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Article

Energy Efficiency and Energy Saving Potential in China: A Directional Meta-Frontier DEA Approach

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Abstract: Increasing energy efficiency and exploiting energy saving potential are two important practices that can help to ensure future energy security in China. This paper proposes a new total factor energy efficiency indicator, based on the directional meta-frontier data envelopment analysis (DEA) approach, to account for the heterogeneity of production technology among provinces in China. This indicator considers both energy savings and economic development, and can also decompose the energy saving potential. An empirical research study conducted on 29 Chinese provinces indicates that the differences in energy efficiency and production technology among the Chinese regions are quite significant. Most eastern coastal provinces maintain high-energy efficiency and advanced production technology, while energy efficiency in the west is typically lower. As a rule, improvements in technical and management factors are needed to exploit energy saving potentials. However, the emphasis on these two factors in each province should differ. China's general energy efficiency is relatively low; the absolute amount of nationwide energy saving potential is on the rise.

Keywords: energy efficiency; energy saving potential; production technology; meta-frontier

1. Introduction

Energy efficiency plays important role in reducing energy consumption and carbon dioxide emissions and ensuring national energy security, and, as such, it has attracted great attention from the government, scholars, and other sectors of society. China is the second largest economic entity in the world facing the challenges of high-energy consumption, a single energy structure, and heavy environment pollution. Due to industrialization and urbanization, the demand for energy, as well as energy's restrictions on the economy and impact on the environment, are increasing. The Chinese government claims a goal to reduce the energy consumption per unit of gross domestic product (GDP) by 16% in the 12th Five-Year Plan, after initiation of a previous goal to lower the energy consumption per unit of GDP in the 11th Five-Year Plan. Improvement of energy efficiency has become a major focus for both central and local governments.

The government's concern has drawn scholars' attention to the issue of energy efficiency, as well. A large amount of valuable research has been conducted [1–11]. Regarding the evaluation indicator of energy efficiency, there are currently two approaches, namely, single factor energy efficiency (SFEE) and total factor energy efficiency (TFEE) (See Figure 1). The main characteristic of SFEE, as the name would suggest, is a single input factor and single output. Based on type of input and output, SFEE can be divided into four different indicators: thermodynamic, thermodynamic-physical, thermodynamic-economic, and economic [1]. The definitions, advantages, and disadvantages of these four SFEE indicators are outlined in Table 1.

As a type of SFEE, energy intensity (energy/GDP) is most widely used to evaluate macro-economic energy efficiency [1–4]. The advantage of this energy efficiency indicator is its ease of computation, operation, and understanding. We can also use decomposition analysis to break down energy intensity into its industrial structure and technical progress changes [3,4]. The goal of the energy efficiency improvement set by the Chinese government is based on energy intensity. However, the energy intensity indicator also has disadvantages. For example, this indicator regards energy as the only input to produce GDP output, regardless of the substitution effect between energy and capital, labor, and other factors [5,6]. The decomposition analysis adopted also includes many structural factors, which are likely to cause deviation of the result [7].

Hu and Wang [8] were the first to use data envelopment analysis (DEA) to propose the total factor energy efficiency indicator (TFEE-DEA) considering several inputs. The basic idea of TFEE is to investigate the ratio of the objective energy input and the actual input, according to best production practices. It overcomes the limitations of the traditional single factor energy intensity indicator and has become the main method in the field of energy efficiency research [9–13]. Besides the TFEE indicator based on DEA, Zhou *et al.* [14] proposed another TFEE indicator, which can be calculated by stochastic frontier analysis (SFA). It is named as TFEE-SFA in this paper. In recent years, TFEE-SFA was also applied to analyze Chinese energy efficiency [15].

Figure 1. The framework of energy efficiency indicators.

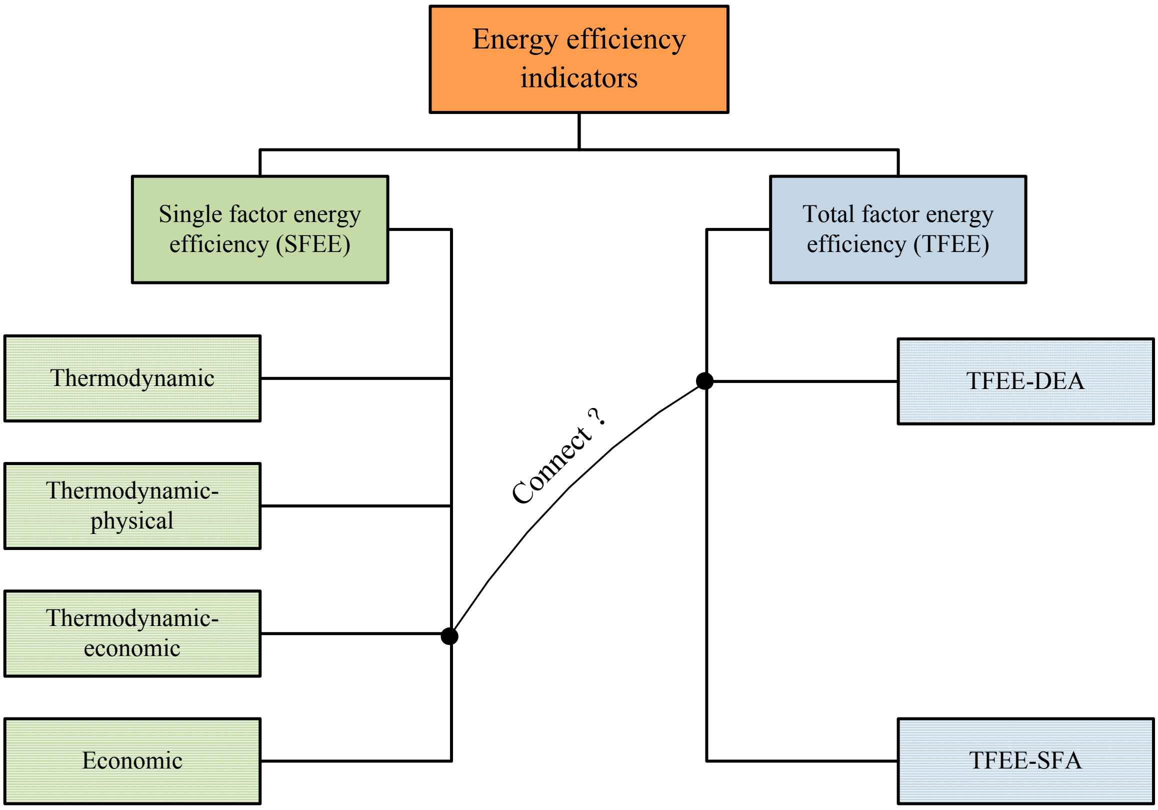


Table 1. The definitions of four single factor energy efficiency (SFEE) indicators.

Indicators	Definition	Advantages	Disadvantages
Thermodynamic	Energy output (J)/ Energy input (J)	Convenient for analyzing a specific process of the energy usage	Fails to embody the end-use of energy usage, and to achieve a macro-aggregation
Thermodynamic-physical	Energy usage (J)/ Energy service (physical unit)	Able to reflect directly the terminal service needed by energy consumers	Applicable only to a specific type of product, and relatively difficult in aggregating between different departments
Thermodynamic-economic	Energy usage (J)/ Energy service (monetary unit)	Able to measure the energy efficiencies at different levels (e.g. enterprise, industry and nation)	Fails to measure the potential technical efficiency of energy, and some non-efficiency factors may cause numerical changes
Economic	Energy usage (monetary unit)/ Energy service (monetary unit)	Able to reflect the economic productivity of energy and provide information on energy prices	Fails to measure the energy prices with an ideal price due to the constant price changes

The evaluation of Chinese energy efficiency has become a hot research topic in recent years, and there have been many achievements in this field [3,8,11,13]. However, there is still room for further discussion. First, the theoretical cycle tends to be evaluated using the total factor energy efficiency indicator [8,13,14], but the government tends to use the energy intensity, which is a single factor indicator. It's worthwhile to consider how to combine them effectively. Second, all the decision-making units are supposed to have similar or same technologies when DEA is used to evaluate the energy efficiency, which is not always the case [15]. Third, evaluation of the energy efficiency mostly regards energy savings as the only goal, and ignores the demand for economic development. For a developing country, the economic development, along with the energy savings, may be a more appropriate choice. This study uses the directional meta-frontier DEA approach to establish a new energy efficiency indicator, considering the premise of production technology heterogeneity. This exercise explores the possibility of uniting energy savings and economic development. It can also be used to consider the inner link between energy intensity and total factor energy efficiency.

2. Methodology

2.1. Directional Distance Function

According to the production theory and ideas of Hu and Wang [8], Zhou and Ang [10], and Honama and Hu [12], we assume that there are N^j provinces, and their inputs, are capital (K), labor (L), and energy (E). The output is GDP (Y). The productive process can be expressed as Equation (1). T is the gathering of technologies during the productive process and it is assumed to be closed, bounded, convex, and to satisfy the strong disposability of inputs and outputs [13,14].

$$T = \{(K,L,E,Y):(K,L,E) \ \textit{can produce} \ Y\} \tag{1}$$

In order to recognize the possibility of extra inputs and production expansion during the productive process, Chung *et al.* [16] and Zhou *et al.* [17] introduce the non-radial directional distance function (Equation 2).

$$\vec{D}(K,L,E,Y;g) = \sup\{\boldsymbol{\omega}^{\mathrm{T}}\boldsymbol{\beta} : (K,L,E,Y) + g \times diag(\boldsymbol{\beta}) \in T\} \tag{2}$$

Here, $\boldsymbol{\omega}^{\mathrm{T}} = (\omega_K, \omega_L, \omega_E, \omega_Y)^T$ determines the input-output variable's weight of capital, labor, energy, and output. The direction vector $g = (-g_K, -g_L, -g_E, g_Y)$ seeks the decrease of input factors and the increase of output factors. The homologous proportion can be expressed as $\boldsymbol{\beta} = (\beta_K, \beta_L, \beta_E, \beta_Y)$. It is obvious that $\boldsymbol{\beta} = (\beta_K, \beta_L, \beta_E, \beta_Y) \geq 0$.

The values of the directional distance function can be calculated by the DEA linear programming in Equation (3) [6,17].

Unlike the Shephard distance function and radial directional distance function, that only consider decrease in inputs or increase in outputs, Equation (3) can account for the slacks of the two variables, namely, the output and input. In addition, the equation may also require the realization of the maximum of the linear array of each increasing or decreasing proportion. This is consistent with the idea of the slacks-based measure proposed by Tone [18]. In the Equation (3), different efficiency goals can be achieved by setting specific weight and direction vectors. It is shown that the province is located in the production frontier when $\vec{D}(K,L,E,Y;g) = 0$ [17].

$$
\begin{aligned}
&\overrightarrow{D}\left(K,L,E,Y;g\right)=\max:\omega_K\beta_K+\omega_L\beta_L+\omega_E\beta_E+\omega_Y\beta_Y\\
&s.t.\ \sum_{n=1}^{N^j}\lambda_n K_n\le\left(1-\beta_K\right)K\\
&\quad\sum_{n=1}^{N^j}\lambda_n L_n\le\left(1-\beta_L\right)L\\
&\quad\sum_{n=1}^{N^j}\lambda_n E_n\le\left(1-\beta_E\right)E\\
&\quad\sum_{i=1}^{N^j}\lambda_n Y_n\ge\left(1+\beta_Y\right)Y\\
&\quad 0\le\beta_K,\beta_L,\beta_E<1,\ \beta_Y\ge 0\\
&\quad \lambda_n\ge 0,\ \ n=1,2,\cdots,N^j
\end{aligned}
\tag{3}
$$

2.2. Energy Efficiency Indicator

In this paper, we focus on the evaluation of energy efficiency; therefore, we set the direction vectoras $g=\left(0,0,-g_E,g_Y\right)$. This requires the realization of decrease in energy consumption and increase in economic output. This is different from Hu and Wang [8], and Wu *et al.* [11], who consider the decrease of energy consumption only by setting $g=\left(0,0,-g_E,0\right)$. For a large developing country, the policy of energy efficiency put into practice should take two factors into consideration: energy savings and economic development. This addresses the reality of China, and is required by the policy on energy efficiency. Therefore, Equation (3) becomes Equation (4).

$$
\begin{aligned}
&\overrightarrow{D}^j\left(K,L,E,Y;g\right)=\max:\omega_E\beta_E^j+\omega_Y\beta_Y^j\\
&s.t.\ \sum_{n=1}^{N^j}\lambda_n K_n\le K\\
&\quad\sum_{n=1}^{N^j}\lambda_n L_n\le L\\
&\quad\sum_{n=1}^{N^j}\lambda_n E_n\le\left(1-\beta_E^j\right)E\\
&\quad\sum_{i=1}^{N^j}\lambda_n Y_n\ge\left(1+\beta_Y^j\right)Y\\
&\quad 0\le\beta_E^j<1,\beta_Y^j\ge 0\\
&\quad \lambda_n\ge 0,\ \ n=1,2,\cdots,N^j
\end{aligned}
\tag{4}
$$

The optimized combination of energy consumption and economic output for a province is $\left(\left(1-\beta_E^{j*}\right)E,\left(1+\beta_Y^{j*}\right)Y\right)$, which can be derived from Equation (4). According to Zhang *et al.* [19], we can define the energy efficiency as the ratio of the theoretical energy intensity and the actual energy intensity, as in Equation (5).

$$
GEE=\frac{\left(1-\beta_E^{j*}\right)E\big/\left(1+\beta_Y^{j*}\right)Y}{E/Y}=\frac{1-\beta_E^{j*}}{1+\beta_Y^{j*}}
\tag{5}
$$

Because $0 \le \beta_E^j < 1$ and $\beta_Y^j \ge 0$, we can conclude that $0 < GEE \le 1$. When GEE is approaching 1, the province's energy efficiency is high and the potential to decrease energy consumption, and increase the economic output, is low. Conversely, when GEE is close to 0, the province's energy efficiency is low, and the potential of decreasing the energy consumption and increasing the economic output is greater. In Equation (5), the derivation of values for energy consumption and economic output, after optimization, rely on the idea of total factor energy efficiency indicator proposed by Hu and Wang [8]. By comparing the theoretical energy intensity with the actual energy intensity, efficiency then represents the combination of the single factor energy efficiency indicator and the total factor energy efficiency indicator.

2.3. Heterogeneity of Production Technology and Energy Efficiency

The heterogeneity of production technology, related to the use of energy, was mostly ignored under the DEA approach [15,19]. This leads to a biased efficiency assessment. The meta-frontier proposed by Hayami and Ruttan [20] can be used to solve this issue [21,22]. Assume that all N provinces are split into different groups, according to the source of the heterogeneity of production technology, and that every group is formed as a group frontier. The meta-frontier can then be formed by enveloping all the group frontiers. The number of provinces in the *Jth* group is N^j, and $\sum_{j=1}^{J} N_j = N$. T^j and T^{meta} represent the technology sets in the specific production process of a group, and all provinces, respectively, and $T^{meta} = \left\{ T^1 \cup T^2 \cdots T^J \right\}$ [21,23]. The directional distance function optimizing energy savings and economic output, under the meta-frontier, can be expressed as Equation (6).

$$\begin{aligned} &\overrightarrow{D}^{meta}\left(K,L,E,Y;g\right) = \max : \omega_E \beta_E^{meta} + \omega_Y \beta_Y^{meta} \\ &s.t.\ \sum_{j=1}^{J}\sum_{n=1}^{N^j} \mu_n K_n \le K \\ &\sum_{j=1}^{J}\sum_{n=1}^{N^j} \mu_n L_n \le L \\ &\sum_{j=1}^{J}\sum_{n=1}^{N^j} \mu_n E_n \le \left(1-\beta_E^{meta}\right)E \\ &\sum_{j=1}^{J}\sum_{i=1}^{N^j} \mu_n Y_n \ge \left(1+\beta_Y^{meta}\right)Y \\ &0 \le \beta_E^{meta} < 1, \beta_Y^{meta} \ge 0 \\ &\mu_n \ge 0,\ n = 1,2,\cdots,N \end{aligned} \tag{6}$$

Comparing Equation (6) to Equation (4), we find that Equation (6) is a linear programming that includes J groups. The ratio of decreasing energy consumption and increasing economic output is changed from β_E^j and β_Y^j to β_E^{meta} and β_Y^{meta}. According to Equation (5), the energy efficiency indicator, with respect to meta-frontier, can be defined as Equation (7).

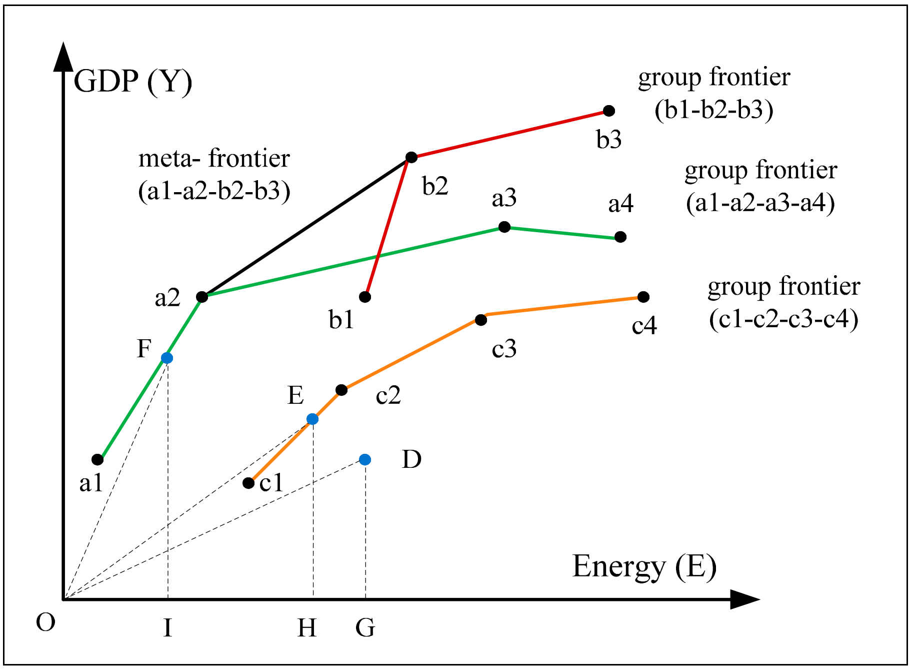
$$MEE = \frac{\left(1-\beta_E^{meta*}\right)E \Big/ \left(1+\beta_Y^{meta*}\right)Y}{E/Y} = \frac{1-\beta_E^{meta*}}{1+\beta_Y^{meta*}} \tag{7}$$

Because T^j is a subset of T^{meta}, the values of energy efficiency, with respect to the meta-frontier, are always lower than the efficiency level in the group frontier, after including further reference objects. Therefore, $MEE \leq GEE$. Referring to Batters *et al.* [24], the relationship between *MEE* and *GEE* may be described by the technology gap ratio (*TGR*) of energy efficiency in Equation (8), as $0 < TGR \leq 1$. When *TGR* is approaching 1, the difference between energy efficiencies, with respect to two reference technology conditions, is less and the level of the corresponding heterogeneity of technology is lower.

$$TGR = \frac{MEE}{GEE} \quad (8)$$

The basic idea of energy efficiency measurement can be illustrated, in general, by Figure 2. The meta-frontier (a1-a2-b2-b3) is enveloped by three group frontiers (a1-a2-a3-a4, b1-b2-b3 and c1-c2-c3-c4) with different production technologies. Point D is a province to be evaluated in group frontier c1-c2-c3-c4. Reducing energy consumption and increasing GDP is required, according to Equation (4). Therefore, E and F are the targets points when group frontier and meta-frontier are regarded as the references, respectively. Then, the actual energy intensity (*AEI*) of point D is $AEI = OG/DG$. The potential energy intensity with respect to group frontier (*GEI*) is obtained as $GEI = OH/EH$. The potential energy intensity with respect to meta-frontier (*MEI*) is obtained as $MEI = OI/FI$. Energy efficiencies with respect to group frontier and meta-frontier can be expressed as $GEE = \frac{OH/EH}{OG/DG}$ and $MEE = \frac{OI/FI}{OG/DG}$, respectively. The energy efficiency technology gap ratio is obtained as $TGR = \frac{OI/FI}{OH/EH}$.

Figure 2. Meta-frontier and the measurement of energy efficiency.



3. Empirical Analysis and Discussion

3.1. Data Sources and Group Formulation

This study considers input-output data for 29 provinces in China (excluding Tibet and combining Chongqing with Sichuan) from 2001 to 2010. The energy consumption data is taken from the *Chinese Energy Statistics Yearbook* [25]. The labor and GDP data is obtained from the *Chinese Statistics Yearbook* [26]. To eliminate the influence of inflation, GDP data is adjusted to year 2000 prices. Capital stocks are estimated by the perpetual inventory method according to Shan *et al.* [27].

Geographical location, market conditions, stages of economic development, and resource endowments can be the sources of the heterogeneity of production technology. This leads to difficulty in dividing the provinces into groups. Oh [22], Battese *et al.* [24], and O'Donnell *et al.* [21] point out that the technologies of regions close to each other geographically, are relatively close. There is strong heterogeneity of technology in regions far away from each other, due to difficulties in technology diffusion. The regional differences between East, Central and West China are easy to understand [15,28]. Therefore, this study splits 29 provinces of China into three groups: east, central, and west. Table 2 shows the average level of input-output variables in the east, central, and west groups.

Table 2. The average of input-output variables in the three regions of China.

		East (Group 1)	Central (Group 2)	West (Group 3)	All
Input	Capital Stock(billion CNY)	679.5	328.1	210.6	420.9
	Labor (million)	24.9	27.5	19.5	23.8
	Energy(million tons)	121.5	89.2	65.8	93.4
Output	GDP(billion CNY)	1062.8	576.6	334.5	677.5

3.2. The Differences of Energy Efficiency

To avoid occurrences of no solution due to small number of DMUs and sparse data, the inter-temporal frontier approach, regarding all the input-output data during the sample period as the referential technology set in the current period, is used [29]. If energy savings and economic development are assigned the same importance, we give them the same weights $\omega_E = \omega_Y = 0.5$. Therefore, according to Equation (4) and Equation (7), we can calculate the ratio of decreasing energy consumption and increasing economic output. Then, the corresponding energy efficiency values for each province, referring to the specific group frontier technology and the meta-frontier technology, are obtained. Table 3 shows the average energy efficiency during the period.

In Table 3, we consider Heilongjiang (central group) as an example. The average energy efficiency with respect to the group frontier is 0.829. This shows that Heilongjiang's potential to increase energy efficiency is 17.1%, based on the central group's production technology. While based on the meta-frontier, Heilongjiang's average energy efficiency is 0.585 and the potential to improve energy efficiency is 41.5%, which is much higher than that in the group frontier. Most provinces are similar to Heilongjiang, illustrating that energy efficiency in the meta-frontier is not higher than that of the group frontier. Because the meta-frontier is determined by all the samples, we refer to the best technology level nationwide. However, the group frontier only includes the best technology in the corresponding region [24]. At the same time, we can also find that Liaoning, Shanghai, Fujian, Guangdong, Yunnan, and some other provinces, show great energy utilization efficiencies. This signifies that these provinces are the leaders in energy efficiency in their respective regions and nation. They represent the best level of production technology in energy utilization. This is due to the existence of developed economies and advanced technologies in these provinces; moreover, the low-energy consumption industries including tourism and finance account for a large proportion in these regions [30]. The provinces, such as Hebei, Shanxi, Guizhou, Gansu, Qinghai, and Ningxia, are the major bases of energy production, with the industrial sector primarily focusing on energy intensive industries. In addition, they are located in inland China, far below the eastern coastal provinces in economic stature, and weak in technological capabilities [15,28,30]. Hence, their energy efficiencies are relatively lower under the two conditions of production technologies.

Table 3. The average energy efficiency with respect to meta-frontier and group frontier.

Province	GEE	MEE	Province	GEE	MEE
East	0.777	0.773	Heilongjiang	0.829	0.585
Central	0.755	0.547	Anhui	0.990	0.712
West	0.662	0.462	Jiangxi	0.889	0.641
Beijing	0.799	0.799	Henan	0.705	0.508
Tianjin	0.754	0.754	Hubei	0.703	0.511
Hebei	0.389	0.387	Hunan	0.798	0.573
Liaoning	0.987	0.947	Inner Mongolia	0.623	0.379
Shanghai	0.833	0.833	Guangxi	0.946	0.599
Jiangsu	0.785	0.785	Chongqing	0.854	0.511
Zhejiang	0.769	0.769	Guizhou	0.424	0.327
Fujian	0.967	0.967	Yunnan	0.967	0.967
Shandong	0.537	0.536	Shaanxi	0.778	0.478
Guangdong	0.906	0.906	Gansu	0.539	0.330
Hainan	0.827	0.827	Qinghai	0.439	0.352
Shanxi	0.428	0.368	Ningxia	0.368	0.315
Jilin	0.698	0.478	Sinkiang	0.683	0.363

We find that the energy efficiency in the eastern group is 0.773, higher than 0.547 in the central group, and 0.462 in the west group, with respect to the meta-frontier. At the same time, from the boxplot of energy efficiency in the east, central, and west groups (Figure 3), we can see that the 25%, 50%, and 75% quantiles present multi-step decreasing. The difference in the three regions is significant. The energy efficiency in the eastern region is high and the energy efficiency in the central and west groups is low. This conclusion differs from that of Hu and Wang [8], but is similar to Wang *et al.* [28] and Wei *et al.* [30]

To further test the significant differences of energy efficiency with respect to group frontier and meta-frontier, the Mann-Whitney test, a non-parametric statistical method for two independent samples, was used. The results are listed in Table 4. Two groups reject the null hypothesis of efficiency equality at a 5% significance level, suggesting that different references lead to significant energy efficiency differences in the central and the west groups.

Figure 3. The boxplot of energy efficiencies in the three groups.

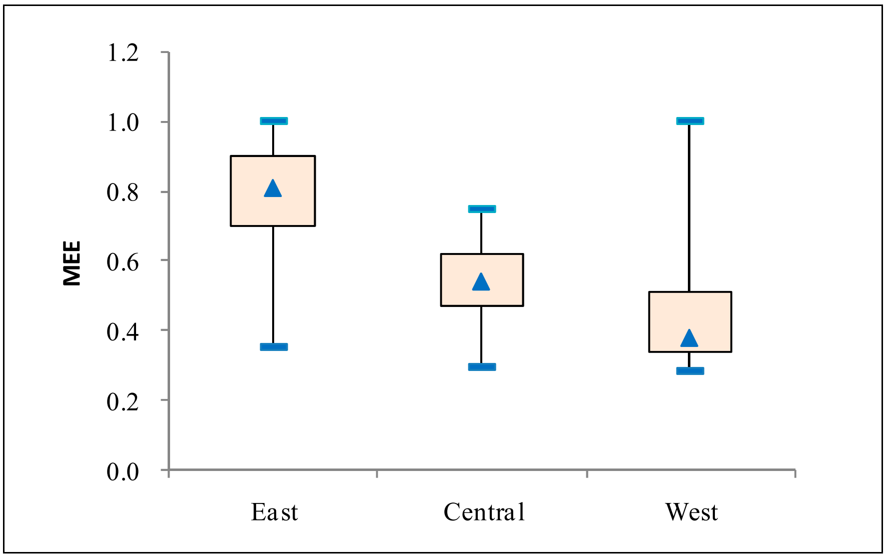


Table 4. The results of Mann-Whitney test.

	Null Hypothesis	U-Statistics	Z-Statistics	*p*-Value
East		59.000	−0.099	0.921
Central	The center position of two population distributions is same	10.000	−2.310	0.021
West		20.500	−2.231	0.026

The above results are due in-part to the following facts. When the group frontier is treated as the reference, the energy efficiency obtained reflects the level under the existing conditions of regional production technologies. However, when the meta-frontier acts as the reference, the energy efficiency reflects the level under the condition of the most advanced production technology nationwide. Because of the levels of central and west fall far below the national level in economic and technological strength and management ability, the energy efficiencies of both groups are over estimated when group frontier is chosen as the reference. Unlike those two groups, the energy efficiency of east does not vary significantly under the group frontier and meta-frontier, as its economic level, technical capability, and management ability are in a leading position nationwide, being a leader in energy efficiency.

3.3. The Technology Gap of Energy Efficiency

According to Equation (8), we can calculate the technology gap ratio. Figure 4 shows the trend of technology gap ratios in the east, central, and west regions. Table 5 illustrates the nonparametric Kruskal-Wallis test under the condition of multiple independent samples. The test result rejects the null hypothesis at a 1% significance level, which means the energy efficiency technology gap ratio in the three groups is significantly different. As can be seen, the technology gap ratio in the east is much higher than that in the central and west groups, and is sustained at levels over 0.98 (1 in some years). There is little difference between the energy utilizing technology in the east and nationwide. The east is the leader in energy technology innovation. It was the earliest "open" region and features the most advanced levels of technology and improved management systems [15,30]. This is consistent with the observations of high energy efficiency in the eastern provinces under both meta-frontier and group frontier, as mentioned above.

Figure 4. The technology gap ratio in the three groups.

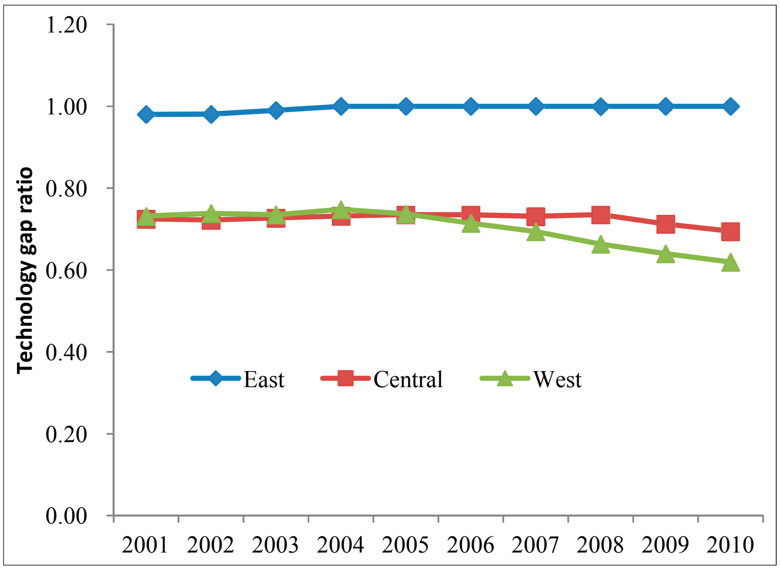


Table 5. The results of Kruskal-Wallis test.

Null Hypothesis	H-Statistics	*p*-Value
The center position of the three population distributions is the same.	18.181	0.000

The provinces in the central and west regions are located inland and lag in technological innovation and import. The energy efficiency technology gap ratios in the central and west regions are similar during the 2001 to 2005 period, reaching about 75% at the highest level. Since 2006, the technology gap ratios in the central and west regions have tended to decline. In particular, the technology gap ratio of the west region fell to 0.6 in recent years, which means the gap between the west and the east is getting larger. The provinces in the west must promote the upgrade and import of energy technology further and adapt advanced practices of energy management. Otherwise, the west region will struggle to save energy and reduce energy consumption.

3.4. The Decomposition of Energy Intensity

From Equation (4) and Equation (6), the theoretical energy intensity with respect to the group frontier (*GEI*), and the meta-frontier (*MEI*) can be obtained. *MEI* is obtained with the best production technology nationwide. Therefore, we define the difference between *MEI* and actual energy intensity (*AEI*) as the total potential of cutting energy intensity (ΔEI). Now, ΔEI can be decomposed into two parts, ΔEI_1 and ΔEI_2 . The corresponding relationship can be described as Equation (9).

$$\Delta EI = AEI - MEI = (AEI - GEI) + (GEI - MEI) = \Delta EI_1 + \Delta EI_2 \tag{9}$$

The potential of the first part (ΔEI_1) is obtained on the basis of the group frontier. Because the same group has similar technology, we can mainly improve the management level, not pure technology factors, to improve on this part's potential [28,31]. The potential of the second part (ΔEI_2) mainly relies on narrowing the technology gap. Table 6 shows the average *AEI*, *GEI*, *MEI*, ΔEI, ΔEI_1, and ΔEI_2 for each province during the sample period.

In Table 6, consider again Heilongjiang, a central province, as an example. Its total potential of improving energy intensity is 0.547 tons per ten thousand CNY (0.547 = 1.356 − 0.809). This potential can be reduced by 0.200 ton by improving management level and reduced by 0.348 tons by narrowing the technology gap. The latter is larger than the former. Therefore, Heilongjiang's energy saving policies should focus on improving the level of technology. There are other provinces similar to Heilongjiang, including Anhui, Jiangxi, Hunan, Guangxi, Sichuan, Shaanxi, and Xinjiang. In other provinces ΔEI_1 is larger than ΔEI_2. These provinces include Shanxi, Jilin, Henan, Hubei, Guizhou, Gansu, Qinghai, and Ningxia. They should assign higher importance to the management factor. Because Beijing, Tianjin, Jiangsu, Zhejiang, Fujian, and some other provinces in the east represent the most advanced production technology nationwide, their potential to decrease energy intensity through technological factors can be mostly ignored. Their energy saving policies should put further emphasis on management-level improvements concerning the utilization of energy.

It needs to be emphasized that improvement of the technology level was always prioritized in the past energy conservation practices in China [11,30]. However, the results in Table 6 show that both technology and management factors represent significant opportunities for decreasing energy intensity. In most provinces, the potential energy savings realized through management is greater than that of technical energy savings. Therefore, the future policy on energy efficiency must be comprehensive, focusing on improvements in production technology and at the management level.

Table 6. The decomposition of energy intensity.

Province	***AEI***	***GEI***	***MEI***	**ΔEI**	**ΔEI_1**	**ΔEI_2**	**Policy priority**
			(tons of standard coal/ten thousand CNY)				
Beijing	0.902	0.740	0.740	0.162	0.162	0.000	M
Tianjin	1.151	0.920	0.920	0.231	0.231	0.000	M
Hebei	2.099	0.853	0.828	1.271	1.246	0.025	M
Liaoning	1.605	1.588	1.542	0.063	0.017	0.045	T
Shanghai	0.917	0.781	0.781	0.136	0.136	0.000	M
Jiangsu	0.951	0.749	0.749	0.202	0.202	0.000	M
Zhejiang	0.977	0.764	0.764	0.213	0.213	0.000	M
Fujian	0.862	0.832	0.832	0.030	0.030	0.000	M
Shandong	1.448	0.812	0.788	0.660	0.636	0.024	M
Guangdong	0.823	0.754	0.754	0.069	0.069	0.000	M
Hainan	0.915	0.764	0.764	0.151	0.151	0.000	M
Shanxi	2.966	1.235	1.162	1.804	1.731	0.073	M
Jilin	1.612	1.160	0.786	0.827	0.452	0.374	M&T
Heilongjiang	1.356	1.157	0.809	0.547	0.200	0.348	T&M

Table 6. *Cont.*

Province	***AEI***	***GEI***	***MEI***	**ΔEI**	**ΔEI_1**	**ΔEI_2**	**Policy priority**
			(tons of standard coal/ten thousand CNY)				
Anhui	1.280	1.269	0.914	0.366	0.010	0.356	T
Jiangxi	1.129	1.019	0.737	0.392	0.109	0.283	T&M
Henan	1.520	1.084	0.780	0.740	0.437	0.304	M&T
Hubei	1.554	1.115	0.809	0.745	0.439	0.306	M&T
Hunan	1.384	1.099	0.792	0.592	0.285	0.307	T&M
Inner Mongolia	2.784	1.881	1.058	1.726	0.903	0.823	M&T
Guangxi	1.292	1.227	0.777	0.515	0.065	0.451	T
Sichuan	1.523	1.333	0.790	0.733	0.190	0.543	T
Guizhou	3.406	1.478	1.131	2.276	1.929	0.347	M
Yunnan	1.766	1.703	1.703	0.063	0.063	0.000	M
Shanxi	1.577	1.249	0.760	0.817	0.328	0.489	T&M
Gansu	2.307	1.268	0.773	1.534	1.039	0.495	M&T
Qinghai	3.269	1.428	1.165	2.104	1.841	0.263	M&T
Ningxia	4.314	1.492	1.320	2.994	2.823	0.172	M
Xinjiang	2.354	1.705	0.862	1.492	0.649	0.842	T&M

M indicates that improving management is the policy priority to reduce energy intensity; T indicates that improving technology is the policy priority to reduce energy intensity.

3.5. The Potential of Energy Savings

Using β_E^j and β_E^{meta} in Equation (4) and Equation (6), we can obtain the proportion which energy consumption can be reduced in the group frontier and meta-frontier. Then, each province's absolute energy saving potential can be calculated according to actual energy consumption. Figure 5 shows the three groups' energy saving potentials, with respect to the meta-frontier. Though the energy efficiency in the west is the lowest, its absolute energy saving potential is not very large because its energy consumption accounts for only about twenty percent of the nation's total (See Figure 6). The east's energy efficiency is high, but its consumption is also large (about fifty percent of the nation's total consumption). A small loss of efficiency in the east results in a significant waste of energy. When viewed as a whole, the total energy saving potential for the country tends to increase in recent years. The potential has increased from less than 0.2 billion tons of standard coal in 2001 to about 0.45 billion tons in 2010. The increase from 2004 to 2007 is particularly large. From the level of a single province, the top five provinces with maximum energy saving potential are Shanxi, Shandong, Hebei, Chongqing, and Heilongjiang. Their aggregated energy saving potential in 2010 is over 30 million tons of standard coal. The energy saving potential of Fujian, Hainan, and Yunnan, located in the produnction frontier, is low.

Figure 5. The energy saving potential in the three groups.

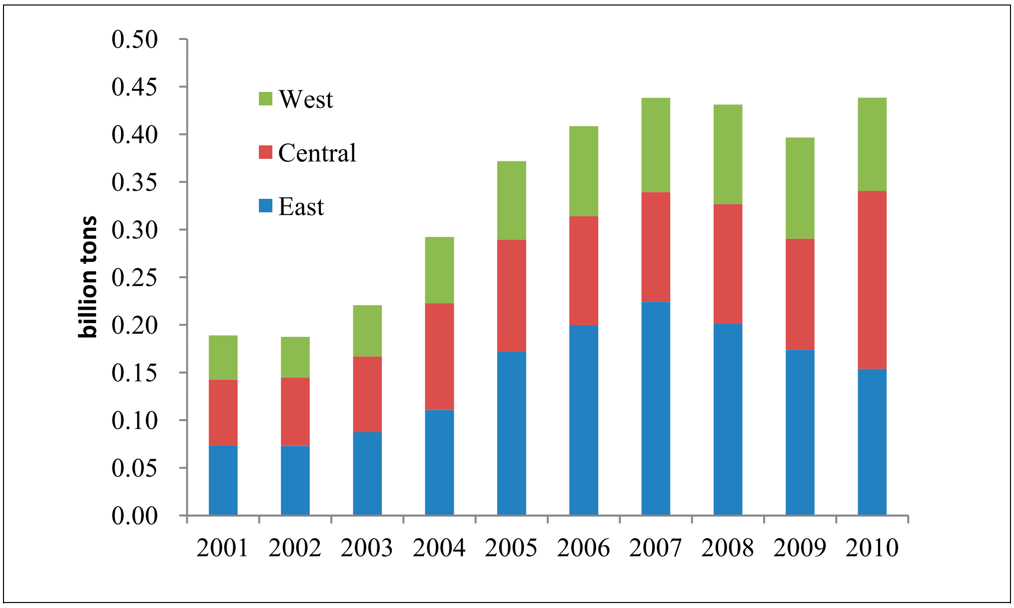
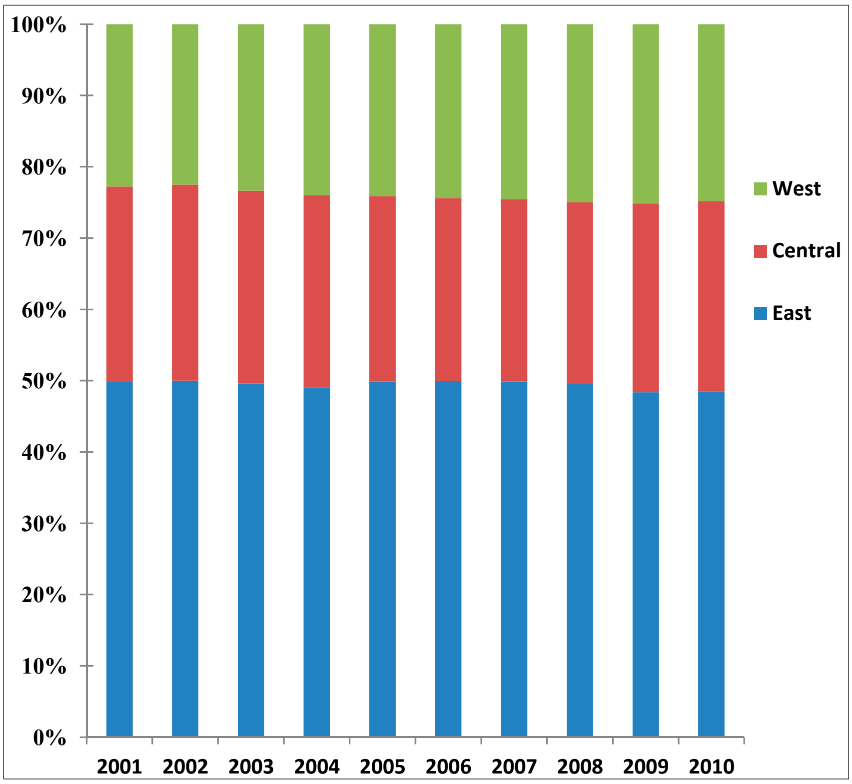


Figure 6. The proportions of energy consumption by the three groups.



4. Conclusions

Increasing energy efficiency is an effective strategy to ease the excessive growth of energy consumption and reduce carbon dioxide emissions. However, there are wide variations among Chinese provinces in economic development, industrial structure, resource endowment, and development. These differences pose challenges for the evaluation of energy efficiencies and the formulation and implementation of energy saving policies.This study combines the concepts of single factor energy efficiency and total factor energy efficiency, and proposes a new indicator using the meta-frontier and DEA approach. An empirical research on Chinese provinces from 2001 to 2010 is presented.

China's overall energy efficiency is still relatively low, with the provinces on the east coast exhibiting higher energy efficiency than inland western provinces.The energy efficiency with respect to a group frontier is obtained by comparing similar technology and reflects each province's efficiency level with the current regional level.The energy efficiency with respect to a meta-frontier, however, ranks the efficiency each province based on the best production technology nationwide. Liaoning, Shanghai, Fujian, Guangdong, and Yunnan represent high energy utilization efficiencies under both production frontiers. Yet Hebei, Shanxi, Guizhou, Gansu, Qinghai, and Ningxia exhibit poor energy utilization efficiencies. The east, central, and west regions' energy efficiency technology gap ratios vary significantly. The technology gap ratio in the east has sustained a level over 0.98. It is the leader in energy utilization technology. The technology gap rations in the central and west regions are relatively low and have tended to decrease since 2006.

Potential energy intensity reductions vary greatly among provinces. The eastern provinces possess the most advanced technology; therefore, they can gain the most through improvements at the management level. Other provinces must consider both technological and management aspects, and the emphasis on each may be different for individual provinces. Heilongjiang, Anhui, Jiangxi, Hunan, and Guangxi have tended to narrow the technology gap. Shanxi, Jilin, Henan, and Hubei have emphasized the management factor regarding energy utilization. The absolute amount of energy saving potential varies among regions due to both energy efficiencies and total consumption. The total energy saving potential nationwide, on the other hand, increases constantly because of the rapid increase in total energy consumption.

This study primarily focuses on how to best measure and decompose energy efficiency. It may not fully address the factors or their mechanisms affecting energy efficiency, or the developmental tendency for energy efficiency, which represents further research opportunity for the future. For the time being, a combination of both meta-frontier and Malmqusit productivity [19] indicators may be adopted to investigate the dynamic changes and convergence characteristics of energy efficiency.

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Author Contributions

Peng Zhou gave the framework of this research. Qunwei Wang analyzed the results. Neng Shen collected the data. Zengyao Zhao gave some advices and checked the whole paper.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Patterson, M.G. What is energy efficiency? Concepts, indicators and methodological issues. *Energ. Policy* **1996**, *24*, 377–390.
2. Zhang, M.; Li, H.; Zhou, M.; Mu, H. Decomposition analysis of energy consumption in Chinese transportation sector. *Appl. Energ.* **2011**, *88*, 2279–2285.
3. Ang, B.W. Monitoring changes in economy-wide energy efficiency: From energy-GDP ratio to composite efficiency index. *Energ. Policy* **2006**, *34*, 574–582.
4. Choi, K.H.; Ang, B.W. Attribution of changes in Divisia real energy intensity index: An extension to index decomposition analysis. *Energ. Econ.* **2012**, *34*, 171–176.
5. Ramanathan, R. Combining indicators of energy consumption and CO_2 emissions: a cross-country comparison. *Int. J. Global Energ. Issues* **2002**, *17*, 214–227.
6. Zhang, N.; Choi, Y. Environmental energy efficiency of China's regional economies: A non-oriented slacks-based measure analysis. *Soc. Sci. J.* **2013**, *50*, 225–234.
7. Ghali, K.H.; El-Sakka, M.I. Energy use and output growth in Canada: A multivariate cointegration analysis. *Energ. Econ.* **2004**, *26*, 225–238.
8. Hu, J.L.; Wang, S.C. Total-factor Energy Efficiency of Regions in China. *Energ. Policy* **2006**, *34*, 3206–3217.
9. Hu, J.L.; Kao, C.H. Efficient energy-saving targets for APEC economies. *Energ. Policy* **2007**, *35*, 373–382.
10. Zhou, P.; Ang, B.W. Linear programming models for measuring economy-wide energy efficiency performance. *Energ. Policy* **2008**, *36*, 2911–2916.
11. Wu, F.; Fan, L.W.; Zhou, P.; Zhou, D.Q. Industrial energy efficiency with CO_2 emissions in China: A nonparametric analysis. *Energ. Policy* **2012**, *49*, 164–172.
12. Honma, S.; Hu, J.L. Industry-level total-factor energy efficiency in developed countries: A Japan-centered analysis. *Appl. Energ.* **2014**, *119*, 67–78.
13. Wang, Z.H.; Zeng, H.L.; Wei, Y.M.; Zhang, Y.X. Regional total factor energy efficiency: An empirical analysis of industrial sector in China. *Appl. Energ.* **2012**, *97*, 115–123.
14. Zhou, P.; Ang, B.W.; Zhou, D.Q. Measuring economy-wide energy efficiency performance: A parametric frontier approach. *Appl. Energ.* **2012**, *90*, 196–200.
15. Lin, B.; Du, K. Technology gap and China's regional energy efficiency: A parametric metafrontier approach. *Energ. Econ.* **2013**, *40*, 529–536.
16. Chung, Y.H.; Färe, R.; Grosskopf, S. Productivity and undesirable outputs: A directional distance function approach. *J. Environ. Manag.* **1997**, *51*, 229–240.
17. Zhou, P.; Ang, B.W.; Wang, H. Energy and CO_2 emission performance in electricity generation: A non-radial directional distance function approach. *Eur. J. Oper. Res.* **2012**, *221*, 625–635.
18. Tone, K. A slacks-based measure of efficiency in data envelopment analysis. *Eur. J. Oper. Res.* **2001**, *130*, 498–509.
19. Zhang, N.; Zhou, P.; Choi, Y. Energy efficiency, CO_2 emission performance and technology gaps in fossil fuel electricity generation in Korea: A meta-frontier non-radial directional distance function analysis. *Energ. Policy* **2013**, *56*, 653–662.

20. Hayami, Y.; Ruttan, V. Agricultural development: An international perspective. *J. Econ. Hist.* **1973**, *33*, 484–487.
21. O'Donnell, C.J.; Rao, D.S.P.; Battese, G.E. Metafrontier frameworks for the study of firm-level efficiencies and technology ratios. *Empir. Econ*. **2008**, *34*, 231–255.
22. Oh, D.H. A metafrontier approach for measuring an environmentally sensitive productivity growth index. *Energ. Econ.* **2010**, *32*, 146–157.
23. Lin, C.H.; Chiu, Y.H.; Huang, C.W. Assessment of technology gaps of tourist hotels in productive and service processes. *Serv. Ind. J.* **2012**, *32*, 2329–2342.
24. Battese, G.E.; Rao, D.S.P.; O'Donnell, C.J. A metafrontier production function for estimation of technical efficiencies and technology gaps for firms operating under different technologies. *J. Productivity Anal.* **2004**, *21*, 91–103.
25. National Bureau of Statistics of China (NBSC). *China Energy Statistical Year Book*; China Statistics Press: Beijing, China, 2002–2012.
26. National Bureau of Statistics of China (NBSC). *China Statistical Year Book*; China Statistics Press: Beijing, China, 2002–2011.
27. Shan, H.J. Re-estimating the capital stock of China: 1952–2006. *Q. Tech. Econ.* **2008**, *10*, 17–31. (In Chinese)
28. Wang, Q.; Zhao, Z.; Zhou, P.; Zhou, D. Energy efficiency and production technology heterogeneity in China: A meta-frontier DEA approach. *Econ. Model* **2013**, *35*, 283–289.
29. Tulkens, H.; Vanden, E.P. Non-parametric efficiency, progress, and regress measure for panel data: Methodological aspects. *Eur. J. Oper. Res.* **1995**, *80*, 472–479.
30. Wei, C.; Ni, J.; Shen, M. Empirical analysis of provincial energy efficiency in China. *China World Econ*. **2009**, *17*, 88–103.
31. Chiu, C.R.; Liou, J.L.; Wu, P.I.; Fang, C.L. Decomposition of the environmental inefficiency of the meta-frontier with undesirable output. *Energ. Econ.* **2012**, *34*, 1392–1399.