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# China's regional energy and environmental efficiency: A DEA window analysis based dynamic evaluation

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**Abstract:** Data envelopment analysis (DEA) has recently become a popular approach in measuring the energy and environment performance at the macro-economy level. A common limitation of several previous studies is that they ignored the undesirable outputs and did not consider the separation of inputs into energy resources and non-energy resources under the DEA framework. Thus, within a joint production framework of considering both desirable and undesirable outputs, as well as energy and non-energy inputs, this study analysis China's regional total-factor energy and environment efficiency. This paper utilizes improved DEA models to measure the energy and environment efficiency of 29 administrative regions of China during the period of 2000 to 2008. In addition, the DEA window analysis technique is applied to measure the efficiency in cross-sectional and time-varying data. The empirical results show that east area of China has the highest energy and environmental efficiency, while the efficiency of west area is worst. All three areas of China have similar trend on the variation of efficiency and in general the energy and environment efficiency of China slightly increased from 2000 to 2008. The regions of east area have a more balanced development than the regions of central area and west area according to energy and environment efficiency.

**Keywords:** $CO_2$ emissions; DEA; Dynamic evaluation; Energy and Environmental efficiency; Undesirable outputs; Window analysis

## 1. Introduction

In recent years, a growing number of researches have focused on evaluating, analyzing and improving energy efficiency, which is considered a crucial approach to mitigate global warming, since global warming is one of the world's most important environmental problems at present. And this problem is largely attributed to the emission of greenhouse gas such as carbon dioxide ($CO_2$) which is mainly related to the burning of fossil fuels.

China's economy has rapidly developed since the implement of economic reform and opening up to the outside policy in 1978. China's gross domestic product (GDP) has increased from 364.52 billion RMB in 1978 to 34050.69 billion RMB in 2009. However, this achievement has also led to inefficient nature resource utilization and given rise to serious environmental problems. Nowadays, China has already become the world's second largest economy, the world's largest energy consuming country and the world's largest CO2 emitter. To improve energy utilization efficiency, protect environment and realize sustainable development, Chinese government has put forward the strategic objective to build a resource-saving and environment-friendly society. Chinese government has also announced the target of reducing $CO_2$ emissions per unit GDP by 40-45% till 2020 with that in 2005 as the base. Furthermore, with the growing emphasis on international environmental issues from government and public, China has already faced tremendous pressures in the international negotiation on climate change. Therefore, measuring and improving the energy efficiency with the considering of environmental constraints is very important for China to reduce energy consumption and mitigate environment pollution.

Energy efficiency is a relative concept and there are lots of different definitions of it. According to Ang (2006), three indicators are commonly used to measure energy efficiency: thermodynamic indicator, physical-based indicator, and monetary-based indicator. Monetary-based efficiency, which refers to the energy consumption per unit current output, is often used to measure the economy-wide energy efficiency at the macro level. Since, any economy production activity is a joint-production process and it utilize energy resources (e.g., coal, oil, nature gas) and other resources (e.g., labor, capital) to produce desirable outputs (e.g., GDP) and undesirable outputs as the emission of pollutants (e.g., CO2, SO2). Therefore, a total-factor efficiency evaluation model is necessary. Furthermore, with the emission of pollutants as by-products, the environment efficiency should not be neglected when measuring energy efficiency, so as to provide a more appreciate and comparable efficiency score. Thus, the total-factor efficiency evaluation model also should be able to measure the aggregated energy and environment efficiency.

At the macro-economy level, data envelopment analysis (DEA) has recently been widely applied to studying the energy and environment efficiency for it provides an appropriate method to deal with multiple inputs and outputs in examining relative efficiency. For instance, Hu and Wang (2006) proposed a total-factor energy efficiency evaluation method using DEA, and measured the energy efficiency of 29 regions in China. Zhou et al. (2008) developed several environmental DEA technologies and measured the carbon emission performance of eight world regions. Yeh et al. (2010) calculated the technical efficiency of energy utility in Chinese mainland and Taiwan by using the traditional BCC envelopment model (Banker et al., 1984) and treated the undesirable outputs following Seiford and Zhu (2002)'s approach which increase the good outputs and decrease the bad outputs simultaneously.

One weakness of Hu and Wang (2006)'s energy efficiency evaluation model is that it treats energy consumption as one input and GDP as desirable output, but does not consider any undesirable output. However, this may be unreasonable in the real production process, for the use of energy always results in the emission of pollutants, like CO2 and SO2. In addition, one limitation of Zhou et al. (2008)'s environment efficiency evaluation method is that it just deals with energy input, desirable and undesirable outputs, while omitting other non-energy inputs. Furthermore, in Yeh et al. (2010)'s research, they did not consider the maximization of energy conservation, as they calculated energy efficiency under the condition that other non-energy inputs are not divided from energy inputs, and all the inputs are contracted together. Since the energy that serves as input in real production process is usually not renewable, but other non-energy resources such as labor force or capital are renewable. As a result, nonrenewable energy inputs should be separated and saved as much as possible in order to increase the energy utility efficiency and decrease pollutant emissions.

In recent literatures, there are some DEA based studies on energy efficiency and environment efficiency evaluation that consider total factors and pollutant emissions. Zhou et al. (2007, 2008) proposed several DEA models to evaluate the environment efficiency of 26 OECD countries from 1995 to 1997 and eight world regions in 2002, respectively. The former use labor and primary energy consumption as two inputs, GDP as only desirable output, and CO2, sulphur oxides (SOx), nitrogen oxides (NOx), and carbon monoxide (CO) as undesirable outputs, and apply non-radial DEA approach. The latter simply choose total energy consumption, GDP, and $CO_2$ emissions as the single input, desirable output and undesirable output, respectively, and are based on radial DEA approach. Zhou and Ang (2008) presented several DEA-type linear programming models within a joint production framework for measuring economy-wide energy efficiency and using energy and non-energy inputs as well as desirable and undesirable outputs. Furthermore, they presented three energy efficiency indexes: energy efficiency performance index, average energy utilization performance index, and weighted average energy utilization performance index, according to define the efficiency as energy integrated efficiency or energy mix effects efficiency. However, the researches above just evaluate energy efficiency or environmental efficiency individually, but not consider evaluating aggregated energy and environment efficiency.

Most recently, Bian and Yang (2010) proposed several DEA models to simultaneously measuring resource (energy) and environment efficiency, and applied their models in the resource and environment efficiency evaluation problem of 30 Chinese provinces. Shi et al. (2010) presented three extended DEA model that treat the undesirable outputs as inputs and make them decrease with energy inputs proportionally so as to calculate the energy and environment overall technical efficiency, pure technical efficiency, and scale efficiency of 28 administrative regions in China. Wang et al. (2011) developed a mixed energy economic-environmental efficiency model which attempts to proportionally increase desirable outputs and decrease undesirable outputs simultaneously so as to calculate the aggregated efficiency. However, the research of Bian and Yang (2010) is considered as a static analysis since they only measured the performance for a single year which the variation trend of the efficiency could not be seen. Shi et al. (2010) and Wang et al. (2011) evaluated multi-period efficiency in their studies, but they just calculated the efficiencies of different regions in each year and then simply compared the performances of different years, in which the technical progress was ignored and the efficiencies of different years are less comparable. Furthermore, the DEA based models of Shi et al. (2010) and Wang et al. (2011) have weak discriminating power when evaluating energy and environment efficiency.

In this current study, we propose an improved DEA model which follows Bian and Yang (2010)'s method and combines DEA window analysis in order to give a dynamic evaluation of the energy and environment efficiency of 29 regions in China during the period of 2000 and 2008. The rest of this paper is organized as follows. Section 2 presents the DEA based performance evaluating models and DEA window analysis for total-factor energy and environment efficiency evaluation. Section 3 presents the data and variables. Then the energy and environment efficiency of different regions and areas in China from 2000 to 2008 is analyzed in Section 4. Section 5 concludes the paper.

## 2. Methodology

In this section, we present a non-radial input-oriented DEA models used to evaluate the total-factor energy and environment efficiency. In addition, we explore the total-factor energy and environment efficiency by applying DEA window analysis to measure the efficiency in cross-sectional and time-varying data.

*2.1 Improved DEA model for evaluating the energy and environment performance*

The DEA method is a non-parametric mathematical programming approach used to evaluate a set of comparable decision-making units (DMUs). Here we use the CCR model (Charnes et al., 1978) as the basic model to examine the total-factor energy and environment efficiency of different regions in China.

Suppose there are $n$ DMUs, denoted by $DMU_j$ ($j$=1,…,$n$), and each of them represents an administrative region of China. Every DMU uses $m$ non-energy inputs $x_{ij}$ ($i$=1,2,…,$m$) and $L$ energy inputs $e_{lj}$ ($l$=1,…,$L$) to produce $s$ desirable outputs $y_{rj}$ ($r$=1,…,$s$) along with emission of $K$ undesirable or bad outputs $b_{kj}$ ($k$=1,…,$K$).

In the process of production, on one hand, a DMU likes to produce desirable outputs as much as possible, and to consume resource inputs as little as possible. On the other hand, the energy used in China are mostly non-renewable ones, e.g., coal or oil, and the burning of the energy usually generate waste gas such as $CO_2$ and $SO_2$ which should also be considered. Therefore, when measuring the total-factor energy and environment efficiency, we hope to reduce the consumption of energy as much as possible for a given desirable output and non-energy inputs. And for the undesirable outputs, the less of it is preferable.

However, it is not allowed to reduce the pollutants in standard DEA models. There are several methods can deal with this difficulty, such as using the reciprocals of the undesirable outputs (Fare, 1989), treating the undesirable outputs as input (Reinhard, 2000), and mathematically translate the undesirable outputs into desirable outputs under the classification invariance (Seiford and Zhu, 2002). In our study of energy and environment efficiency, the undesirable outputs are mainly generated by fossil fuel burning in the production process and should be reduced if energy consumption is reduced. Therefore, similar to Shi et. al. (2010), we first present the following radial DEA based model for measuring the total-factor energy and environment efficiency as

$$
\begin{aligned}
& E_1 = \min \theta \\
s.t. \quad & \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^{x-} = x_{ij_0}, i = 1, \dots, m, \\
& \sum_{j=1}^{n} \lambda_j e_{lj} + s_l^{e-} = \theta e_{lj_0}, l = 1, \dots, L, \\
& \sum_{j=1}^{n} \lambda_j y_{rj} - s_r^{y+} = y_{rj_0}, r = 1, \dots, s, \\
& \sum_{j=1}^{n} \lambda_j b_{kj} = \theta b_{kj_0}, k = 1, \dots, K, \\
& \lambda_j, s_i^{x-}, s_l^{e-}, s_r^{y+} \geq 0, \text{for all } j, i, l, r.
\end{aligned} \tag{1}
$$

Note that model (1) make the undesirable outputs proportionally decrease with energy inputs as much as possible for a given level of non-energy inputs and desirable outputs. In model (1), the energy and environment efficiency index $\theta$ for a region is between 0 and 1. The larger the index, the better the corresponding region performs both in energy saving and pollutant emission reduction. If $E_1$=1 ($\theta$=1) and all slacks $s_i^{x-}, s_l^{e-}, s_r^{y+}$ are zeros, the corresponding region is considered to be energy and environment efficient, and could not reduce its energy consumption and pollutant emission. If $E_1$<1 ($\theta$<1), and (or) some of the slacks are not zero, then the corresponding regions is energy and environment inefficient, and have potential of reducing energy utilization and pollutant emission.

The total-factor energy and environment efficiency measure presented by model (1) is a kind of radial efficiency which may have weak discriminating power in energy efficiency comparisons (Zhou et. al., 2007; Zhou and Ang, 2008). Therefore, following Bian and Yang (2010), we extend the radial energy and environment efficiency measure to a non-radial measure as

$$
\begin{aligned}
E_2 = \min \frac{1}{2}\left( \frac{1}{L}\sum_{l=1}^{L}\theta_l^e + \frac{1}{K}\sum_{k=1}^{K}\theta_k^b \right) & \\
s.t. \quad \sum_{j=1}^{n}\lambda_j x_{ij} + s_i^{x-} = x_{ij_0}, i = 1, \ldots, m, & \\
\sum_{j=1}^{n}\lambda_j e_{lj} + s_l^{e-} = \theta_l^e e_{lj_0}, l = 1, \ldots, L, & \\
\sum_{j=1}^{n}\lambda_j y_{rj} - s_r^{y+} = y_{rj_0}, r = 1, \ldots, s, & \\
\sum_{j=1}^{n}\lambda_j b_{kj} = \theta_k^b b_{kj_0}, k = 1, \ldots, K, & \\
\lambda_j, s_i^{x-}, s_l^{e-}, s_r^{y+} \geq 0, \text{for all } j, i, l, r. &
\end{aligned} \tag{2}
$$

Model (2) measure the energy and environment efficiency ($E_2$) by using different non-proportional adjustments for different energy inputs and pollutant outputs, which account for the energy input effects ($\theta_l^e$) and pollutant outputs effects ($\theta_k^b$), respectively. Therefore, model (2) allows energy consumptions and pollutant emissions to be reduced with different proportion so as to let the evaluated regions reach their best practice point on the energy and environment efficiency frontier. Here, we have to point out that in Model (2), the energy efficiency and environment efficiency are evaluated by using different non-proportional adjustments and the unified efficiency is calculated through a decision maker specified weights assigned to each of these two efficiency scores (the weights are both set to 1/2 in this paper). However, the decision maker also could assign different weights to them so as to present different preference on energy utilization performance or environmental protection performance in the unified efficiency evauation.

In model (2), only when $\theta_l^e$=1 and $\theta_k^b$=1 for all $l$ and $k$ (i.e. $E_2$=1), and all slacks are zeros, the corresponding region is known as energy efficient and environment efficient. Obviously, model (2) has a higher discriminating power than model (1), thus we will use model (2) to evaluate the total-factor energy and environment efficiency of different regions in China.

*2.2 DEA window analysis for the dynamic evaluation of energy and environment performance*

In this study, we plan to measure the energy and environment efficiency of different regions in China not only for a single year but a time period of 2000 to 2008, which is considered a dynamic evaluation and could provide us more information about the efficiency changes. Therefore, it is meaningful and practical to explore the energy and environment efficiency by applying DEA window analysis.

DEA window analysis, introduced by Charnes and Cooper (1985), is a variation of the traditional DEA approach that can handle cross-sectional and time-varying data so as to measure dynamic effects. This technique operates on the principle of moving averages and establishes efficiency measures by treating each DMU in different periods as a separate unit. Under window analysis framework, the energy and environment performance of a region in a period can be contrasted to the performance of other regions as well as to its own performance in other periods. Therefore, by applying this technique we can explore the energy and environment efficiency of different regions in different years through a sequence of overlapping windows.

The DEA window analysis for energy and environment efficiency measure in our study is presented below.

A window with $n \times w$ observations is denoted starting at time $t$ ($1 \leq t \leq T$) with window width $w$ ($1 \leq w \leq T\text{-}t$). In our study, there are 29 regions (provinces, autonomous regions, and municipalities) of China with the time period of 9 years' (2000-2008) efficiencies need to be examined, so $n$=29 and $T$=9. The window width is supported by the number of time period (years in this study) under analysis, and the time periods are conceived of in an inter-period manner. According to Zhang et al. (2011), it should be noted that since each of the regions for a specific year within a given window are measured against each other, DEA window analysis implicitly assumes that there are no technical changes during the period under analysis within each window. This is considered to be a general problem in this approach. A narrow window width therefore must be used to relieve the problem. Charnes et al. (1994) proposed that a window width of three or four time period tend to yield the best balance of informativeness and stability of the efficiency measure.

In this study, following Halkos and Tzeremes (2009) and Zhang et al. (2011), we chose a narrow window with the width of three ($w$=3) to get credible energy and environment efficiency results. Therefore, the first three years of 2000, 2001 and 2002 construct the first window. Then the window moves on a one-year period by dropping the original year and adding a new year. Thus, the next three year of 2001, 2002 and 2003 form the second window. This process continues until the last window, which contains the last three years of 2006, 2007 and 2008, is constructed. At last, we obtain 7 windows which are performed for each region and the number of DMUs (regions of China in our study) in each window becomes 87 ($n \times w$=29$\times$3).

The radial and non-radial energy and environment efficiency ($E_1$ and $E_2$) of 29 regions of China in each window can be obtained using DEA window analysis. For each region, each year has three values on energy and environment efficiency, with the exception of 2000 and 2008, which has only one value, and 2001 and 2007, which has two values. Then, we calculate the average results of energy and environment efficiency of each region in the same year so as to get a new efficiency result for the 29 regions.

## 3. Data and variables

In this study, we use annual data of capital stock and labor force as two non-energy inputs, and energy consumption as energy input, while gross domestic product (GDP) as desirable output, and carbon dioxide ($CO_2$) and sulfur dioxide ($SO_2$) emissions as two undesirable outputs. In the case of China, since there has been no large scale survey or census on capital assets in the post-1949 period, therefore, the data on capital stock of each region of China could not be obtained from the statistical yearbook. We use the results proposed by Shan (2008), in which the data on capital stock are based on 1952 prices.

The data on labor, energy, GDP and $SO_2$ emissions are obtained from China Statistical Yearbook, China Energy Statistical Yearbook, and China Statistical Yearbook on Environment from 2001 to 2009. Since our study period is from 2000 to 2008, a more recent price index may be more appropriate, thus, we use the data of GDP in 2000 price. The energy consumption includes all kinds of energies, e.g., coal, oil, and nature gas. The $CO_2$ emissions are mainly from fossil energy consumption, so following Liu et al. (2010), we estimate the data on $CO_2$ emissions from the amounts of fossil energy.

Table I presents the summary statistics of input and output variables. We could see that, on average, the capital stock, number of labor, energy consumption, GDP and $CO_2$ emissions for the 29 regions of China all increased from 2000 to 2008, while, only the $SO_2$ emissions have a slight decrease during 2000-2001 and 2006-2008.

**Table I Summary statistics of inputs and outputs**

| Year | Variable | Non-energy inputs | Energy inputs | Desirable outputs | Undesirable outputs |
|---|---|---|---|---|---|

| | | Capital stock | Labor | Energy | GDP | $CO_2$ | $SO_2$ |
|---|---|---|---|---|---|---|---|
| | Units | RMB billion | Million workers | Million tons of coal equivalent (Mtce) | RMB billion | Million tons(Mt) | Million tons(Mt) |
| 2000 | Mean | 183.83 | 21.67 | 51.92 | 339.26 | 127.67 | 0.68 |
| | Std. Dev. | 176.53 | 15.66 | 30.83 | 259.39 | 75.80 | 0.51 |
| | Max | 665.57 | 60.72 | 113.62 | 1074.13 | 279.38 | 2.06 |
| | Min | 13.54 | 2.39 | 4.80 | 26.37 | 11.80 | 0.02 |
| 2001 | Mean | 205.38 | 21.70 | 53.09 | 372.02 | 130.55 | 0.65 |
| | Std. Dev. | 196.40 | 15.61 | 30.36 | 285.91 | 74.64 | 0.49 |
| | Max | 726.59 | 60.39 | 106.56 | 1186.91 | 262.02 | 1.86 |
| | Min | 14.80 | 2.40 | 5.20 | 29.45 | 12.79 | 0.02 |
| 2002 | Mean | 231.11 | 21.95 | 60.40 | 412.52 | 148.52 | 0.65 |
| | Std. Dev. | 220.36 | 15.56 | 36.46 | 320.08 | 89.66 | 0.48 |
| | Max | 801.02 | 60.49 | 145.99 | 1334.08 | 358.97 | 1.82 |
| | Min | 16.24 | 2.47 | 6.02 | 33.02 | 14.80 | 0.02 |
| 2003 | Mean | 263.75 | 22.32 | 68.74 | 463.26 | 169.02 | 0.74 |
| | Std. Dev. | 249.87 | 15.76 | 41.63 | 365.06 | 102.36 | 0.52 |
| | Max | 879.46 | 61.09 | 166.25 | 1531.53 | 408.79 | 1.97 |
| | Min | 18.19 | 2.54 | 6.84 | 36.95 | 16.82 | 0.02 |
| 2004 | Mean | 302.42 | 22.82 | 79.59 | 526.59 | 195.71 | 0.78 |
| | Std. Dev. | 283.99 | 16.02 | 48.97 | 419.39 | 120.40 | 0.52 |
| | Max | 971.42 | 61.93 | 196.24 | 1758.20 | 482.53 | 2.06 |
| | Min | 20.54 | 2.63 | 7.42 | 41.49 | 18.26 | 0.02 |
| 2005 | Mean | 351.17 | 23.41 | 90.54 | 595.65 | 222.62 | 0.88 |
| | Std. Dev. | 327.36 | 16.54 | 57.37 | 478.72 | 141.07 | 0.57 |
| | Max | 1103.00 | 63.24 | 236.10 | 2000.83 | 580.54 | 2.14 |
| | Min | 23.68 | 2.68 | 8.19 | 46.55 | 20.14 | 0.02 |
| 2006 | Mean | 409.14 | 23.85 | 99.75 | 677.43 | 245.28 | 0.89 |
| | Std. Dev. | 376.26 | 16.78 | 63.43 | 549.11 | 155.96 | 0.57 |
| | Max | 1287.01 | 64.12 | 261.64 | 2292.95 | 643.35 | 2.14 |
| | Min | 27.59 | 2.71 | 9.11 | 52.23 | 22.40 | 0.02 |
| 2007 | Mean | 475.64 | 24.55 | 109.24 | 774.89 | 268.60 | 0.85 |
| | Std. Dev. | 430.37 | 17.36 | 69.53 | 629.61 | 170.96 | 0.53 |
| | Max | 1482.19 | 65.68 | 285.54 | 2630.01 | 702.12 | 2.00 |
| | Min | 32.14 | 2.76 | 10.16 | 58.76 | 24.99 | 0.03 |
| 2008 | Mean | 549.35 | 25.10 | 116.45 | 868.71 | 286.34 | 0.80 |
| | Std. Dev. | 484.23 | 17.72 | 74.74 | 699.42 | 183.77 | 0.50 |
| | Max | 1699.75 | 67.12 | 305.70 | 2903.53 | 751.69 | 1.93 |
| | Min | 35.68 | 2.77 | 11.35 | 66.69 | 27.91 | 0.02 |
| All years | Mean | 330.20 | 23.04 | 81.08 | 558.93 | 199.37 | 0.77 |
| | Std. Dev. | 338.19 | 16.18 | 56.89 | 493.55 | 139.88 | 0.52 |
| | Max | 1699.75 | 67.12 | 305.70 | 2903.53 | 751.69 | 2.14 |
| | Min | 13.54 | 2.39 | 4.80 | 26.37 | 11.80 | 0.02 |

## 4. Regional energy and environment efficiency evaluation of China

### *4.1 Description of the regions and areas of China*

In this study, we examines 29 regions in Mainland China excluding Tibet due to the absence of relevant energy and emission data, and excluding Chongqing which is combined with Sichuan and they together are regarded as one region due to the absence of the separate capital stock data of Chongqing. From the perspective of the development and political factors of China, its provinces, autonomous regions, and municipalities are usually divided into three major areas: east, central, and west (Hu and Wang, 2006; Bian and Yang, 2010). The detailed information of the areas and regions are shown in Table II and Figure 3.

**Table II Areas and regions in China and energy and environment related data**

| Areas | Regions (provinces, autonomous regions, and municipalities) included | Average GDP (RMB billion) | Average energy consumption (Mtce) | Average $CO_2$ emissions (Mt) | Average $SO_2$ emissions (Mt) |
|---|---|---|---|---|---|
| East area | E1.Beijing, E2.Tianjin, E3.Hebei, E4.Liaoning, E5.Shanghai, E6.Jiangsu, E7.Zhejiang, E8.Fujian, E9.Shandong,E10.Guangdong,E11.Hainan; | 877.73 | 104.66 | 257.36 | 77.83 |
| Central area | C1.Shanxi, C2.Inner Mongolia, C3.Jilin, C4.Heilongjiang, C5.Anhui, C6.Jiangxi, C7.Henan, C8.Hubei, C9.Hunan, C10.Guangxi; | 445.79 | 76.85 | 188.97 | 78.24 |
| West area | W1.Sichuan, W2.Guizhou, W3.Yunnan, W4.Shaanxi, W5.Gansu, W6.Qinghai, W7.Ningxia, W8.Xinjiang. | 262.00 | 53.94 | 132.63 | 73.86 |
| Whole country | 29 regions | 528.51 | 78.48 | 192.99 | 76.64 |

As shown in Table II, the east area is constituted by 11 regions including 8 coastal provinces (Hebei, Liaoning, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan) and 3 municipalities (Beijing, Tianjin, and Shanghai). This area has experienced the most rapid economic growth in China in the past 30 years and its average GDP output for our study period (2000 to 2008) is around half of Chinese total GDP output. Most of light industries and quite a few heavy industries, as well as most of service industries and foreign trades in China are located in east area. Because of the convenient transportation system and developed infrastructure, this area has also attracted the most foreign investment and technology. Beijing and Shanghai are considered as the most economic and social developed regions in China.

The central area consists of 10 regions which are inland provinces: Heilongjiang, Jilin, Inner Mongolia, Henan, Shanxi, Anhui, Hubei, Hunan, Jiangxi, and Guangxi. This area has a large population and it is a home base for farming and related industries. The economy growth, attracted investments and technologies in this area are less than those of the east area but more than those of the west area. There are also lots of heavy industries located in northeast (Heilongjiang and Jilin) and central south (Hubei and Hunan) of this area, which are known as another two industrial centers of China. Inner Mongolia and Shanxi are the two largest energy industry regions of China, which export thousands and thousands of coal to the east area each year. Because of the high density of heavy industries in some of the regions in this area, the energy consumption and related pollutant emissions are quite high.

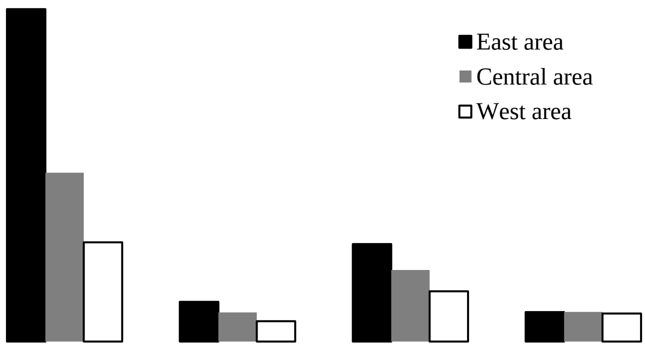


**Figure 1. GDP, energy, and emission comparison of three areas**

The west area covers more than half of the territory in China, which includes 1 municipality of Chongqing and 9 provinces, including Gansu, Guizhou, Ningxia, Qinghai, Shaanxi, Tibet, Yunnan, Xinjiang, and Sichuan. Compared to the other two areas, this area has low population density and high resource reserves as coal, oil, nature gas, and other mineral. The west area is also the least developed area in China. However, in some regions of this area, the natural environment is protected quite well for the low industry and population density. The comparison of the three areas on economy development, energy consumption, and pollutant emission could be seen in Figure 1. It shows that the differences on energy consumption and $CO_2$ emissions are less than the differences on GDP among the three areas, and the differences on $SO_2$ emissions are the least.

*4.2 Operationalizing the improved DEA model and window analysis*

We first use model (2) to compute the efficiency score ($E_2$) of different regions in China, then the DEA window analysis is applied and Beijing is taken as an example in Table III, in which the calculation of the energy and environment efficiency is shown. The calculations for the other 28 regions are similar and omitted here. Through the sequence of overlapping 7 windows from 2000 to 2008, we could explore the evolution of energy and environment performance for each region of China. Viewing the column data of Table III, we could test the stability of the efficiency for each region across the different datasets. And the row data enable us to examine the trends across the same dataset. According to the last row of Table III, we could find that Beijing has a significantly improve on its energy and environment efficiency from 2000 to 2003, while the efficiency fluctuated during 2004 and 2008.

**Table III A three-year window analysis of energy and environment efficiency of Beijing**

| Windows/Years | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|
| Window 1 | 0.8127 | 0.9327 | 1 | | | | | | |
| Window 2 | | 0.8127 | 0.9327 | 1 | | | | | |
| Window 3 | | | 0.8754 | 0.9501 | 1 | | | | |
| Window 4 | | | | 0.8955 | 0.9405 | 1 | | | |
| Window 5 | | | | | 0.8653 | 0.9151 | 1 | | |
| Window 6 | | | | | | 0.8233 | 0.8948 | 1 | |
| Window 7 | | | | | | | 0.7918 | 0.8782 | 1 |
| Average | 0.8127 | 0.8727 | 0.9360 | 0.9486 | 0.9353 | 0.9128 | 0.8955 | 0.9391 | 1 |

*4.3 Results of the regional energy and environment performance*

We present the energy and environment efficiency results of 29 regions of China in Table IV. The average efficiencies of three different areas and the whole country in different years from 2000 to 2008 are also calculated and shown in Table IV. From this table, we could find: i) The efficiencies of Yunnan from 2000 to 2004 and 2008, as well as Liaoning from 2003 to 2008 (both for 6 years) have always been the benchmark for lying on the energy and environment performance frontier. ii) After 2002, Beijing, Shanghai, Fujian, Guangdong, and Hainan almost all gain an efficiency score above 0.9, and all of these regions are measured efficient in 2008. iii) Except the regions above, only Tianjin, Jiangsu, Zhejiang, and Anhui have the efficiencies that above or close to 0.7 for most years during the study period. iv) The efficiencies of the rest regions are below 0.6 for almost all years, and there are 6 regions (Shanxi, Inner Mongolia, Guizhou, Gansu, Qinghai, and Ningxia) have the lowest efficiency scores below 0.3 on every year in the period from 2000 to 2008 with only one exception of Qinghai in 2002.

Furthermore, we illustrate the average energy and environment efficiencies of three areas and 29 regions of China in Figure 2 and Figure 3. These figures show that: i) In the east area, 7 out of 11 regions (Beijing, Tianjin, Liaoning, Shanghai, Fujian, Guangdong, and Hainan) are high energy and environment efficient with the average efficiency scores above 0.8, and 4 out of 11 regions (Hebei, Jiangsu, Zhenjiang, Shandong) have average efficiency scores between 0.3 and 0.8, in which, the performance of Hebei is worst. No region in east area has average efficiency score below 0.3. ii) In the central area, Anhui obtains the highest average efficiency, however the score is no more than 0.8, which means no regions in this area are high energy and environment efficient. All the average efficiency scores of other regions in this area are below 0.6, and Shanxi has the lowest average score of 0.197, followed by Inner Mongolia with an average efficiency score of 0.269. iii) In the west area, Yunnan performances very high with an average score of 0.994, followed by Sichuan, Shaanxi, and Xinjiang. However, the efficiency scores of the latter 3 regions are just around 0.3 to 0.4, which is considered low efficient. The rest regions (Guizhou, Gansu, Qinghai, and Ningxia) of west area all have worst efficiencies below 0.3 and, together with Shanxi and Inner Mongolia, these six regions are ranked lowest all over the country. iv) The average efficiency of China as a whole country is around 0.5 to 0.6 during 2000 to 2008, which is considered no high.

**Table IV Energy and environment efficiency of 29 regions of China**

| Regions and areas | | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| East area | Beijing | 0.813 | 0.873 | 0.936 | 0.949 | 0.935 | 0.913 | 0.896 | 0.939 | 1 | 0.917 |
| | Tianjin | 0.630 | 0.711 | 0.848 | 0.890 | 0.923 | 0.898 | 0.896 | 1 | 1 | 0.866 |
| | Hebei | 0.308 | 0.333 | 0.345 | 0.339 | 0.350 | 0.344 | 0.345 | 0.356 | 0.374 | 0.344 |
| | Liaoning | 0.765 | 0.818 | 0.936 | 1 | 1 | 1 | 1 | 1 | 1 | 0.947 |
| | Shanghai | 0.875 | 0.903 | 0.939 | 0.954 | 0.971 | 0.923 | 0.912 | 0.953 | 1 | 0.937 |
| | Jiangsu | 0.663 | 0.705 | 0.814 | 0.848 | 0.817 | 0.745 | 0.747 | 0.775 | 0.803 | 0.769 |
| | Zhejiang | 0.669 | 0.707 | 0.749 | 0.757 | 0.778 | 0.773 | 0.777 | 0.812 | 0.855 | 0.764 |
| | Fujian | 0.870 | 0.935 | 1 | 0.992 | 1 | 0.970 | 0.969 | 0.971 | 1 | 0.967 |
| | Shandong | 0.482 | 0.541 | 0.544 | 0.527 | 0.546 | 0.515 | 0.517 | 0.539 | 0.559 | 0.530 |
| | Guangdong | 0.863 | 0.891 | 0.966 | 0.991 | 0.987 | 0.939 | 0.937 | 0.971 | 1 | 0.949 |
| | Hainan | 0.952 | 0.972 | 0.978 | 0.972 | 1 | 0.980 | 0.951 | 0.979 | 1 | 0.976 |
| | Average | 0.717 | 0.763 | 0.823 | 0.838 | 0.846 | 0.818 | 0.813 | 0.845 | 0.872 | 0.815 |
| Central area | Shanxi | 0.178 | 0.173 | 0.175 | 0.186 | 0.208 | 0.208 | 0.207 | 0.217 | 0.216 | 0.197 |
| | Inner M* | 0.280 | 0.277 | 0.290 | 0.281 | 0.269 | 0.257 | 0.252 | 0.257 | 0.261 | 0.269 |
| | Jilin | 0.384 | 0.401 | 0.422 | 0.430 | 0.460 | 0.450 | 0.447 | 0.461 | 0.525 | 0.442 |
| | Heilongjiang | 0.426 | 0.451 | 0.525 | 0.557 | 0.595 | 0.580 | 0.578 | 0.590 | 0.607 | 0.545 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Anhui | 0.594 | 0.609 | 0.676 | 0.745 | 0.817 | 0.845 | 0.871 | 0.918 | 0.924 | 0.778 |
| | Jiangxi | 0.539 | 0.584 | 0.620 | 0.603 | 0.615 | 0.596 | 0.583 | 0.588 | 0.600 | 0.592 |
| | Henan | 0.440 | 0.451 | 0.485 | 0.488 | 0.459 | 0.450 | 0.449 | 0.462 | 0.477 | 0.463 |
| | Hubei | 0.405 | 0.431 | 0.476 | 0.480 | 0.463 | 0.472 | 0.473 | 0.490 | 0.513 | 0.467 |
| | Hunan | 0.562 | 0.555 | 0.560 | 0.561 | 0.550 | 0.510 | 0.509 | 0.521 | 0.525 | 0.539 |
| | Guangxi | 0.482 | 0.506 | 0.542 | 0.553 | 0.545 | 0.517 | 0.512 | 0.516 | 0.538 | 0.524 |
| | Average | 0.429 | 0.444 | 0.477 | 0.489 | 0.498 | 0.488 | 0.488 | 0.502 | 0.519 | 0.482 |
| West area | Sichuan | 0.391 | 0.393 | 0.437 | 0.452 | 0.456 | 0.465 | 0.461 | 0.473 | 0.465 | 0.444 |
| | Guizhou | 0.148 | 0.152 | 0.173 | 0.173 | 0.179 | 0.184 | 0.180 | 0.186 | 0.219 | 0.177 |
| | Yunnan | 1 | 1 | 1 | 1 | 1 | 0.987 | 0.993 | 0.968 | 1 | 0.994 |
| | Shaanxi | 0.418 | 0.405 | 0.406 | 0.418 | 0.429 | 0.416 | 0.402 | 0.412 | 0.417 | 0.414 |
| | Gansu | 0.238 | 0.253 | 0.282 | 0.293 | 0.310 | 0.298 | 0.291 | 0.293 | 0.295 | 0.284 |
| | Qinghai | 0.271 | 0.279 | 0.302 | 0.290 | 0.257 | 0.220 | 0.209 | 0.209 | 0.214 | 0.250 |
| | Ningxia | 0.163 | 0.162 | 0.176 | 0.158 | 0.149 | 0.147 | 0.141 | 0.144 | 0.149 | 0.154 |
| | Xinjiang | 0.291 | 0.299 | 0.325 | 0.338 | 0.321 | 0.309 | 0.296 | 0.297 | 0.297 | 0.308 |
| | Average | 0.365 | 0.368 | 0.388 | 0.390 | 0.387 | 0.378 | 0.372 | 0.373 | 0.382 | 0.378 |
| Whole country | Average | 0.521 | 0.544 | 0.584 | 0.594 | 0.600 | 0.583 | 0.579 | 0.597 | 0.615 | 0.580 |

* indicates Inner Mongolia

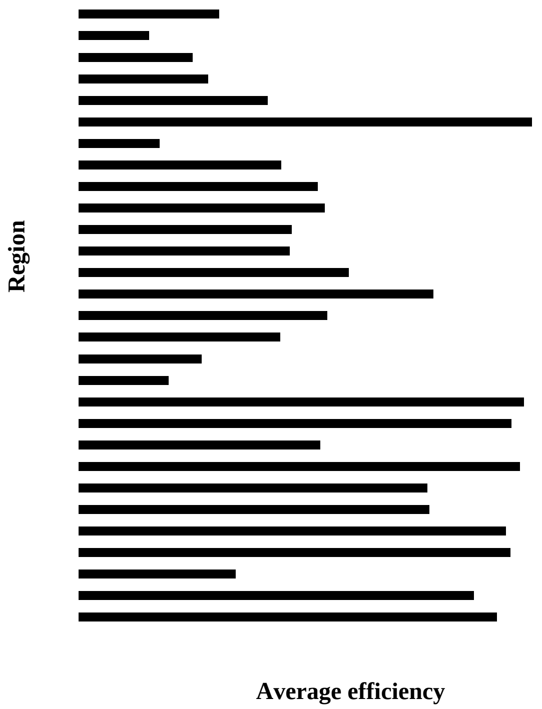


**Figure 2. Regional energy and environment efficiency of China**

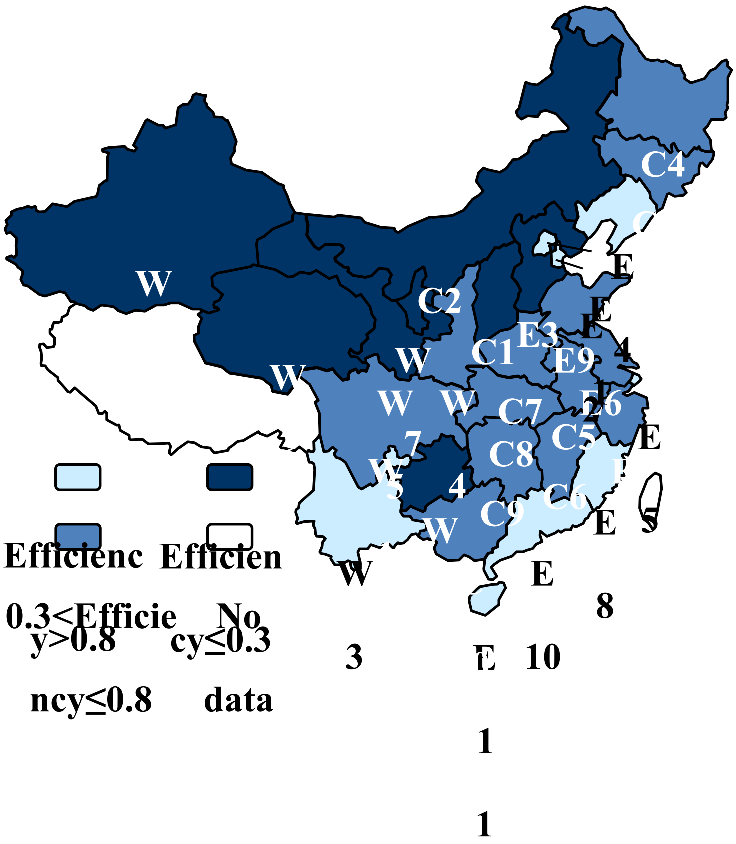


**Figure 3. Cluster analysis map of energy and environment efficiency level of China' 29 regions**

We also calculate the average efficiencies of three areas and the whole country for each year from 2000 to 2008 and the results are shown in Figure 4. This figure indicates that, i) from an area perspective and in each year during our study period, the east area gains the highest average energy and environment efficiency score. The central area has a better average efficiency score than the west area, but both of which are below the average efficiency at the whole country level. ii) All of the three areas have a similar increase and decrease trend during the period from 2000 to 2008. iii) In 2000, the energy and environment efficiency of China was 0.521, which slightly increased from 0.544 in 2001 to 0.6 in 2004. Then the efficiency gently decreased to 0.583 in 2005 and 0.579 in 2006. After that, the efficiency continuously increased to the highest level of 0.615 in the last year of our study period.

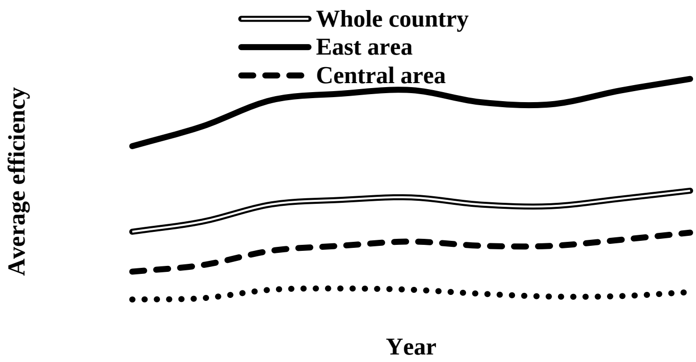


**Figure 4. Average energy and environment efficiency of China and its three areas**

In order to dynamically analysis the efficiency changes for each region during our study period and give a more detailed and clear demonstration, we illustrate 29 regions' energy and environment efficiency of 2000, 2004 and 2008 in figure 5. It could be seen that: i) about half of the 29 regions' efficiencies increased from 2000 through 2004 and 2008, and the most evident increases appeared in Anhui, Tianjin, Liaoning, and Beijing. ii) 4 out of 29 regions experienced an efficiency decrease process during 2000, 2004 and 2008, and the most evident decrease happened in Qinghai. iii) The efficiencies of the rest regions changed a little among these three time point.

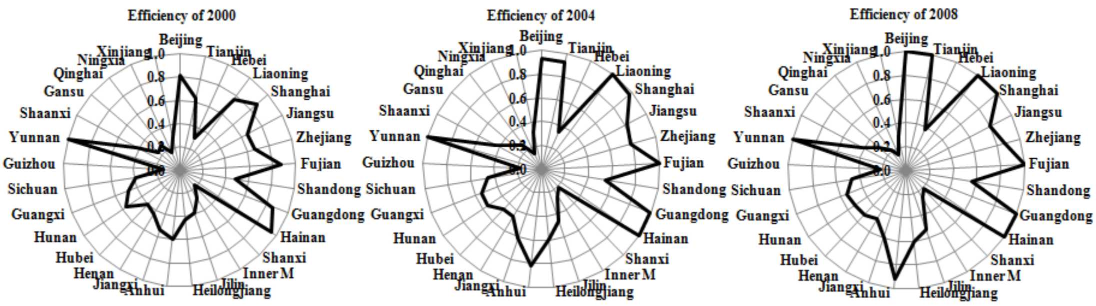


**Figure 5. China's regional energy and environment efficiency changes**

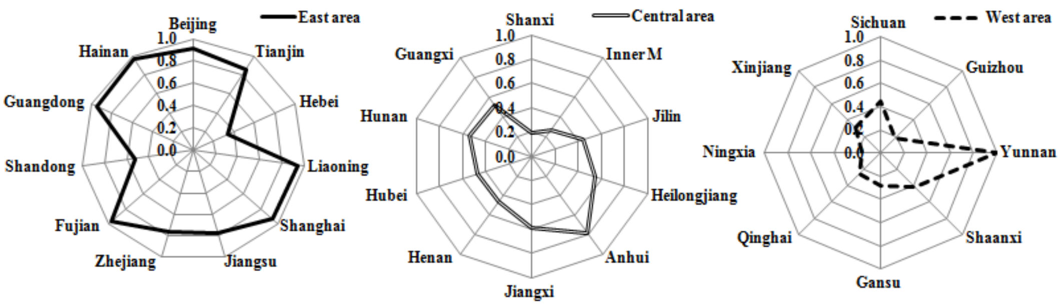


**Figure 6. Comparison of the average energy and environment efficiency of China's three areas**

Figure 6 compares the difference of average energy and environment efficiency among different regions in east, central and west areas of China. We could find that: i) the regions in the east area have a more balanced performance than the regions of the central area and the west area according to energy and environment efficiency. ii) Although the regions in east area enjoy a more balanced development, Shandong and Hebei are considered having relatively too low efficiencies. iii) In the central area, Anhui performs best and Shanxi performs worst, and the performances of all regions in this area are considered roughly balanced. iv) Since almost all regions in the west area suffer from very low energy and environment performance, Yunnan is an exception with very high performance.

*4.4 Discussions on the regional energy and environment efficiency*

The low energy and environmental efficiency of the whole country may result from the economic development mode of China. During our study period, the heavy industry, including steel, cement, electrolytic aluminum, and coal industries, developed rapidly, and economic development mode in some regions of central and west areas turned towards high energy consumption and high pollution discharge (Liao et. al, 2007). From 2000 to 2008, the proportion of gross industrial output value in GDP increase from 44.8% to 48.6%, and heavy industry accounted for as high as 70% of gross industrial output value after 2006.

As Yeh et al. (2010) mentioned in their research, China signed an agreement on trade in goods with Association of Southeast Asian nations in 2002 (which became effective in 2003) in order to promote the industrial development, and this development mainly focused on energy intensive heavy industries. This may be one reason that the energy and environment efficiency declined from 2004 to 2006 at the national level.

By 2006, Chinese government proposed an energy price modification strategy that the subsidies for energy had been dramatically reduced and energy price in China increasingly reflected actual costs (IEA 2007). For example, the coal prices are largely unregulated and they rose through 2006 and continued thereafter. In 2008, coal prices are at the levels higher than those in the United States (Zhou et al., 2010). This can be considered as one reason of the improvement of energy and environment efficiency since 2007.

The west area of China has the lowest energy and environment efficiency compared to the central and east areas. Since most regions in west area have relatively low economic development level, relatively undeveloped communication network, transportation systems, energy and industrial infrastructure. Therefore, the consumption of energy is relatively low and the corresponding efficiency did not experience huge fluctuations during our study period. The standard deviation of efficiency score is 0.009 of the west area compared with 0.048 of the east area.

In general, the energy and environment efficiency of China increased during our study period, and the increase may mainly contributed from a series of energy policies issued and carried out by Chinese government in order to alleviate energy shortage and climate change since the mid-1990s. In the neigh Five-Year-Plan (1996-2000), Chinese government proposed an energy conservation target of 5% annually and reduction for principal pollutant from 1996 to 2000, which is the first energy saving and emission reducing target among the developing countries (Zhang et al., 2011). Since then, efficiency improvements have been particularly marked in energy-intensive industries such as iron and steel, cement, oil and coal processing, and electrical power generation (Liao et al., 2007). In 2002, Chinese government officially took sustainable development as the crucial state policy. Then, in 2004, the Medium and Long-Term Plan for Energy Conservation was approved which indicated that GDP energy intensity should decrease by 2.2% annually until 2010. This plan became a milestone in China’s energy policy and financial incentive and market mechanism came into operation from then on (Zhang et al., 2011). As we mentioned above, although the energy and environment efficiency of China is still low compared with developed countries, China has been dedicating in improving energy and environment efficiency and has achieved a success. Practice in China shows that effective energy policies play an important role in forcing energy-using units to improve energy and environment efficiency.

## 5. Conclusion

Within a joint production framework of both desirable output (GDP) and undesirable outputs ($CO_2$ and $SO_2$), as well as energy input (total energy consumption) and non-energy inputs (labor and capital stock), this study employs a data envelopment analysis based model to evaluate the total-factor energy and environment efficiency of 29 administrative regions and three areas of China. In addition, this study applies DEA window analysis technique to measure the efficiency in cross-sectional and time-varying data, so as to calculate the efficiency score during the study period of 2000 to 2008. The empirical results show that the east area of China has higher energy and environment efficiency than the central area, and the efficiency of west area is worst. The efficiencies of all three areas have similar variation trend, and in general the energy and environment efficiency of China increased a little from 2000 to 2008. The energy and environment efficiencies of the regions in the east area have a more balanced performance than the regions of the central area and the west area. The efficiency differences of three areas may arise from the unbalance of economic development, and the not high energy and environment efficiency of the whole country may caused by the economic development mode of China. However, effective energy and environment protection policies issued and implemented by Chinese government may contributed a lot in the improvement of Chinese energy and environment efficiency in the past decade.

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