region is obtained from SBM with the undesirable outputs accounted for, which is defined as:

$$\text{Target energy input}(i,t)=\text{Actual energy input}(i,t)-\text{Total energy input slack}(i,t)\tag{10}$$

In other words, the target energy input is the projection on the energy axis when a DMU improves and reaches the efficient frontier. The gap between the target level and the actual level is named total energy input slack, which is regarded as the inefficient portion of actual energy consumption. The ETFEE score is always between zero and one. If the target energy input is equal to the actual level, then the ETFEE is one, indicating the highest efficiency level of energy consumption. If the actual energy input is much higher than the target, then the index approaches zero, indicating very low efficiency.

2.4. ETFEE for an area

The ETFEE index can be used to evaluate energy efficiency not only in a region, but also in an area or for a country consisting of several regions. The ETFEE in an area is equal to the total target energy inputs divided by the total actual energy input of the area. Assuming area a covers q regions, the ETFEE of area a at time t can be calculated as:

$$\text{ETFEE}(a,t)=\frac{\sum_{q\in a}\text{Target energy input}(q,t)}{\sum_{q\in a}\text{Actual energy input}(q,t)}.\tag{11}$$

3. Data source, variable definitions, and descriptive statistics

There are 31 provinces, autonomous regions, and municipalities in mainland China: Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, and Tibet. Due to serious absence of data, Tibet is excluded. The SBM model with undesirable outputs is applied to the other 30 provinces, autonomous regions, and municipalities in China from 2005 to 2009. This paper employs total energy consumption, capital stock, and labor as inputs, and desirable GDP is accompanied by undesirable CO_2 and SO_2 as outputs.

All the data for GDP, labor, and SO_2 emission come from *China Statistical Yearbook*. GDP as a monetary output is transformed into 2005 prices with a GDP deflator. The total energy consumption is collected from China Energy Statistical Yearbook.

Capital stock is not available in any China statistical data, but it can be calculated as follows. First, we get the capital stock in 2000 from Zhang et al. (2004) and capital formation and capital price indices from *China Statistical Yearbook*. Second, the capital stock in 2000 and capital formation from 2001 to 2009 should be transformed into 2005 prices with capital price indices. Third, we consider a capital depreciation rate. The capital stock from 2001 to 2009 with 2005 prices can then be calculated, taking 2000 as the starting year. Finally, the capital stock from 2005 to 2009 is taken as the sample data.

$$\text{Capital Stock in Current Year}=\text{Capital Stock in Previous Year}\times(\text{1-Depreciation rate})+\text{Capital Formation in Current Year}.\tag{12}$$

There is no available official data on regional CO_2 emission in China. However, we can obtain detailed energy consumptions (including fuel oil, coke coal, gasoline, kerosene, diesel oil, and natural gas liquids) from China Energy Statistical Yearbook and net calorific value and the effective CO_2 emission factor for each kind of energy from *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006). The CO_2 emission of region i at time t is estimated as:

$$\text{Regional }CO_2\text{ emission}_{i,t}=\sum_{j=1}^{n}(\text{Energy consumption}_{it,j}\times\text{Net calorific value}_j\times\text{Effective }CO_2\text{ emission factor}_j)\tag{13}$$

where j denotes different kinds of energies.

Table 1
Descriptive statistics of the data.

Variable	Definition	Unit	Minimum	Maximum	Mean	Standard deviation
Desirable outputs						
y_1	Real GDP	100 million RMB in 2005 prices	543.320	36,035.129	8,671.620	7,270.075
Undesirable outputs						
y_2	SO_2 Emission	Ten thousand tons	2.175	200.200	80.926	47.004
y_3	CO_2 Emission	Ten thousand tons	1025.162	74,295.068	21,827.533	15,425.980
Inputs						
x_1	Energy consumption	Ten thousand tons of standard coal equivalence	822.000	32,420.000	10,452.733	6,747.828
x_2	Capital stock	100 million RMB in 2005 prices	1878.801	77,955.769	20,397.321	15,721.950
x_3	Labor	Ten thousand persons	128.700	5,948.800	2,174.531	1,533.290
Influential factors						
z_1	Ratio of intramural expenditure on R&D to GDP	%	0.178	5.502	1.190	0.949
z_2	Degree of foreign dependence	%	4.530	166.816	35.571	40.798
z_3	Ratio of the secondary industry to GDP	%	23.500	61.500	47.809	7.611
z_4	Ratio of government subsidies for industrial pollution treatment to GDP	%	0.000	0.100	0.012	0.015

This paper investigates the relations between four influential factors, including the ratio of intramural expenditure on R&D to GDP, the ratio of the secondary industry to GDP, the foreign dependence degree which is the ratio of total imports and exports to GDP, and the ratio of government subsidies for industrial pollution treatment to GDP and the ETFEE scores. The data of intramural expenditure on R&D are from *China Statistical Yearbook on Science and Technology*. The added value of the secondary industry, the total imports and exports, and the government subsidies for industrial pollution treatment are from *China Statistical Yearbook*. To sum up, there are 150 observations in all and the descriptive statistics of the original data are portrayed in Table 1.

4. Empirical analysis

4.1. Comparison of ETFEE and TFEE

The essential difference between total-factor energy efficiency and ecological total-factor energy efficiency is whether to incorporate the environmental impacts. The ecological total-factor energy efficiency is based on the viewpoint of sustainability and considers not only the good outputs, but also the bad outputs. Compared to traditional total-factor energy efficiency, it evaluates energy efficiency much more accurately. Table 2 shows the regional ETFEE and TFEE of China.

The regional ETFEE in China on average is at a low level of about 60%, which urgently needs to be improved. The actual energy input could be reduced by almost 40%, with output unchanged, through energy efficiency improvement. This indicates that energy efficiency improvement is an effective way to solve the dilemma between the rising energy consumption demand from rapid economic growth and the increasing pressure on emission reduction.

Without incorporating environmental impacts, regional energy efficiency can be overestimated. As Table 2 shows, the average ETFEE is always lower than the average TFEE. From 2005 to 2009, the average ETFEE in China is 0.609, 0.607, 0.617, 0.617, and 0.597, while the average TFEE is 0.716, 0.740, 0.715, 0.734, and 0.726, respectively. The Mann-–Whitney *U* rank test proves that the difference between ETFEE and TFEE presents a statistical significance with a *P*-value less than 0.001 as Table 3 shows. The comparative result means that the consideration of undesirable outputs has a significant influence on regional energy efficiency.

The energy efficiency is much higher with only one dimension of energy savings and becomes much lower with the added dimension of emission reduction. Under the consideration of environmental impacts, most regions are landing much more below the efficient frontier due to poor performance on pollution emission. This indicates that China has achieved much more improvement in energy savings than that of emission reduction.

In order to improve energy efficiency and achieve sustainable development, China should concentrate on both energy saving and emission reduction at the same time. The reduction of emissions is not only affected by energy saving, but also by the optimization of energy consumption type. China's government should be concerned about energy savings, as well as put much more emphasis on the adjustment of energy type. In fact, the government has become aware of this problem, and the readjustment of energy type is one of the main tasks in the Comprehensive Program on Energy-Saving and Emission Reduction during the Twelfth Five-Year Plan (2011–2015) enacted by the State Council of China.

At the regional level, Table 4 shows the gap between ETFEE and TFEE. The regions are divided into three groups. The first group includes Beijing, Guangdong, and Shanghai. There are no gaps between ETFEE and TFEE for these three regions, because they always stand on the efficient frontier for both ETFEE and TFEE for each year. The only thing for this group to do is to keep advancing continually in all the regions. The second group consists of Chongqing, Fujian, Guizhou, Hebei, Heilongjiang, Hubei, Liaoning, Qinghai, and Shaanxi. Their gaps between ETFEE and TFEE are becoming narrower, indicating that their ability to manage the undesirable outputs is enhanced. The third group contains Anhui, Gansu, Guangxi, Hainan, Henan, Hunan, Inner Mongolia, Jiangsu, Jiangxi, Jilin, Ningxia, Shandong, Shanxi, Sichuan, Tianjin, Xinjiang, Yunnan, and Zhejiang, whose gaps between ETFEE and TFEE are becoming larger. These regions have paid more attention to energy savings, with less attention towards emission reduction. They should vigorously promote energy savings and emission reduction at the same time.

4.2. ETFEE discrepancy of different areas

According to economic development and geographical location, China can be divided into four areas as in Fig. 1. The east area consists of Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan, which is the most developed

Table 2
Regional ETFEE and TFEE in China from 2005 to 2009.

ID	Region	ETFEE					TFEE				
		2005	2006	2007	2008	2009	2005	2006	2007	2008	2009
1	Anhui	0.653	0.657	0.663	0.665	0.600	0.876	0.896	0.914	0.918	0.904
2	Beijing	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3	Chongqing	0.557	0.560	0.567	0.571	0.512	0.812	0.681	0.872	0.889	0.681
4	Fujian	0.847	0.850	0.819	0.785	0.757	1.000	1.000	0.904	0.913	0.896
5	Gansu	0.352	0.351	0.354	0.356	0.367	0.460	0.476	0.497	0.529	0.540
6	Guangdong	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
7	Guangxi	0.650	0.648	0.649	0.646	0.573	0.819	0.851	0.890	0.915	0.975
8	Guizhou	0.282	0.283	0.285	0.292	0.291	0.471	0.472	0.470	0.478	0.466
9	Hainan	1.000	0.828	0.780	0.736	0.713	1.000	1.000	1.000	1.000	0.924
10	Hebei	0.401	0.402	0.435	0.449	0.444	0.523	0.533	0.435	0.468	0.475
11	Heilongjiang	0.544	0.546	0.578	0.585	0.591	0.665	0.625	0.578	0.585	0.591
12	Henan	0.575	0.575	0.581	0.586	0.529	0.714	0.747	0.799	0.847	0.719
13	Hubei	0.519	0.521	0.526	0.494	0.488	0.674	0.698	0.721	0.589	0.590
14	Hunan	0.540	0.542	0.549	0.564	0.522	0.665	0.680	0.694	0.719	0.719
15	Inner Mongolia	0.355	0.320	0.349	0.359	0.362	0.355	0.334	0.404	0.438	0.464
16	Jiangsu	0.859	0.866	0.833	0.819	0.806	0.940	0.983	0.939	0.962	0.952
17	Jiangxi	0.752	0.754	0.762	0.697	0.688	1.000	1.000	1.000	1.000	1.000
18	Jilin	0.541	0.543	0.594	0.602	0.602	0.724	0.658	0.701	0.790	0.836
19	Liaoning	0.512	0.473	0.515	0.522	0.516	0.512	0.655	0.531	0.598	0.591
20	Ningxia	0.192	0.188	0.204	0.210	0.211	0.317	0.354	0.330	0.357	0.377
21	Qinghai	0.258	0.249	0.269	0.270	0.271	0.440	0.394	0.418	0.414	0.422
22	Shaanxi	0.561	0.564	0.572	0.631	0.620	0.888	0.921	0.730	0.767	0.762
23	Shandong	0.604	0.607	0.663	0.652	0.565	0.657	0.775	0.663	0.694	0.698
24	Shanghai	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
25	Shanxi	0.264	0.261	0.284	0.297	0.295	0.334	0.347	0.284	0.310	0.341
26	Sichuan	0.497	0.498	0.504	0.503	0.511	0.699	0.709	0.727	0.740	0.723
27	Tianjin	0.832	1.000	0.843	0.871	0.870	0.841	1.000	0.867	0.871	0.935
28	Xinjiang	0.421	0.369	0.397	0.395	0.376	0.555	0.478	0.560	0.551	0.521
29	Yunnan	0.457	0.450	0.454	0.456	0.458	0.730	0.744	0.774	0.764	0.749
30	Zhejiang	0.884	0.892	0.855	0.835	0.821	0.974	1.000	0.970	1.000	0.993
	Average	0.609	0.607	0.617	0.617	0.597	0.716	0.740	0.715	0.734	0.726

Table 3
Significance test between ETFEE and TFEE in China.

	Mann-Whitney U	Wilcoxon W	*Z*-Value	*P*-value
ETFEE vs. TFEE	7558.000	18883.000	−4.923	<0.001

area in China. The west area contains Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, and Tibet, which is the most undeveloped area in China. Because of the absence of data, Tibet is not included in this research. The central area includes Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan. The northeast area includes Liaoning, Jilin, and Heilongjiang. Both the northeast and central areas are more developed than the western area, but less developed than the east area.

The regional energy efficiency of China is very imbalanced, as Fig. 2 presents. There are big gaps among the east, central, west, and northeast areas. The east area has the highest ETFEE, where the ETFEE scores are all larger than 0.7. Three regions, including Beijing, Shanghai, and Guangdong, are found to always have the optimal efficiency during the research period, and they are all located in the east area. To put this into more detail, Beijing is the political and cultural center of China and is the only one region whose third industry ratio is more than 50%. Shanghai is the economic and financial center of China and has developed service and high-tech industries. Guangdong is an export-oriented region, whose total imports and exports hit 611.09 billion USD in 2009 and occupy more than 25% of the total imports and exports in China. These three regions are the most developed in China.

Table 4
Gaps between ETFEE and TFEE in China from 2005 to 2009.

Group	Region	2005	2006	2007	2008	2009
1	Beijing	0.000	0.000	0.000	0.000	0.000
	Guangdong	0.000	0.000	0.000	0.000	0.000
	Shanghai	0.000	0.000	0.000	0.000	0.000
2	Chongqing	−0.255	−0.121	−0.305	−0.318	−0.169
	Fujian	−0.153	−0.150	−0.085	−0.128	−0.139
	Guizhou	−0.189	−0.189	−0.185	−0.186	−0.175
	Hebei	−0.122	−0.131	0.000	−0.019	−0.031
	Heilongjiang	−0.121	−0.079	0.000	0.000	0.000
	Hubei	−0.155	−0.177	−0.195	−0.095	−0.102
	Liaoning	0.000	−0.182	−0.016	−0.076	−0.075
	Qinghai	−0.182	−0.145	−0.149	−0.144	−0.151
	Shaanxi	−0.327	−0.357	−0.158	−0.136	−0.142
3	Anhui	−0.223	−0.239	−0.251	−0.253	−0.304
	Gansu	−0.108	−0.125	−0.143	−0.173	−0.173
	Guangxi	−0.169	−0.203	−0.241	−0.269	−0.402
	Hainan	0.000	−0.172	−0.220	−0.264	−0.211
	Henan	−0.139	−0.172	−0.218	−0.261	−0.190
	Hunan	−0.125	−0.138	−0.145	−0.155	−0.197
	Inner Mongolia	0.000	−0.014	−0.055	−0.079	−0.102
	Jiangsu	−0.081	−0.117	−0.106	−0.143	−0.146
	Jiangxi	−0.248	−0.246	−0.238	−0.303	−0.312
	Jilin	−0.183	−0.115	−0.107	−0.188	−0.234
	Ningxia	−0.125	−0.166	−0.126	−0.147	−0.166
	Shandong	−0.053	−0.168	0.000	−0.042	−0.133
	Shanxi	−0.070	−0.086	0.000	−0.013	−0.046
	Sichuan	−0.202	−0.211	−0.223	−0.237	−0.212
	Tianjin	−0.009	0.000	−0.024	0.000	−0.065
	Xinjiang	−0.134	−0.109	−0.163	−0.156	−0.145
	Yunnan	−0.273	−0.294	−0.32	−0.308	−0.291
	Zhejiang	−0.090	−0.108	−0.115	−0.165	−0.172

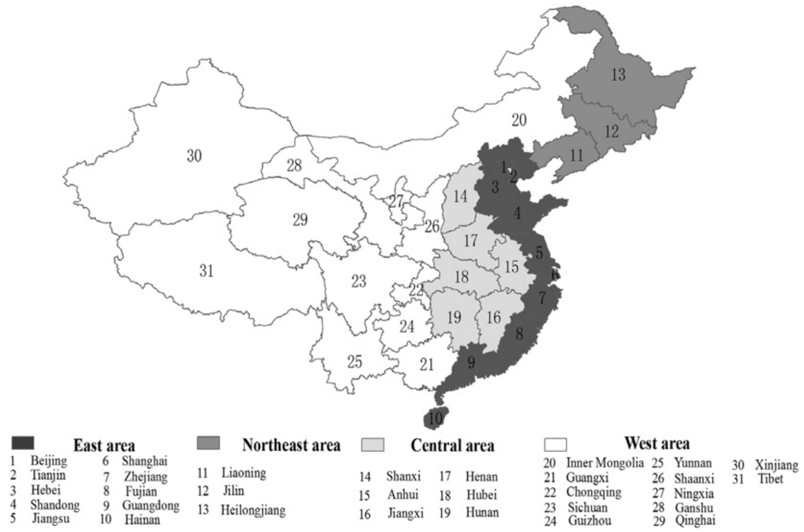

Fig. 1. Administrative regions and four major areas in China.

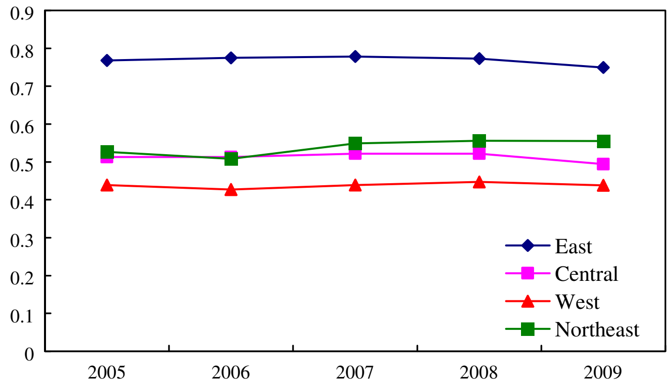

Fig. 2. ETFEE of different areas in China from 2005 to 2009.

Table 5
Significance test of ETFEE among different areas in China.

Indicator	Chi-square value by the Kruskal–Wallis rank test	*P*-value
ETFEE	81.103	< 0.001

Compared to the east area, the northeast, central, and west areas obviously fall behind. The ETFEE of the northeast and central areas is between 0.500 and 0.600. The northeast area ranks third in 2006 and second in the other years. The central area ranks second in 2006 and third in the other years. The west area ranks last and all its ETFEE scores are less than 0.500. The Kruskal–Wallis rank test proves ETFEE discrepancy among the different areas, showing statistical significance with a *p*-value less than 0.001. Table 5 shows the details.

A monotone increasing relation exists between each area's ETFEE and per capita GDP in China. The per capita GDP represents the economic development level in an area. As Fig. 3 shows, the east has the highest level of per capita GDP and also the highest ETFEE score. The northeast and central areas respectively have the second and third highest per capita GDP, and their efficiency levels perform the same as with the rank of the economic development level. The west has the lowest per capita GDP and the worst ETFEE score.

The monotone increasing relation reveals that energy efficiency tends to improve with economic development in China during the research period. This discovery matches the real condition of regional development in China. The main reasons are as follows. Throughout the thirty-year development after the reform and opening-up in 1978, all areas in China have already crossed the 'pollution first and treatment after' stage. In the 21st century, China has especially paid attention to the environmental impacts from regional economic growth. As Fig. 3 shows, China is over the inflection point similar to the environmental Kuznets curve and entering the stage of 'energy efficiency improvement parallel with economic development'. With a higher per capita GDP, an area is inclined to have better industrial structure, better production technology and better environmental protection technology, which are beneficial to improving energy efficiency.

Industrial structure is especially an important interaction carrier between economy development and energy efficiency. Taking the inefficient regions as examples, we describe the three most inefficient regions based on the average scores of the five-year period in order to discover the relationship between industrial characteristics and energy efficiency. All three provinces are located in the most undeveloped area of China, i.e., the west area.

The province with the lowest energy efficiency score is Ningxia, whose main industries are energy-intensive. Ningxia has five main industries, of which four are the main industries, including metallurgy, coal mining and processing, electricity manufacturing, and building material manufacturing, with the characteristics of high energy consumption and high pollution emission.

Qinghai is the most inefficient province after Ningxia. There are four main industries in Qinghai, including petroleum, electricity, non-ferrous metals, and salt chemical manufacturing industries. These four main industries occupy more than 66% of industry's total value-added. It should be noted that all of the main industries are energy-intensive in Qinghai.

Shanxi is the third inefficient province and is a typical resource-based region in the west area of China. The output of raw coal in Shanxi occupies more than 20% of China's total in 2009. Coal mining and processing, coke mining and processing, metallurgy, and electricity manufacturing are the four main industries in Shanxi. All four main industries are energy-intensive in Shanxi.

The above descriptions reveal that energy efficiency depends on regions' industrial structure and the inefficient regions are

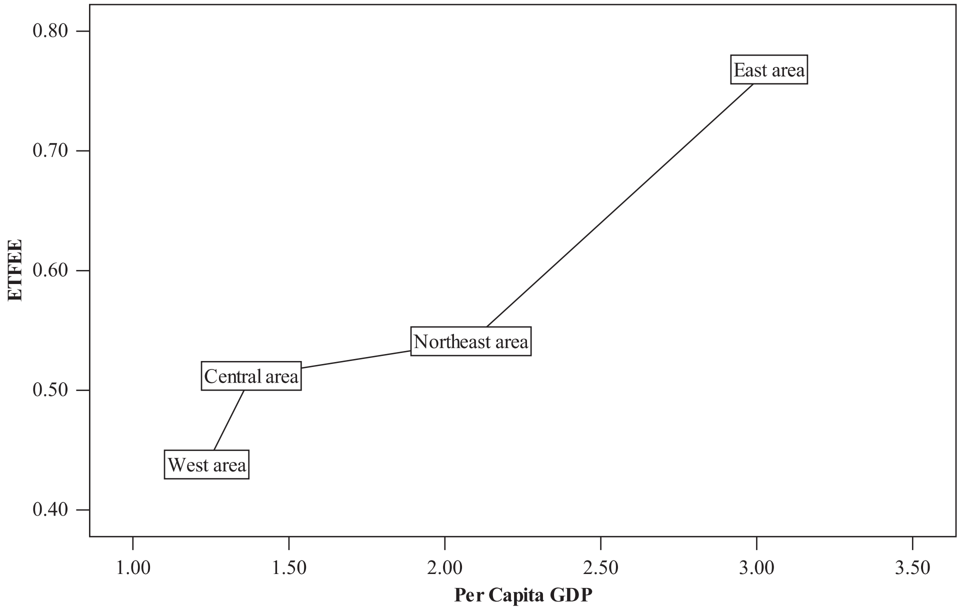

Fig. 3. Relationship between ETFEE and per capita GDP of areas in China.

concentrated on energy-intensive industries such as coal, metallurgy, electricity manufacturing, and salt chemical manufacturing. In order to improve energy efficiency, both the national and local governments must endeavor to change the industrial structure from energy-intensive industries to technology-intensive industries, service industries, and others. The national government should construct a mechanism at reasonably controlling the total energy consumption in regions and strengthen supervision of regional energy consumption, in order to force these energy-inefficient regions to readjust their industry structure. The local government should eliminate outdated production capacity, encourage service industry and high-tech industry development, and actively introduce energy conserving equipment and technologies.

4.3. Factors of regional ETFEE

The identification of factors that affect regional ETFEE is very significant for regional energy efficiency improvement, but is always neglected in most existing research studies. In order to distinguish the influential factors of regional ETFEE in China, we employ the truncated regression model based on the truncated characteristics of ETFEE data. The applicability of the truncated regression model in the two-stage procedures to account for exogenous factors that might affect productive efficiency is supported by Simar & Wilson (2007).

This paper investigates four factors. Factor z_1 represents the ratio of intramural expenditure on R&D to GDP. Factor z_2 is on behalf of the foreign dependence degree, which is the ratio of total imports and exports to GDP. Factor z_3 refers to the ratio of the secondary industry to GDP. Factor z_4 is the ratio of government subsidies for industrial pollution treatment to GDP. The model is set as:

$$ETFEE=\beta_0+\beta_1 z_1+\beta_2 z_2+\beta_3 z_3+\beta_4 z_4+\varepsilon,$$

where β_0 is the constant term; β_1, β_2, β_3, and β_4 are the parameters of the independent variables, respectively; and ε is the error term.

Taking the ETFEE of 30 regions in China from 2005 to 2009 as the dependent variables, we list the detailed truncated regression results in Table 6. It can be seen that all of the four variables show statistical significance in the truncated regression model of ETFEE.

Table 6
Factors of regional ETFEE scores in China.

	Coefficient	Significance test	
		Z-Value	*P*-Value
Constant term	71.70917	10.17566	<0.001
Dependent variable			
z_1	5.858229	4.771630	<0.001
z_2	0.345841	12.09995	<0.001
z_3	−0.579405	−4.164364	<0.001
z_4	−336.1687	−4.700679	<0.001

First, the higher ratio of R&D expenditure to GDP contributes to the higher ETFEE. For example, the ratio of R&D expenditure to GDP for Beijing, which is on the efficient frontier, is 5.482%, whereas that of Ningxia, which has the worst energy efficiency, is only 0.571% in 2005. Augmenting R&D expenditure is a very effective way to boost technical progress, and so it can be called the ‘technical improvement effect’. On the one hand, technical progress increases the resources’ usage efficiency and reduces the input per unit of output, hence relieving the environmental impact from the production process. On the other hand, much cleaner technology will be innovated to replace the dirty technology, hence decreasing the pollution emission per unit of output.

Both the central and local governments should establish a perfect system to encourage R&D activities and technical innovations. For example, the governments can give preferential tax rates of imported R&D equipments and permit the accelerated depreciation of R&D equipments based on fiscal and tax policies. For the financial policy, the governments can support R&D activities through low-interest loans, discount loans, and so on. For the technology input policy, the governments should increase the financial input on R&D activity, optimize financial input usage, and support some major research projects. The government should especially give priority towards supporting R&D activities on energy savings and emission reduction.

Second, the higher foreign dependence degree is beneficial to the higher regional ETFEE, which can be called the ‘internationalization effect'. Open and frequent communication with the international market is propitious to introducing advanced technology and modern management methods from abroad. Based on imports and exports, Chinese enterprises are affected by the strict environmental regulations of developed countries, and so their environmental protection awareness and technology level have improved.

The east area is much more open than the northeast, central, and west areas. An improvement of the internationalization level in the northeast, central, and west areas will be beneficial to raise the energy efficiency of China. The total imports and exports in the northeast, central, and west areas only occupied 11.5% of China's total in 2005, and the foreign direct investment in these three areas occupied 20.8% of China's total at the same time. With the implementation of Western Development Strategy, Central Rise Strategy, and Reviving Northeastern Old Industries Strategy, the proportions of imports and exports and foreign direct investment in the northeast, central, and west areas rose to 12.4% and 22.1% of China's totals in 2009, respectively. In the future, the central government should keep the preferential policies on the enterprise income tax so as to guide foreign direct investment to invest in the central and west areas. The local governments should make efforts to improve the environments for foreign investment, such as convenient procedures for commercial registration, an efficient governmental system, and financial support.

Third, there is a negative relation between the ratio of the secondary industry to GDP and regional ETFEE in China. This matches the fact that the ratio of the high-tech industry to the secondary industry still stays at a relatively low level, but the energy-intensive industry occupies a high percentage. Compared to the third industry, which is called the service industry, the secondary industry consumes much more energy input and produces much more pollution. To achieve intensive economic growth, more and more regions in China are energetically developing the third industry, while reducing the secondary industrial ratio.

Service industry development and the optimization of the secondary industry are very important for improving China's energy efficiency. The State Council of China put forward Opinions on Accelerating the Development of Service Industry and proposed the domestic industrial structure to transform from the secondary industry into the third industry. Most regions in China, such as Beijing, Tianjin, Shanghai, and Zhengjiang, have established special funds to support service industry development. Except for Beijing whose service industry occupies more 70% of GDP, the secondary industry dominates all the regions in China as of now, and hence the readjustment of the secondary industry is quite imperative in China for energy efficiency improvement and sustainable development. China's government has adopted the following measures to optimize the secondary industry: to inhibit the fast growth of energy-intensive and emission-intensive industries by enhancing the industry access threshold, to accelerate the elimination of outdated production capacity by strict government supervision, to promote the upgrading of traditional industries by high-technology application, etc.

Fourth, a region with a high ratio of government subsidies for industrial pollution treatment to GDP is probably due to having a low ETFEE, which can be called the 'inverse subsidy effect'. The more pollution a region produces, the more government subsidies for pollution treatment are needed. If a region has a higher ratio of government subsidies for industrial pollution treatment to GDP, then the enterprises of this region prefer to have a lower initiative to reduce pollution and a higher dependence on pollution subsidies.

The government should push enterprises to save energy and reduce emission actively with capital investment. Direct government subsidies for industrial pollution treatment are remedial measures, which do not encourage enterprises to reduce emission. If the direct government subsidy is changed to preferential fiscal, tax, and financial policies for enterprises with good performance on energy saving and emission reduction, then such policies will become an invisible hand to encourage enterprises to reduce energy consumption and pollution emission.

5. Conclusions

The ETFEE index is constructed on the viewpoint of sustainability by taking the ratio of target energy input from an SBM model with undesirable outputs to the actual energy input. The ETFEE inherits the total-factor framework from the traditional TFEE based on DEA, taking energy consumption with capital and employment as multi-inputs. The essential difference between ETFEE and TFEE is whether undesirable outputs are considered. In the calculation of the ETFEE index, the SBM model with undesirable outputs takes not only GDP as a desirable output, but also undesirable CO_2 and SO_2 as outputs. Environmental pollution is nowadays a worldwide concern. Therefore, the ETFEE index evaluates energy efficiency through an appropriate approach.

Under the framework set up herein, this paper studies regional energy efficiency in China from 2005 to 2009. In the first phase, a comprehensive evaluation of regional energy efficiency in China is accomplished by a comparison between ETFEE and TFEE. In the second phase, the ETFEE discrepancy of different areas is analyzed. In the third phase, the influential factors of regional ETFEE are identified by a truncated regression model.

Regional ETFEE in China is found to be at a low level of about 0.600. Without taking into account environmental impacts, regional energy efficiency can be overestimated by more than 0.100. The ETFEE is always significantly less than TFEE on average. Three regions – Beijing, Shanghai, and Guangdong – are found to always have optimal efficiency during the research period, and all three are located in the east area. Except for Beijing, Shanghai, and Guangdong, there are definite gaps between regional ETFEE and TFEE in the other regions.

The regional energy efficiency of China is extremely unbalanced: the east area ranks first with the highest ETFEE of above 0.7, the northeast and central areas follow, and the west area falls behind with the lowest ETFEE of less than 0.5. A monotone increasing relation exists between each area's ETFEE and per capita GDP in China, and energy efficiency tends to improve with economic development. The higher ratio of R&D expenditure to GDP and the higher degree of foreign dependence both contribute to a higher ETFEE. The ratio of the secondary industry to GDP and the ratio of government subsidies for industrial pollution treatment to GDP both have negative effects on regional ETFEE.

In China the demand for energy is showing rigid sustained growth with the acceleration of industrialization and urbanization. Energy consumption is constrained by domestic resource supplies, environmental capacity, and global energy security. China's energy policy thus faces substantial difficulties, and so energy efficiency is becoming an important issue.

For energy efficiency improvement, China should concentrate on energy savings as well as pay close attention to pollution emission reduction. Emission reduction not only depends on total energy consumption reduction, but also depends on the adjustment of energy consumption type. China's high dependence on coal should be changed, and much more renewable and clean energy should be developed and used. The industrial structure is a decisive factor for energy efficiency, and so both the national and local governments must endeavor to change the industrial structure from energy-intensive industries to service industries, technology-intensive industries, and others. In order to save energy as well as reduce emission, China's government should promote an increase in R&D expenditure, a rise in the internationalization level, and the industrial structure transition. Direct subsidies for industrial pollution should be carefully used to avoid any inverse subsidy effect, and they can be changed to preferential fiscal, tax, and financial policies to push enterprises to save energy and reduce emission.

This paper still has some limitations. With more available statistical data, more factors including the high-technology ratio can be considered, and the estimated CO_2 emission can be substituted by statistical data. Global energy efficiency can be evaluated with the same method to find the ETFEE rank of China, which is helpful for energy efficiency improvement in China. As China is now falling into a dilemma between high economic growth, high energy consumption, and high ecological pollution, ETFEE improvement is an effective way to achieve sustainable development for the country.

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