CEEP-BIT WORKING PAPER SERIES

CEEP-BIT

Energy and emissions efficiency patterns of Chinese regions: A multi-directional efficiency analysis

Ke Wang
Yi-Ming Wei
Xian Zhang

Working Paper 60
http://ceep.bit.edu.cn/english/publications/wp/index.htm

Center for Energy and Environmental Policy Research
Beijing Institute of Technology
No.5 Zhongguancun South Street, Haidian District
Beijing 100081
July 2014

This paper can be cited as: *Wang K, Wei Y-M, Zhang X. 2014. Energy and emissions efficiency patterns of Chinese regions: A multi-directional efficiency analysis. CEEP-BIT Working Paper.*

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions. The authors also gratefully acknowledge the financial support from the National Natural Science Foundation of China under grants nos. 71101011, 71020107026; the China Postdoctoral Science Foundation under grant nos. 20110490298, 2012T50049; and the National Basic Research Program of China under grant no. 2012CB95570004. The views expressed herein are those of the authors and do not necessarily reflect the views of the Center for Energy and Environmental Policy Research.

The Center for Energy and Environmental Policy Research, Beijing Institute of Technology (CEEP-BIT), was established in 2009. CEEP-BIT conducts researches on energy economics, climate policy and environmental management to provide scientific basis for public and private decisions in strategy planning and management. CEEP-BIT serves as the platform for the international exchange in the area of energy and environmental policy.

Currently, CEEP-BIT Ranks 82, top 5% institutions in the field of Energy Economics at IDEAS（http://ideas.repec.org/top/top.ene.htm), and Ranks 104, top 5% institutions in the field of Environmental Economics at IDEAS (http://ideas.repec.org/ top/top.env.html).

Yi-Ming Wei
Director of Center for Energy and Environmental Policy Research, Beijing Institute of Technology

For more information, please contact the office:

Address:
Director of Center for Energy and Environmental Policy Research
Beijing Institute of Technology
No.5 Zhongguancun South Street
Haidian District, Beijing 100081, P.R. China

Access:
Tel: +86-10-6891-8551
Fax: +86-10-6891-8651
Email: ceeper@vip.163.com
Website: http://ceep.bit.edu.cn/english/index.htm

Energy and emissions efficiency patterns of Chinese regions: A multi-directional efficiency analysis

Ke Wang [a,b,*], Yi-Ming Wei [a,b], Xian Zhang [a,c]

[a] Center for Energy and Environmental Policy Research, BIT, 5 S. Zhongguancun Street, Beijing 100081, China

[b] School of Management & Economics, Beijing Institute of Technology, 5 S. Zhongguancun Street., Beijing 100081, China

[c] The Administrative Center for China's Agenda 21, Ministry of Science and Technology of China, 8 S. Yuyuantan Road, Beijing 100038, China

Abstract: Evaluation of the energy and emissions efficiency of Chinese regions has recently attracted increasing interest. A number of previous studies have contributed to the measurement of energy efficiency using various types of data envelopment analysis (DEA) techniques. However, most of these DEA-based energy efficiency analyses were restricted to the radial expansions of outputs or radial contractions of inputs. In this paper, we utilize the multi-directional efficiency analysis (MEA) approach instead of the traditional radial DEA to investigate Chinese regional energy and emissions efficiency. Since MEA selects benchmarks such that the input contractions or output expansions are proportional to the potential improvement identified by considering the improvement potential in each input or output variable separately, not just the efficiency status but also the efficiency patterns of different Chinese regions and areas can be detected. The empirical study results indicate that, in general, the MEA efficiency of China experienced an increasing process over the study period 1997-2010; the east area overall is more MEA efficient than the central area and the west area of China during the study period; the significant higher MEA efficiency of the east area to the central area and the west area are due to both the higher energy specific efficiency and the higher emissions specific efficiency of the east area compared to the other two areas; the provinces of Hebei, Shanxi, Inner Mongolia, Shandong, Henan, and Hubei etc. have both high energy saving potentials and high emissions reduction potentials, thus they will play the most important roles in China's effort on energy conservation and CO_2 emissions mitigation.

Keywords: Energy efficiency, CO_2 emissions, Multi-directional efficiency analysis (MEA), China

1 Introduction

Evaluating and improving energy utilization efficiency and CO_2 emissions efficiency, which is considered a crucial approach to save energy and mitigate CO_2 emissions, has recently attracted increasing interest from both the academic researchers and the general public, as global warming has become one of the most serious environmental problems

* Corresponding author. Tel.: +86 10 68918551; fax: +86 10 68918651.
E-mail addresses: kewang2083@gmail.com (K. Wang), wei@bit.edu.cn (Y.M. Wei), zhangxian@acca21.org.cn (X. Zhang).

worldwide. Global warming is largely attributed to the effect of emissions of greenhouse gases (GHG) such as CO_2 from the combustion of fossil fuels.

Between the 1980s and 2000, China significantly improved its energy efficiency and limited its energy demand growth to less than half of its GDP growth. Its energy intensity (energy consumption per unit of GDP) annually declined by approximate 5% during this period. However, during the period 2001-2005, its energy intensity decreasing trend was reversed and its energy consumption per unit of GDP on average increased by 1.6% per year. In order to slow down the overly rapid growths of China's energy demand and related CO_2 emissions, the Chinese government announced a mandatory goal of reducing energy intensity by 20% between 2006 and 2010, based on the level of 2005. This goal was officially incorporated into China's 11^{th} Five-Year Plan, further decomposed at the regional level and assigned to each of the Chinese provinces. Furthermore, a series of policies, programs, laws and regulations were put forward to support the realization of this 20% energy intensity reduction goal [1]. It appears that the implementations of these energy efficiency policies and programs have been sufficient to meet the energy saving target, as the latest report issued by the Chinese central government in 2011 indicated that by the end of 2010, China's energy intensity had decreased by 19.1% based on 2005 level, and the energy demand growth reverted to less than the GDP growth during the period 2006-2010.

Despite the major energy efficiency improvements achieved during the last three decades, the rapid growth of China's economy since its reforms and its opening up to the outside world began in 1978 has substantially increased China's primary energy consumption and total CO_2 emissions. This is because China's economic growth has been attributable mainly to the growth of heavy industries and infrastructure constructions, which are all energy intensive and high energy consumption industries [2, 3]. In 2010, China's primary energy consumption was 3.2 billion tonnes of coal equivalent (tce), and energy consumption related total CO_2 emissions of China rose to approximate 9.1 billion tonnes. Since 2007, China has already overtaken the US and become the world's largest energy consumer and the largest contributor of CO_2 emissions in the world. Therefore, in an effort to advance towards the construction of a resource-saving and environmental-friendly society, and the realization of sustainable development for China, it is worthwhile evaluating its regional energy and emissions efficiencies and estimating each area's potential for the energy saving and emissions reduction. This may provide useful information for energy and environmental policy making and management.

To date, a number of studies of Chinese regional energy and/or environmental efficiency using the frontier based approach have been published [4-14]. The conclusions of the extant studies are varied, particularly concerning the efficiency rankings of Chinese provinces, the efficiency difference of Chinese areas, and the estimated energy saving potentials for different Chinese regions. In this paper, we aim to investigate the issue of Chinese regional energy and emissions performance in greater depth through analyzing not just the level and variance trend of China's energy and emissions efficiency, but also the patterns and differences of the efficiencies in Chinese 30 provinces and three areas (east, central and west China). The realization of this research objective is made possible through applying the multi-directional efficiency analysis (MEA) approach [15], as MEA can identify both the status and the patterns of energy and emissions efficiencies for different regions and areas.

The remainder of this paper is organized as follows. An overview of Chinese regional development and Chinese energy efficiency policies and related management are proposed in Section 2. Section 3 reviews the related literatures. Section 4 outlines the methodology of MEA. The data and variables are described in Section 5. Section 6 presents the evaluation results and discussion, and the final section concludes this paper.

2 Chinese energy efficiency policies and Chinese regional development

The economic reform and opening up policy begun in the 1980s has allowed China to achieve significant progress in economic and social development over the past three decades. During this period, China's nominal GDP has increased more than 80-fold from 455 billion RMB to 40120 billion RMB. At the same time, China's total energy consumption has also risen tremendously from 603 million tce to 3250 million tce. The scale-oriented and energy intensive economic growth mode of China has given rise to a number of problems associated with high energy consumption and GHG emissions, as well as serious environmental pollution.

In order to realize sustainable development, and build a resource-saving and environment-friendly society, the Chinese government has proposed and implemented a number of energy efficiency policies and programs. According to [1], the main features of these energy efficiency policies, regulations, programs and laws include i) close oversight of industrial energy consumption; ii) financial incentives for energy efficiency investments; iii) consultation services on energy conservation; iv) training, education, and policy advocacy on energy saving and efficiency promotion; and v) research and development, and demonstrative projects of energy conservation and emissions reduction. During the period between the 1980s and 2000, the effect of these policies and programs was noticeable, in that the growth of energy demand was less than the growth of GDP, and energy intensity declined about 5% annually from 1980 to 2001. In addition, because of the Asian financial crisis which began in 1997 and the slowdown of economic growth in China during the period 1998-2001, energy intensity declined by more than 24% from 1997 to 2001. The emphasis on energy efficiency and the economic conditions of China during this period provided many benefits in terms of China's energy conservation and energy related CO_2 emissions reduction. In this paper, we consider this period (1997-2000) as the first study period for energy and emissions efficiency analysis.

The period 2001-2005 saw a noticeable reversal in China's energy intensity decline. The continuous decrease in energy intensity began to reverse in 2001, and the energy intensity increased by an average of 1.6% per year between 2001 and 2005. Energy demand also significantly increased by 57% during this period. In 2005, around 40% of global energy demand growth was the contribution of China, and since 2007, China has caught up with and surpassed the US as the world's largest CO_2 emitter. In this study, we consider this period (2001-2005, which was also the 10^{th} Five-Year Plan period) as the second study period for energy and emissions efficiency evaluation.

In recognition of the overly rapid growth of energy demand and related CO_2 emissions, as well as the associated environmental problems, the Chinese government agreed in 2005 that the total energy consumption of China had to be brought under control. In November of 2005, a national energy intensity reduction goal was announced by the Communist Party that the energy intensity of China had to be reduced by 20% within the five years between 2006 and 2010 (i.e. period of the 11th Five-Year Plan), based on the 2005 level. This ambitious energy intensity reduction goal was further confirmed and ratified by the National People's Congress and stated in the 11th Five-Year Plan. Around 2005 and 2006, a series of policies, regulations and laws were proposed to support the realization of the 20% reduction goal. These policies and laws include the Medium- and Long-term Plan for Energy Conservation issued in 2005, the energy conservation law revised in 2006, the policy on reducing export tax rebates for low value-added but high energy-consuming products proposed in 2006, and the Top-1000 energy-consuming enterprise program started in 2006. Shortly after the announcement of the national goal of reducing energy intensity by 20%, in 2006, a scheme for disaggregating the national goal into the energy saving target for each Chinese province was issued, under which 19 provinces were assigned a 20% decrease target, 7 provinces were given the targets of decreases between 12% and 17% decreases, and the decrease targets of 4 provinces were set above 20% (for an evaluation of and discussion on the disaggregation of energy intensity reduction, see [16]).

It appears that China has been on track to meet this energy intensity reduction goal since 2006, for its energy intensity consistently decreased from 0.128 tce per thousand RMB in 2005 to 0.103 tce per thousand RMB in 2010. The latest report issued in 2011 announced that the energy intensity of China had declined by 19.1% (close to the 20% goal) during the period 2006-2010. This achievement was mainly due to the implementation of strict energy efficiency policies and programs, and the efforts on energy conservation did have brought China back to the normal relationship between energy consumption and economic growth experienced during the 1990s. In this study, we consider this period 2006-2010 to be our third study period for energy and emissions efficiency analysis.

Since different Chinese provinces had different natural resources endowments and had different development priorities, they experienced very different development processes and are now at different stages of social and economic development with varying energy utilization and CO_2 emissions performance. From a geographical perspective and according to political classifications, China's mainland provinces can be divided into three regions: the east, central and west China areas.

The east area consists of ten coastal and northeast provinces (Hebei, Liaoning, Jilin, Heilongjiang, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan) and three municipalities (Beijing, Tianjin, and Shanghai). This region has enjoyed strong economic development and its GDP in 2010 was 26,952 billion RMB (2010 price), which is more than 60% of China's total GDP. The energy consumption and related CO_2 emissions of east China also accounted for more than half of China's total energy consumption and CO_2 emissions in 2010.

The central area is composed of eight provinces (Shanxi, Inner Mongolia, Anhui, Jiangxi, Henan, Hubei, Hunan, and Shaanxi). The provinces in this area are all landlocked regions with large populations. The economic growth of this area is less than that of the east area but more than that of the west area and the GDP of central China is just around one quarter of China's total GDP of 2010. However, the energy consumption and related CO_2 emissions of central China are around 30% of China's total.

The west area is composed of one municipality (Chongqing) and eight inland and mountainous provinces (Guangxi, Sichuan, Guizhou, Yunnan, Gansu, Qinghai, Ningxia, and Xinjiang). West China covers more than half of China's territory and sustains about 20% of the Chinese population. This area is less economically developed than east and central China, and its GDP was less than 15% of China's total GDP in 2010. However, this area is rich in natural resources, particularly raw coal and crude oil. The energy consumption of the west area in 2010 accounted for around 18% of China's total and the CO_2 emissions of this area accounted for around 16% of China's total.

3 Literature review: China's regional energy efficiency analysis

The most commonly used measurement for macro economy-wide energy efficiency is monetary-based energy efficiency, which refers to the energy consumption per unit current output [17]. Recently, an increasing number of studies have focused on total-factor efficiency evaluation issues, as any economy production process could be seen as a joint-production process in which multiple inputs of energy and other materials and resources are utilized to produce multiple desirable outputs (e.g. GDP) and undesirable outputs (e.g. CO_2 emissions) as by-products. In addition, most of the energy efficiency evaluation at a macro-economic level and using a total-factor framework has adopted the data envelopment analysis (DEA) method, as DEA provides an appropriate mechanism for dealing with multiple inputs and outputs in measuring the relative efficiency of each decision making unit (DMU) under evaluation.

Several recent studies have examined energy efficiency using the DEA approach in western and developed economies such as the US [18], Canada [19], Japan [20], the APEC countries [21], and the OECD countries [22, 23], as well as in Asian developing countries like India [24, 25] and Korea [26]. There have also been several studies measuring the regional energy and emissions or environmental efficiency of China.

Hu and Wang [4] utilized the DEA approach to analyze the total-factor energy efficiencies of 29 Chinese provinces during the period 1995-2002. They found that the central area of China was the least energy efficient and its energy consumption redundancy was over half of China's total redundancy. Zhang et al. [8] investigated the eco-efficiency of industrial sectors of Chinese 30 provinces in 2004 through a DEA model and found that, for most Chinese regions, those with higher levels of GDP per capita would have higher eco-efficiency. Wang et al. [12] adopted a traditional DEA model to evaluate the energy efficiency of industrial sectors in Chinese 30 provinces from 2005 to 2009. Their study indicated that the provinces in the west area have a greater amount of energy redundancies than the provinces in the east and the central area and, in general, most provinces in the east area and a few provinces in the central area outperformed all the other Chinese provinces in industrial energy utilization.

The aforementioned studies just separately evaluated the energy efficiency or the environmental efficiency of Chinese regions under a total-factor DEA framework, as the inputs and outputs selections of these studies are limited to the traditional factors of labor, capital, energy, GDP or industrial added value, and some environmental factors such as solid and liquid wastes. One of the most important undesirable outputs of energy consuming related CO_2 emissions is not included in these studies. Thus, as Watanabe and Tanaka [5] and Wu et al. [14] indicated, these studies may lead to biased energy efficiency evaluation results. Wang et al.'s [11] comparative analysis of energy and emissions efficiency evaluation further confirmed that such a bias did exist if the undesirable output (CO_2) was omitted in evaluation. In order to solve this problem, recent studies began to take the undesirable outputs into consideration, and evaluate aggregate energy and environmental efficiency. Yeh et al. [10] evaluated the energy utilization efficiency of China during the period 2002-2007, and two undesirable outputs, CO_2 and SO_2 emissions, were included in their DEA framework. Their study results indicated that the east region of China enjoyed higher energy and environmental efficiency than the west area, and in general, there is the potential for a CO_2 emissions reduction of 11.28% for the whole country. Shi et al. [7] investigated the industrial energy efficiencies of China's 28 regions in 2000-2006 by utilizing a DEA model and the undesirable output of industrial waste gas was considered in their evaluation. The maximum energy saving potential in each Chinese region was identified in their study and the results indicated that industries in the central area have the largest energy saving potential, followed by the east and the west areas of China. Similar studies of DEA based energy efficiency evaluation of China can also be found in [3, 6, 9, 13].

Most of the studies on Chinese regional energy and environmental efficiency mentioned above are based on the traditional DEA approach, in which the DMUs under evaluation are restricted to the radial contractions on all input variables or radial expansions on all output variables. However, this assumption may be somewhat inappropriate in efficiency evaluation, since different input or output variables may adjust with different proportions so as to get more reasonable and specific efficiency measures.

The multi-directional efficiency analysis (MEA) approach is considered to be an alternative of the traditional DEA approach [15]. This method selects benchmarks such that the input reductions or output expansions are proportional to the potential improvement on efficiency identified by considering the improvement potential in each input or output variable separately. Thus, this approach is more suitable for separately investigating the efficiency patterns of each DMU. In addition, since MEA considers the improvement potential in each variable separately, it is suitable in the evaluation situations that the aim of each DMU is to simultaneously reduce the utilization of some inputs and increase the production of some outputs, without presetting the priorities on improvements of some variables over other variables. Furthermore, since the energy and environmental efficiency measures and improvements come from a combination of both reducing the energy input and increasing the GDP output, as well as abating the CO_2 emissions, and not necessarily increasing or decreasing these variables in the same proportions, the adoption of the MEA approach will be more appropriate.

Although the MEA approach has been used successfully in several applications such as health care [28], transportation [29, 30], banking [31], and agriculture [32], no study, to our knowledge, on energy and emissions efficiency evaluation has applied this method. In this study, we utilize the MEA method and show how it enables the investigation of both the levels and the patterns of efficiency, and how it provides additional insights into the characteristics of the energy and emissions efficiency of each Chinese region.

4 Methodology: multi-directional efficiency analysis (MEA)

As we aim to gain a deeper insight into the regional energy and environmental efficiency of China by investigating not just the status of each region and area but also by analyzing the efficiency patterns in each area, multi-directional efficiency analysis (MEA) is utilized instead of the traditional radial DEA approach. The MEA approach specifies a group of efficiency measures relative to a group of benchmarks constructed from the improvement potential associated with each of the variables. Therefore, the efficiency measure of MEA is not restricted to the radial expansions or radial contractions of all output or input variables of the traditional DEA, and both the status and patterns of the efficiencies among different regions and areas can be determined by this approach.

MEA was first proposed in [15], further developed in [27, 28] and utilized in [29-32]. The advantage of using MEA is that it selects the input reduction and output expansion benchmarks according to the specified improvement potential related to each input and output separately, which enables a specific investigation of the patterns of efficiencies. In this study, we consider N to the set of Chinese regions in the data set observed in each study period t. A region $j \in N$ at period t utilizes m inputs of $x_{i,j}^{t}$, i=1,…,m to produces s outputs of $y_{r,j}^{t}$, r=1,…,s. In order to find the ideal reference point for a specific observation $(x_{i,j_0}^{t}, y_{r,j_0}^{t})$, we first solve the following model (1), for each of the input variables. As we are mainly concerned with the reduction potentials for some of the inputs (energy and emissions) whilst keeping the other input and output variables (labor, capital stock and GDP) fixed for each Chinese region, here, the input oriented MEA model is utilized, and both the discretionary and non-discretionary variables are considered.

$$\begin{aligned}
&\min d_{i,j_0}^{t} \\
&s.t. \ \sum_j \lambda_j x_{i,j}^{t} \le d_{i,j_0}^{t}, \\
&\quad \sum_j \lambda_j x_{-i,j}^{t} \le x_{-i,j_0}^{t}, -i = 1,...,i-1, i+1,...,k, \\
&\quad \sum_j \lambda_j x_{i,j}^{t} \le x_{i,j_0}^{t}, i = k+1,...,m, \\
&\quad \sum_j \lambda_j y_{r,j}^{t} \ge y_{r,j_0}^{t}, r = 1,...,s, \\
&\quad \lambda_j \ge 0, j \in N.
\end{aligned} \tag{1}$$

In model (1), the first k inputs of $x_{i,j}^{t}$, i=1,…,k are discretionary inputs, and the remaining inputs of $x_{i,j}^{t}$, i=k+1,…,m are non-discretionary inputs. The notation (-i) denotes all input dimensions except dimension i. λ_j are the intensity variables associated with each region for connecting the inputs and outputs. d_{i,j_0}^{t} is the target value for the ith input reduction. Then, the ideal reference point for $(x_{i,j_0}^{t}, y_{r,j_0}^{t})$ could be given by

$(d_{i,j_0}^{t*}, y_{r,j_0}^{t})$, where * denotes the optimal solutions of model (1). Next, we consider the following model (2).

$$\begin{aligned}
&\max \beta_{j_0}^{t} \\
&s.t. \ \sum_j \lambda_j x_{i,j}^{t} \le x_{i,j_0}^{t} - \beta_{j_0}^{t}(x_{i,j_0}^{t} - d_{i,j_0}^{t*}), i = 1,...,k, \\
&\quad \sum_j \lambda_j x_{i,j}^{t} \le x_{i,j_0}^{t}, i = k+1,...,m, \\
&\quad \sum_j \lambda_j y_{r,j}^{t} \ge y_{r,j_0}^{t}, r = 1,...,s, \\
&\quad \lambda_j \ge 0, j \in N.
\end{aligned} \tag{2}$$

The optimal solution of model (2) is $(\lambda_j^{*}, \beta_{j_0}^{t*})$, and the relative variable specific MEA efficiency for the input variable x_{i,j_0}^{t} is defined as follows.

$$\frac{x_{i,j_0}^{t} - \beta_{j_0}^{t*}(x_{i,j_0}^{t} - d_{i,j_0}^{t*})}{x_{i,j_0}^{t}} \tag{3}$$

Based on the individual variable specific efficiencies, a single aggregated measure of MEA efficiency for the observation of $(x_{i,j_0}^{t}, y_{r,j_0}^{t})$ could be defined as follows.

$$\theta_{j_0}^{t} = 1 - \frac{1}{k}\left[\sum_{i=1}^{k} \frac{\beta_{j_0}^{t*}(x_{i,j_0}^{t} - d_{i,j_0}^{t*})}{x_{i,j_0}^{t}}\right] \tag{4}$$

5 Data and variables

The MEA models and efficiency measures described in Section 3 have been utilized to evaluate the energy and environmental efficiency of each province of China during the period 1997-2010. In our study framework, three inputs, one desirable output and one undesirable output are considered to measure energy and emissions efficiency. These three inputs are energy consumption (x_1), labor (x_2), and capital stock (x_3). The desirable output is gross domestic product (GDP) (y), and the undesirable output is CO_2 emissions (x_4). When measuring the energy and environmental efficiency, we always hope to reduce the energy consumption as much as possible for a given amount of desirable output, and for the undesirable output, the less of it is preferable. Therefore, in this study, we model the undesirable output as input. In addition, to treat the undesirable output as input is reasonable when considering that the emissions of CO_2 is a kind of "right" for each Chinese region under the emissions constraints and environment protection regulations that each region needs to "pay" for such "emissions right".

Thirty regions of China are included in our study. Tibet, Taiwan, Hong Kong and Macao are omitted because of the data absence. The data on labor and GDP are collected from the China Statistical Yearbook (1998-2011). Capital stock data are obtained from [33] and our estimation [11] through the perpetual inventory method as in [9]. The monetary based variables of GDP and capital stock are converted into constant prices. Energy consumption includes all types of energy such as coal, oil and natural gas, and the data are obtained from the China Energy Statistical Yearbook (1998-2011) and converted into tonnes of coal equivalent (tce) according to conversion factors provided in the China Energy Statistical Yearbook. Since the data on regional CO_2 emissions are not available in China's official statistics, in this study, we estimate the data of CO_2 emissions based on the amounts of fossil fuel consumptions and the CO_2 emissions factors for fossil fuel combustion provided in [34] (for the calculation of China's regional CO_2 emissions, see [35]). Table 1 illustrates the descriptive statistics of the input and output data.

[Insert Table 1 here]

6 Results and discussions

Utilizing the MEA models (1) and (2), and definitions (3) and (4), the relative variable specific MEA efficiencies, and the aggregated MEA efficiency for each province of China can be evaluated.

6.1 Efficiency levels of China's regions

We first consider the pooled data meta-analysis in which 420 observations (30 provinces for 14 years) are pooled into one data set for efficiency evaluation. The average aggregated MEA efficiencies for the east, central and west areas of China for each year across our whole study period are illustrated in Figure 1 and listed in the second row of Table 2.

[Insert Figure 1 here]

[Insert Table 2 here]

In Figure 1, we could first see that the MEA efficiencies of all three areas gradually increased during 1997-2000, slightly fluctuated during 2001-2005, and consistently improved from 2006 onwards. In general, the average MEA efficiency of China experienced an increasing process over our whole study period, and the non-parametric one-tailed Kruskal-Wallis test (K-W test for short, see [36] for this test) results indicate that this increase is statistically significant at 5% level.

Then, according to the average MEA efficiency scores, it can be seen that, in general, east China has higher aggregated MEA efficiency than central China, and the aggregated MEA efficiency of west China is the lowest. In order to examine the differences among these three areas and further confirm the aggregate MEA efficiency dominance and the variable specific MEA efficiency dominances, the two-tailed K-W test was used, and the test results are shown in the last three columns of Table 2. Here the aggregated MEA efficiency dominance of one area over another area means that the former area is more efficient than the latter area in terms of aggregated MEA efficiency score. And the variable specific MEA efficiency dominances of one area over another area indicate that the former area respectively has higher energy specific efficient score or higher emissions specific efficiency score than the later area. Based on the test results, it can be confirmed that, across the whole observation period (1997-2010), i.e., evaluated against the pooled frontier, the east area is more MEA efficient than the central area at the significance level of 1%, and the central area is more MEA efficient than the west area at the significance level of 5%.

The above evaluation, comparison and test might be somewhat inappropriate because all the 420 observations from 14 years are pooled and measured against a single frontier. However, the efficiency frontier for different years may shift during the whole study period; thus, the benchmarks on the pooled frontier might be inappropriate and unattainable for all the observations [37]. In order to solve this potential problem, Asmild and Matthews [31] performed the MEA method both in pooled data set and in various sub-samples of data sets separately. Following their approach, we further evaluate the MEA efficiency in several sub-samples: i) the three periods sub-samples (1997-2000, 2001-2005, and 2006-2010); and ii) the moving 3-year window sub-samples (12 overlapping windows within our study period). Here we point out that, since the DEA window analysis can handle cross-sectional and time-varying data, by applying this technique we can explore the energy and emissions efficiency of different regions in different years through a sequence of overlapping windows. In addition, since DEA window analysis implicitly assumes that there are no technical changes during the period under analysis within each window, a window width of three or four periods tends to yield the best balance of informativeness and stability of the efficiency measure.

The average aggregated MEA efficiencies for the east, central and west areas of China calculated separately in three periods are illustrated in Figure 2 and listed in the third to the fifth rows of Table 2. Figure 2 shows that the average aggregated MEA efficiency of east China continued to improve in all the three periods, and those efficiencies of central and west China slightly increased during the first and third periods, but fluctuated in the second period. The one-tailed K-W test results indicate that, the efficiency increases of east China in the first and third periods are significant at 5% level. However, none of the efficiency increases of central and west China in the first and third periods can be statistically confirmed.

Figure 2 again clearly indicates that east China is more MEA efficient than central and west China in all of the three periods analyzed separately. However the efficiency difference between central and west China in these three periods are not obvious, especially during the early years of each period.

[Insert Figure 2 here]

The two-tailed K-W test results for the efficiency comparisons among China’s three areas are also shown in the last three columns of Table 2, which statistically confirm that the east area is significantly more efficient than the central area and the west area in all three periods and the central area is significantly more efficient than the west area just in the second and third periods (all at the significance level of 5%). However, the efficiency difference between the west area and the central area is not significant in the first period. Furthermore, for the single year’s MEA efficiencies obtained from the moving 3-year window analysis, as shown in the sixth to the nineteenth rows of Table 2, the MEA efficiency dominances of east China over central and west China are all significant at 5%

level, but none of the efficiency differences between the central area and the west area in each year during 1997-2010 is significant.

Thus, we can conclude that the east area overall is more MEA efficient than the other two areas of China during the whole study period, but there is no significant MEA efficiency difference between the central and the west areas during the same period.

This result is similar to those of most studies on China's regional energy efficiency, which shown that the east area has the best efficiency measurement. However, the efficiency difference between the west and the central area is mixed in previous studies. For example, Hu and Wang [4] and Shi et al. [7] indicate that the central area has the worst energy efficiency, but Choi et al. [3] and Yeh et al. [10] show that the west area suffered the lowest energy efficiency. In this study, we point out that, in fact, there is no significant difference in efficiency between the central and the west areas of China, since the economic growth mode, the energy consumption structure, and the character of CO_2 emissions of these two areas are close to each other. Compared with the other two areas, the east area is a more economically advanced area; therefore, its government can allocate additional capital and resources to environmental governance, emissions control, and energy efficiency technology in this area to support its sustainable development. However, the central and the west areas have relatively low levels of economic development, less developed transportation and communication networks, and poorer energy infrastructures, and some provinces still adopt old and less efficient energy utilization technologies; thus, the central and the west area still have low energy and emissions efficiencies.

6.2 Efficiency patterns and differences of China's regions

The above evaluation results indicate that east China has higher aggregated MEA efficiency than central and west China. However, the aggregated MEA efficiency just provides the efficiency levels and their increasing or decreasing trends for different regions and areas. To investigate the relative efficiencies on individual variables of each observation so as to discover the sources of inefficiency and detect the patterns of efficiency differences among different Chinese areas, we, in addition, calculate the relative variable specific MEA efficiencies through definition (3). Since in this study, there is a greater focus on energy and emissions specific efficiencies, here we having the MEA models (1) and (2) reducing only the energy and emissions variables whilst keeping the other variables fixed. This is reasonable because the variables of GDP and capital stock are not easily changeable or cannot be changed in the short run.

Figure 3 illustrates the average relative variable specific efficiencies (i.e. energy and emissions relative efficiencies). It seems that both of the variable specific efficiencies for Chinese three areas overall experienced a process of slight promotion over the study period. However, none of these overall efficiency promotions can be statistically confirmed by the one-tailed K-W test.

[Insert Figure 3 here]

From Figure 3, it can be seen that the east area is the most MEA efficient area in China since it consistently outperforms other Chinese areas on both of the two variable specific efficiencies. However, the relative variable specific efficiency differences between the central area and the west area are mixed. For the energy variable specific efficiency, it appears that central China continuously outperforms west China over the whole study period. But for the emissions variable specific efficiency, Figure 3 shows no obvious efficiency difference between central China and west China.

Figure 3 clearly illustrates that the efficiency patterns for the individual variables (energy and emissions) vary considerably for China's three areas, with the central area being consistently more efficient than the west area on energy efficiency, but with no obvious differences between them on emissions efficiency.

In order to further confirm the variable specific MEA efficiency differences, we again adopt the two-tailed K-W test to examine the efficiency differences among three areas for each of the variable specific efficiency. The results of the average variable specific MEA efficiencies and the tests, shown in the third row of Table 3, first indicate that, against the pooled frontier, the variable specific MEA efficiency dominances of east China over central and west China on both of the variables are significant at 1% level, and the efficiency dominance of central China over west China on energy variable is significant at 5% level. However, on emissions variable, there is no significant efficiency difference between central China and west China.

[Insert Table 3 here]

The test above is based on the pooled data set and is against the pooled frontier. We additionally adapt the two-tailed K-W test to examine the variable specific efficiency differences among Chinese three areas based on their single year's variable specific MEA efficiencies obtained from the window analysis, and the test results are shown in the fourth to the seventeenth rows of Table 3.

For energy specific efficiency, it can be seen that the efficiency dominances of the east area over the central area and the west area are all significant at 5% level in every year over the whole study period. However, the efficiency differences between the central area and the west area are significant just in few years over the whole study period (1999-2000, 2005 and 2010).

For emissions specific efficiency, it can been seen that, similarly, the efficiency dominances of the east area over the central area and west area are all significant at 5% level in every year over the whole study period. However, none of the efficiency differences between the central area and the west area are significant during the same period.

Therefore, it can be conclude that the significant aggregated MEA efficiency dominances of the east area over the central area and the west area are the contributions of both the significant higher energy variable specific efficiency and the significant higher emissions variable specific efficiency of the east area to the other two areas. However, the insignificant emissions variable specific efficiency difference between the central area and the west area in every year during the whole study period, as well as the insignificant energy variable specific efficiency difference between them in most years during the same period leads the aggregated MEA efficiency difference between these two areas insignificant.

The evaluation and test results given above indicate the differences in the efficiency levels and efficiency patterns on aggregated and variable specific MEA efficiencies among China's three areas. In order to investigate further the efficiency difference within each Chinese area, we calculate the coefficient of variation (CV) of the average MEA efficiency and variable specific MEA efficiencies for each Chinese area and the whole country, which are documented in Table 4.

[Insert Table 4 here]

In general, both the aggregated MEA efficiency differences and the variable specific efficiency differences within the west area are the largest, followed by the central area, and the efficiency differences within the east area are the smallest.

6.3 Efficiency related reduction potentials on energy and emissions of China's regions

According to the MEA theory, the variable specific inefficient regions can become efficient on each of their input and output variables and reach the benchmark by improvement potential adjustment associated with each of the variables. Therefore, in this section, we further use MEA to survey the energy saving potential and emissions reduction potential for different Chinese provinces and areas during the study period.

Based on the definition (3) in Section 4, the potential redundancy of each input variable could be calculated as $\beta_{j_0}^{t*}(x_{i,j_0}^{t} - d_{i,j_0}^{t*})$, and the target value of each input after improvement potential adjustment is $x_{i,j_0}^{t} - \beta_{j_0}^{t*}(x_{i,j_0}^{t} - d_{i,j_0}^{t*})$. Table 5 and Figures 4 and 5 respectively show the MEA relative energy saving and emissions reduction potentials and their percentages, as well as the adjusted targets of total energy consumption and total CO_2 emissions for different Chinese regions in 2010. Figure 6 shows the energy saving and emissions reduction potentials of three Chinese areas during the entire study period 1997-2010.

[Insert Figure 4 here]

[Insert Table 5 here]

Remarking on the comparatively high reduction potentials for certain regions shown in Table 5 and Figure 4, we should point out that the current calculations are not a benchmarking exercise per se, but rather, a discussion on the theoretically largest variable redundancy reductions under the MEA model framework. Therefore, we do not presume that the energy saving potential or emissions reduction potential indicated by the variable specific MEA efficiencies can in fact be fully realized. From Figure 4 and Table 5 we see that the MEA relative energy saving potentials of five provinces are more than 80 million tce in 2010, with Hebei has the largest energy saving potential, followed by Inner Mongolia, Shandong, Shanxi and Henan (in decreasing ranking). Hainan has the lowest energy saving potential in energy inefficient provinces, followed by Zhejiang, Jiangxi, Qinghai, and Guangxi (in ascending order). Furthermore, the potential for energy saving of eight provinces are zero in 2010. These provinces are Beijing, Tianjin, Liaoning, Shanghai, Anhui, Fujian, Guangdong, and Yunnan, which are all energy specific efficient provinces in China. We notice that, although Hebei has the highest energy saving potential, its potential energy saving rate is not the highest, and its energy efficiency score is not the lowest. Compared with Hebei, Qinghai and Ningxia's potential energy saving rates are higher, and their energy efficiency scores are also quite low. In addition, as well as Hebei, Qinghai and Ningxia, the potential energy saving rates of another five provinces, Shanxi, Inner Mongolia, Guizhou, Gansu and Xinjiang, are also more than 60%, and their energy specific efficiencies are all below 0.5.

These results indicate that the above provinces should pay greater attention to the implementations of their energy efficiency policies and energy efficiency management in order to reduce energy redundancies, promote energy utilization performance, and catch up with the high efficiency benchmark provinces. Furthermore, several provinces such as Shandong and Sichuan, although their energy efficiencies are highly ranked and their potential energy saving rates are ranked as medium in China, should also pay greater attention to seriously implementing the energy efficiency policies, because their total energy consumptions are ranked in the top 6 in China. Shandong's total energy consumption in 2010 is almost ten times of that of Ningxia (whose energy efficiency is the lowest in China), and the energy saving potential of Shandong is more than four times of that of Ningxia. Thus, compared with Ningxia, Shandong plays a more important role in China's efforts towards total energy saving and energy efficiency improvement.

Figure 4 and Table 5 also show similar results on emissions reduction potentials for Chinese provinces in 2010. The potential emissions reduction rates of Ningxia, Inner Mongolia, Gansu, Shanxi and Guizhou are highly ranked in China in 2010, and Ningxia has the highest rate. Hainan, Chongqing, Zhejiang, and Hunan's potential emissions reduction rates are below 25%, and the rate of Hainan is the lowest. Similarly to energy saving potential, Hebei has the largest MEA relative emissions reduction potential of more than 600 million tonnes of CO_2. The emissions reduction potentials of Shandong, Inner Mongolia, Shanxi and Henan are following and their potentials are all above 300 million t CO_2. The provinces with unit emissions efficiency scores and zero emissions reduction potentials are the same as the benchmark provinces under energy specific efficiency evaluation.

The above results indicate that, in general, the provinces of Hebei, Shanxi, Inner Mongolia, Gansu, Ningxia, and Guizhou should pay greater attention to their energy consuming related CO_2 emissions controls or mitigations in order to improve their emissions efficiencies, reduce their emissions redundancies, and catch up with the high-performing benchmark provinces. In addition, Shandong and Henan should also pay great attention to their emissions controls for their total CO_2 emissions are large and highly ranked in China.

The rates of emissions reduction potentials and energy saving potentials for the 30 Chinese provinces in 2010 are compared and illustrated in Figure 5. Among the 22 inefficient provinces, there are 17 provinces located above the diagonal line in Figure 5, and these provinces all have higher emissions reduction potential rates than energy saving potential rates. This means that, compared with the other 5 provinces, these provinces are more reliant on the high carbon intensive energy. Therefore, in order to increase their energy and emissions efficiencies, these provinces should focus mainly on adjusting their energy consumption structure to replace some of the fossil fuels with low carbon intensive energy and renewable energy, such as natural gas and hydropower.

[Insert Figure 5 here]

The other 5 provinces, which located below the diagonal line, have higher energy saving potential rates than emissions reduction potential rates. We note that, among these provinces, the shares of non-fossil fuel consumptions in the total energy consumptions of Qinghai, Sichuan, and Hunan are much higher than those of other provinces in China, and this may explain their comparatively low emissions reduction potential rates, since their energy consumption structures are low carbon intensive characterized. Therefore, in order to increase their energy and emissions efficiencies, these provinces should focus mainly on increasing their fossil fuel utilization efficiencies.

Furthermore, we point out that among the 30 Chinese regions, the provinces of Gansu, Inner Mongolia, Ningxia, Guizhou, Shanxi, Xinjiang, Hebei and Shandong should be paid close attention. Because these provinces are evaluated as hiving low energy and emissions efficiencies, and having both high MEA relative energy saving potentials and emissions reduction potentials, or are ranked highly in China with very large amounts of total energy consumptions and total CO_2 emissions. Therefore, they will continue to play the most important role in China's effort on energy conservation and emissions mitigation.

To sum up, as shown in Figure 6, the total MEA relative energy saving potential of China fluctuated slightly in the first period 1997-2000 and continuously increased from 2001 onwards, but the increase slowed down in the third period began from 2006, particularly for the east area, whose MEA relative energy saving potential remained stable during the period 2007-2010. The total MEA relative emissions reduction potential of China shows a trend towards similar variation as the total energy saving potential, but its increase accelerated during the third period. The central area has the largest energy saving potential and the east area has the largest emissions reduction potential among the three Chinese areas in 2001-2006. The reduction potentials of both energy saving and emission reduction of the west area are the smallest during the same period.

[Insert Figure 6 here]

6.4 Discussions on China's regional energy and emissions efficiency

Since the MEA approach measures the variable specific efficiency according to the improvement potential associated with each variable, the energy saving and emissions reduction potentials for each region identified above are closely linked with the energy and emissions efficiencies investigated. It can be clearly seen from Figures 3 and 6 that during the first period (1997-2000), the energy efficiencies of central and west China, as well as the emissions efficiencies of east and central China, increased slightly over time; thus, the MEA relative energy saving potentials and emissions reduction potentials of the corresponding areas slightly decreased at the same time. Then, during the second period (2001-2005), the emissions efficiency of west China and the energy efficiency of central China kept stable, which resulted in the MEA relative emissions reduction potentials and energy saving potentials of the corresponding areas also remaining stable. However, in the last year of the second period (2005) and during the third period (2006-2010), the emissions efficiency of east China underwent a process of sudden decrease and fluctuation; therefore, during the same period, the MEA relative emissions reduction potential of east China clearly increased in 2005 and remained at a relatively high level from 2006 onwards.

Starting in 1997, China's economy underwent a downturn due to the Asian financial crisis and domestic insufficient demand [2]; thus, during the first period 1997-2000, China's industrial energy intensity (energy consumption per unit of industrial value-added) decreased by about 25%, and the intensity decreases in most of the energy intensive industrial sub-sectors (e.g. the sectors of the smelting and press of ferrous metals, and the manufacture of non-metallic mineral products) were even more significant. In addition, the industrial energy consumption in China accounted for more than 70% of the nation's total energy consumption in 2005. Therefore, the decline of industrial energy intensity led directly the increase of energy efficiency and associated emissions efficiency over the first period.

Contrary to the first period, China's energy consumption grew faster than its economic growth in the second period 2001-2005; thus its energy intensity began to increase. During this period, China was undergoing a large-scale construction boom and most of its energy intensive industrial sub-sectors and products (steel, cement, electrolytic aluminum, etc.) have expanded rapidly. Particularly since 2002, China entered a new cycle of rapid economic growth and its industrialization and urbanization process has accelerated [2]. In addition, China's energy intensive and resource intensive economic growth mode did not substantially shift, and economic development still relied on low value-added but high energy-consuming industries over this period. Therefore, the energy and emissions efficiency of China fluctuated and even declined slightly over the second period.

Before 2005, the Chinese government did not pay great attention to energy conservation and energy efficiency, but from 2006, the central government recognized that the overly rapid growth on energy demand and associated emissions and pollutions were adverse to China's sustainable development. Thus, in 2006, the Chinese government clearly stated its goal of building a resource-saving and environment-friendly society, and further announced the goal of 20% reduction in energy intensity between 2006 and 2010. Several associated laws, regulations, policies and programs were additionally issued to support the realization of this goal. Therefore, it is likely that the government's effort in energy efficiency has played a role and begun to increase the energy and emissions efficiencies of China during the third period.

7 Conclusions

Evaluating the energy and emissions efficiency, and estimating the energy saving and emissions reduction potentials of China and its different regions, are considered crucial approaches for China to realize its goal of constructing a resource-saving and environment-friendly society, as the evaluation results may provide useful information for energy and environmental policy making and management both at the national and the provincial levels. In the study, we utilize the MEA approach to investigate China's regional energy and emissions efficiencies during the period 1997-2010. Not just the energy and emissions efficiency level and variance trend of China, but also the efficiency patterns and differences of Chinese 30 provinces and three areas are investigated.

The results of our empirical study are as follows. i) In general, the average MEA efficiency of China experienced an increasing process over our study period, particularly the MEA efficiency of the east area, which increased significantly during the period 1997-2000 and 2006-2010. ii) The east area overall is more MEA efficient than the central and the west areas of China over the whole study period, but there is no significant MEA efficiency difference between the central and the west areas over the same period. iii) The significant aggregated MEA efficiency outperformance of the east area over the central and the west areas are due to both the higher energy specific efficiency and the higher emission specific efficiency of the east area compared to the other two areas. iv) In general, the MEA efficiency differences and the variable specific efficiency differences within the west area are the largest, and those within the east area are the smallest, during our study period.

Since the MEA approach measures variable specific efficiency according to the improvement potential on each variable, the MEA relative energy saving potentials and emissions reduction potentials for different Chinese provinces and areas during our study period are also calculated in this study.

The calculation results first indicate that the provinces of Gansu, Inner Mongolia, Ningxia, Guizhou, Shanxi, Xinjiang, and Hebei should be paid close attentions to, as they have both high MEA relative energy saving potentials and emissions reduction potentials, and thus will play the most important roles in China's effort on energy conservation and emissions mitigation. Furthermore, among the 30 Chinese regions, 17 provinces (e.g., Shandong, Henan and Shaanxi) have higher emissions reduction potential rates and 5 provinces (e.g., Hunan and Qinghai) have higher energy saving potential rates, which indicates that, in order to increase MEA efficiency, and reduce the energy and emissions redundancies, for the former 17 regions, it will be more effective to adjust their energy consumption structures and replace some of their fossil fuels with low carbon intensive energy or renewable energy, and for the latter 5 regions, efforts to increase their fossil fuel utilization efficiencies should be given priority.

In China's 11th Five-Year Plan (2006-2010), a mandatory energy saving target was proposed by Chinese government, which was to reduce the national energy intensity by 20% by 2010, based on the 2005 level. This target was further disaggregated into the regional level and was assigned to different Chinese provinces. Nineteen regions, such as Beijing, Liaoning, Shanghai, and Hunan, were assigned a 20% reduction burden; four regions (Shanxi, Inner Mongolia, Jilin, and Shandong) were assigned a 22% reduction burden; and the burdens of the remaining seven regions were between 12% (e.g., Hainan) and 17% (e.g., Yunnan), which are all below the national level. According to the regional GDP of the 30 Chinese provinces during the period 2006-2010, we translate each province's energy intensity reduction target into the absolute energy saving target and further calculate the total amount of energy saving over 2006-2010 for each province. These regional total amount energy savings, which are considered the government assigned energy saving targets, are, in addition, compared with the MEA relative energy saving potentials (2006-2010) of the 30 Chinese regions identified in this study.

The comparison shows that, firstly, for the 14 regions of Jilin, Heilongjiang, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangxi, Chongqing, Sichuan, Shaanxi, Hebei, Shanxi, and Inner Mongolia, the government energy saving target assigned to each of these regions is respectively quite close to their respective MEA relative energy saving potential. This indicates that the government targets for these regions are reasonable and could be achieved with comparatively little difficulty. Then, for another 7 regions (Beijing, Tianjin, Liaoning, Shanghai, Jiangsu, Zhejiang and Guangdong), although their MEA relative energy saving potentials are comparatively low (because these 7 regions are evaluated with high energy and emissions efficiencies under MEA framework), the government energy saving targets assigned to them are considered reasonable and achievable, as these 7 regions are all economically well-developed regions in China, and have the ability to invest more in the replacement of energy consuming equipment and in CO_2 emissions control in industry, and to allocate more resources on adjusting the energy consumption structure so as to promote their energy utilization efficiency. Thirdly, there are also several regions whose energy saving targets assign by the government are comparatively lower than their MEA relative energy saving potentials. These regions include Guizhou, Gansu, Ningxia, and Xinjiang, whose MEA relative energy saving potentials are higher than their assigned targets by about 10-16%. However, it should be noticed that all these regions are the least-developed provinces of west China, and considering their less-developed economies, low incomes and high carbon intensive energy resource endowments, their low assigned energy saving targets are also reasonable which could balance their economic growths and energy intensity reductions.

As the energy and emissions efficiency evaluation for the 30 Chinese regions in this study is based on the general variables of total energy consumption and total CO_2 emissions, as well as on the use of the overall data of regional economic status, the effects of different energy consumption structures and economic structures for different regions on the efficiency evaluation results cannot be investigated at present. This should be considered as one future improvement on this study regarding the application of the MEA model. In addition, an evaluation of regional energy and emissions efficiency should also be specifically carried out in the industrial sector (for it is the largest energy consumer and largest CO_2 emitter in China), in order to delve more deeply into the issue of investigating the efficiency patterns of different regions, and providing more specific suggestions for energy and emissions policy making. This is considered another potential improvement on this study.

Acknowledgement

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions. The authors also gratefully acknowledge the financial support from the National Natural Science Foundation of China under grants nos. 71101011, 71020107026; the China Postdoctoral Science Foundation under grant nos. 20110490298, 2012T50049; and the National Basic Research Program of China under grant no. 2012CB95570004.

References

[1] Zhou N, Levine MD, Price L. Overview of current energy-efficiency policies in China. Energy Policy 2010;38:6439-52.

[2] Liao H, Fan Y, Wei YM. What induced China's energy intensity to fluctuate: 1997-2006. Energy Policy 2007;35:4640-9.

[3] Choi Y, Zhang N, Zhou P. Efficiency and abatement costs of energy-related CO_2 emissions in China: A slacks-based efficiency measure. Appl Energy 2012;98:198-208.

[4] Hu JL, Wang SC. Total-factor energy efficiency of regions in China. Energy Policy 2006;34:3206-17.

[5] Watanabe M, Tanaka K. Efficiency analysis of Chinese industry: A directional distance function approach. Energy Policy 2007;35:6323-31.

[6] Bian YW, Yang F. Resource and environment efficiency analysis of provinces in China: A DEA approach based on Shannon's entropy. Energy Policy 2010;38:1909-17.

[7] Shi GM, Bi J, Wang JN. Chinese regional industrial energy efficiency evaluation based on a DEA model of fixing non-energy inputs. Energy Policy 2010;38:6172-9.

[8] Zhang B, Bi J, Fan Z, Yuan Z, Ge J. Eco-efficiency analysis of industrial system in China: A data envelopment analysis approach. Ecol Econ 2008;68:306-16.

[9] Wang K, Yu S, Zhang W. China's regional energy and environment efficiency: A DEA window analysis based dynamic evaluation. Math Comput Model 2011. http://dx.doi.org/10.1016/j.mcm.2011.11.067.

[10] Yeh TL, Chen TY, Lai PY. A comparative study of energy utilization efficiency between Taiwan and China. Energy policy 2010;38:2386-94.

[11] Wang K, Wei YM, Zhang X. A comparative analysis of China's regional energy and emission performance: Which is the better way to deal with undesirable outputs? Energy Policy 2012;46:574-84.

[12] Wang ZH, Zeng HL, Wei YM, Zhang YX. Regional total factor energy efficiency: An empirical analysis of industrial sector in China. Appl Energy 2012;97:115-23.

[13] Wang Q, Zhou P, Zhou D. Efficiency measurement with carbon dioxide emissions: The case of China. Appl Energy 2012;90:161-6.

[14] Wu F, Fan LW, Zhou P, Zhou DQ. Industrial energy efficiency with CO_2 emissions in China: A nonparametric analysis. Energy Policy 2012;49:164-72.

[15] Bogetoft P, Hougaard JL. Efficiency evaluations based on potential (non-proportional) improvements. J Product Anal 1998;12:233-47.

[16] Wang K, Zhang X, Wei YM, Yu S. Regional allocation of CO_2 emissions allowance over provinces in China by 2020. Energy Policy 2012; in press.

[17] Ang BW. Monitoring changes in economy-wide energy efficiency: from energy-GDP ratio to composite efficiency index. Energy Policy 2006;34:574-82.

[18] Mukherjee K. Energy use efficiency in US manufacturing: a nonparametric analysis. Energy Econom 2008;30:76-96.

[19] Hailu A, Veeman TS. Non-parametric productivity analysis with undesirable outputs: An application to the Canadian pulp and paper industry. American J Agric Econom 2001;83:605-16.

[20] Honma S, Hu JL. Total-factor energy efficiency of regions in Japan. Energy Policy 2008;36:821-33.

[21] Hu JL, Kao CH. Efficient energy-saving targets for APEC economies. Energy Policy 2007;35:373-82.

[22] Zhou P, Poh KL, Ang BW. A non-radial DEA approach to measuring environmental performance. Eur J Oper Res 2007;178:1-9.

[23] Halkos GE, Tzeremes NG. Exploring the existence of Kuznets curve in countries' environmental efficiency using DEA window analysis. Ecol Econ 2009;68:2168-76.

[24] Mukherjee K. Measuring energy efficiency in the context of an emerging economy: The case of Indian manufacturing. Eur J Oper Res 2010;201:933-41.

[25] Mandal SK. Do undesirable output and environmental regulation matter in energy efficiency analysis? Evidence from Indian Cement Industry. Energy Policy 2010;38:6076-83.

[26] Lee JD, Park JB, Kim TY. Estimation of the shadow prices of pollutants with production/environment inefficiency taken into account: A nonparametric directional distance function approach. J Environ Manag 2002;64:365-75.

[27] Bogetoft P, Hougaard JL. Super efficiency evaluations based on potential slack. Eur J Oper Res 2004;152:14-21.

[28] Asmild M, Pastor JT. Slack free MEA and RDM with comprehensive efficiency measures. Omega 2010;38:475-83.

[29] Asmild M, Holvad T, Hougaard JL, Kronborg D. Railway reforms: do they influence operating efficiency? Transp 2009;36:617-38.

[30] Holvad T, Hougaard JL, Kronborg D, Kvist HK. Measuring inefficiency in the Norwegian bus industry using multi-directional efficiency analysis. Transp 2004;31:349-69.

[31] Asmild M, Matthews K. Multi-directional efficiency analysis of efficiency patterns in Chinese banks 1997-2008. Eur J Oper Res 2012;219:434-41.

[32] Asmild M, Hougaard JL, Kronborg D, Kvist HK. Measuring inefficiency via potential improvements. J Product Anal 2003;19:59-76.

[33] Wu Y. China's capital stock series by region and sector. The University of Western Australia Discussion Paper. 09.02; 2009.

[34] IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume II Energy. Japan: Institute for Global Environmental Strategies; 2006.

[35] Liu LC, Wang JN, Wu G, Wei YM. China's regional carbon emissions change over 1997-2007. Int J Energy & Environ 2010;1:161-76.

[36] Hollander M, Wolfe DA. Nonparametric Statistical Methods. New York: John Wiley & Sons Inc.; 1999.

[37] Charnes A, Cooper WW, Lewin AY, Seiford LM. Data envelopment analysis: Theory, methodology, and application. Norwell: Kluwer Academic Publishers; 1994.

Table and figure captions

Table 1 Descriptive statistics of inputs and outputs (4 selected years between 1997 and 2010 for 30 regions)

Table 2 Comparisons of average aggregated MEA efficiencies in different subsamples and significance of ranking tests

Table 3 Comparisons of average relative variable specific efficiencies in different subsamples and significance of ranking tests

Table 4 Coefficient of variation (CV) for MEA efficiency and variable specific efficiencies

Table 5 MEA relative energy saving and emissions reduction potentials of 30 Chinese regions in 2010

Figure 1 Average aggregated MEA efficiencies of three areas of China across the whole observation period (1997-2010)

Figure 2 Average aggregated MEA efficiencies of three areas of China within three separate periods (1997-2000; 2001-2005; 2006-2010)

Figure 3 Average relative variable specific efficiencies of three areas of China (1997-2010)

Figure 4 MEA relative energy saving and emissions reduction potentials of 30 Chinese regions (2010)

Figure 5 MEA relative energy saving and emissions reduction potential rates of 30 Chinese regions (2010)

Figure 6 MEA relative energy saving and emissions reduction potentials of three areas of China (1997-2010)

Tables and figures

Table 1 Descriptive statistics of inputs and outputs (4 selected years between 1997 and 2010 for 30 regions)

Inputs and outputs	Year	1997	2001	2006	2010
Energy	Mean	45.9	51.3	96.8	129.8
(million tce)	Std. dev.	25.1	28.5	60.5	79.7
	Max	94.7	106.6	267.6	348.1
	Min	3.9	5.2	9.2	13.6
Labor	Mean	21.2	21.0	23.1	25.6
(million people)	Std. dev.	13.7	14.1	15.4	17.2
	Max	50.2	55.2	56.9	60.4
	Min	2.3	2.4	2.7	2.9
Capital	Mean	123.4	198.5	395.5	724.1
(billion RMB)	Std. dev.	121.6	197.0	383.0	685.3
	Max	486.0	726.6	1287.0	2326.7
	Min	9.2	14.8	27.6	49.5
GDP	Mean	343.1	491.2	897.1	1455.1
(billion RMB)	Std. dev.	258.6	384.8	745.8	1184.2
	Max	1034.3	1515.7	2941.8	4601.3
	Min	32.0	46.1	82.6	135.0
CO_2	Mean	104.9	115.9	220.5	313.3
(million tCO_2)	Std. dev.	57.1	65.7	144.4	200.6
	Max	234.4	281.1	632.1	856.8
	Min	7.1	8.5	17.7	26.5

Table 2 Comparisons of average aggregated MEA efficiencies in different subsamples and significance of ranking tests

Data set	Period	Average efficiency of east China	Average efficiency of central China	Average efficiency of west China	Diff. east-central	Diff. east-west	Diff. central-west
Pooled	1997-2010	0.647	0.472	0.439	SIG**	SIG**	SIG*
Three periods	1997-2000	0.727	0.497	0.457	SIG*	SIG*	INSIG
	2001-2005	0.752	0.515	0.472	SIG*	SIG*	SIG*
	2006-2010	0.756	0.535	0.491	SIG*	SIG*	SIG*
Window analysis	1997	0.645	0.436	0.430	SIG*	SIG*	INSIG
	1998	0.714	0.478	0.445	SIG*	SIG*	INSIG
	1999	0.761	0.518	0.454	SIG*	SIG*	INSIG
	2000	0.763	0.527	0.469	SIG*	SIG*	INSIG
	2001	0.790	0.537	0.478	SIG*	SIG*	INSIG
	2002	0.787	0.539	0.509	SIG*	SIG*	INSIG
	2003	0.796	0.565	0.507	SIG*	SIG*	INSIG
	2004	0.799	0.576	0.512	SIG*	SIG*	INSIG
	2005	0.768	0.569	0.507	SIG*	SIG*	INSIG
	2006	0.768	0.561	0.512	SIG*	SIG*	INSIG
	2007	0.785	0.548	0.509	SIG*	SIG*	INSIG
	2008	0.786	0.551	0.499	SIG*	SIG*	INSIG
	2009	0.804	0.558	0.504	SIG*	SIG*	INSIG
	2010	0.814	0.570	0.513	SIG*	SIG*	INSIG

Diff. indicate difference between two areas; SIG and INSIG indicate significant and insignificant; * and ** indicate significance at 5% and 1% levels under two-tailed K-W test.

Table 3 Comparisons of average relative variable specific efficiencies in different subsamples and significance of ranking tests

Data set	Period	Energy specific efficiency						Emissions specific efficiency					
		East	Central	West	Diff. E-C	Diff. E-W	Diff. C-W	East	Central	West	Diff. E-C	Diff. E-W	Diff. C-W
Pooled	1997-2010	0.691	0.539	0.459	SIG**	SIG**	SIG*	0.603	0.404	0.419	SIG**	SIG**	INSIG
Window analysis	1997	0.680	0.501	0.446	SIG*	SIG*	INSIG	0.611	0.371	0.413	SIG*	SIG*	INSIG
	1998	0.762	0.549	0.462	SIG*	SIG*	INSIG	0.665	0.406	0.428	SIG*	SIG*	INSIG
	1999	0.801	0.587	0.469	SIG*	SIG*	SIG*	0.720	0.449	0.440	SIG*	SIG*	INSIG
	2000	0.780	0.598	0.491	SIG*	SIG*	SIG*	0.747	0.456	0.447	SIG*	SIG*	INSIG
	2001	0.819	0.601	0.494	SIG*	SIG*	INSIG	0.761	0.474	0.461	SIG*	SIG*	INSIG
	2002	0.801	0.606	0.526	SIG*	SIG*	INSIG	0.773	0.472	0.493	SIG*	SIG*	INSIG
	2003	0.811	0.614	0.522	SIG*	SIG*	INSIG	0.782	0.516	0.492	SIG*	SIG*	INSIG
	2004	0.815	0.619	0.520	SIG*	SIG*	INSIG	0.782	0.532	0.505	SIG*	SIG*	INSIG
	2005	0.800	0.610	0.507	SIG*	SIG*	SIG*	0.736	0.529	0.508	SIG*	SIG*	INSIG
	2006	0.803	0.595	0.501	SIG*	SIG*	INSIG	0.733	0.526	0.524	SIG*	SIG*	INSIG
	2007	0.820	0.595	0.499	SIG*	SIG*	INSIG	0.751	0.501	0.519	SIG*	SIG*	INSIG
	2008	0.819	0.600	0.501	SIG*	SIG*	INSIG	0.753	0.501	0.498	SIG*	SIG*	INSIG
	2009	0.836	0.612	0.510	SIG*	SIG*	INSIG	0.771	0.504	0.497	SIG*	SIG*	INSIG
	2010	0.851	0.629	0.518	SIG*	SIG*	SIG*	0.777	0.511	0.507	SIG*	SIG*	INSIG

Diff. indicate difference between two areas; SIG and INSIG indicate significant and insignificant; * and ** indicate significance at 5% and 1% levels under two-tailed K-W test.

Table 4 Coefficient of variation (CV) for MEA efficiency and variable specific efficiencies

CV	Energy efficiency	Emissions efficiency	MEA efficiency
China	0.391	0.462	0.419
East China	0.273	0.343	0.304
Central China	0.322	0.424	0.359
West China	0.487	0.533	0.503

Table 5 MEA relative energy saving and emissions reduction potentials of 30 Chinese regions in 2010

2010	Energy saving potential	Energy saving potential rate	Total energy consumption	Energy specific efficiency	Emissions reduction potential	Emissions reduction potential rate	Total CO_2 emissions	Emissions specific efficiency
Beijing	0.0	0%	69.5	1.000	0.0	0.0%	116.2	1.000
Tianjin	0.0	0%	68.2	1.000	0.0	0.0%	154.0	1.000
Hebei	159.3	58%	275.3	0.421	615.5	74.4%	827.4	0.256
Shanxi	113.2	67%	168.1	0.327	338.9	76.7%	442.0	0.233
In. Mongolia	106.7	63%	168.2	0.365	437.6	80.4%	544.1	0.196
Liaoning	0.0	0%	209.5	1.000	0.0	0.0%	558.6	1.000
Jilin	33.4	40%	83.0	0.597	137.5	60.2%	228.3	0.398
Heilongjiang	48.1	43%	112.3	0.572	109.3	46.6%	234.6	0.534
Shanghai	0.0	0%	112.0	1.000	0.0	0.0%	220.3	1.000
Jiangsu	23.4	9%	257.7	0.909	237.6	35.7%	665.6	0.643
Zhejiang	5.8	3%	168.7	0.966	70.3	18.8%	374.3	0.812
Anhui	0.0	0%	97.1	1.000	0.0	0.0%	276.9	1.000
Fujian	0.0	0%	98.1	1.000	0.0	0.0%	209.2	1.000
Jiangxi	17.0	27%	63.6	0.733	73.4	48.5%	151.1	0.515
Shandong	126.7	36%	348.1	0.636	454.3	53.0%	856.8	0.470
Henan	83.6	39%	214.4	0.610	337.2	58.6%	575.5	0.414
Hubei	51.0	34%	151.4	0.663	186.3	48.2%	386.6	0.518
Hunan	43.1	29%	148.8	0.710	65.3	22.7%	288.0	0.773
Guangdong	0.0	0%	269.1	1.000	0.0	0.0%	500.1	1.000
Guangxi	18.4	23%	79.2	0.768	70.4	36.4%	193.5	0.636
Hainan	0.5	3%	13.6	0.965	0.3	1.1%	26.5	0.989
Chongqing	24.9	32%	78.6	0.683	21.9	15.9%	138.1	0.841
Sichuan	66.8	37%	178.9	0.626	82.1	26.1%	315.3	0.739
Guizhou	54.9	67%	81.8	0.329	161.2	76.3%	211.1	0.237
Yunnan	0.0	0%	86.7	1.000	0.0	0.0%	215.9	1.000
Shaanxi	33.2	37%	88.8	0.626	128.3	56.4%	227.4	0.436
Gansu	38.9	66%	59.2	0.343	114.0	77.1%	147.9	0.229
Qinghai	18.1	70%	25.7	0.297	19.4	58.3%	33.2	0.417
Ningxia	27.0	73%	36.8	0.267	80.6	81.6%	98.7	0.184
Xinjiang	53.6	65%	82.9	0.353	131.2	71.8%	182.6	0.282
China	1147.6	29%	3895.1	0.692	3872.2	41.2%	9399.7	0.625
East China	397.1	19%	2085.1	0.851	1624.7	32.7%	4971.9	0.777
Central China	447.8	41%	1100.3	0.629	1566.8	54.2%	2891.5	0.511
West China	302.6	43%	709.8	0.518	680.7	44.3%	1536.3	0.507

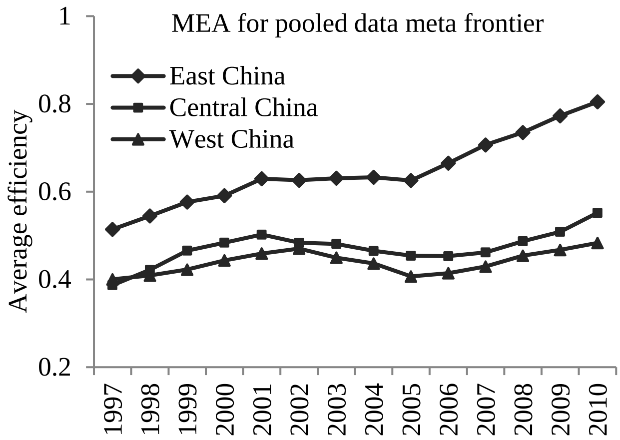

Figure 1 Average aggregated MEA efficiencies of three areas of China across the whole observation period (1997-2010)

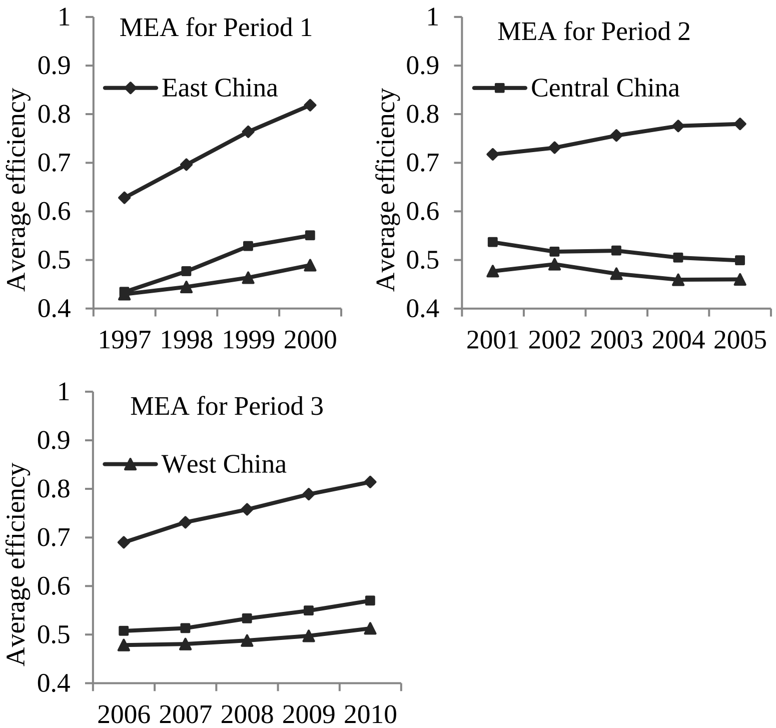

Figure 2 Average aggregated MEA efficiencies of three areas of China within three separate periods (1997-2000; 2001-2005; 2006-2010)

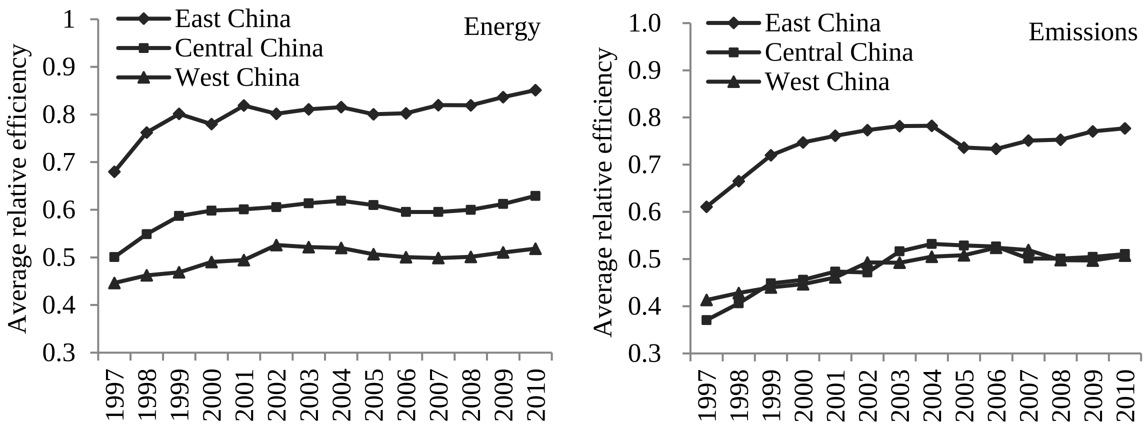

Figure 3 Average relative variable specific efficiencies of three areas of China (1997-2010)

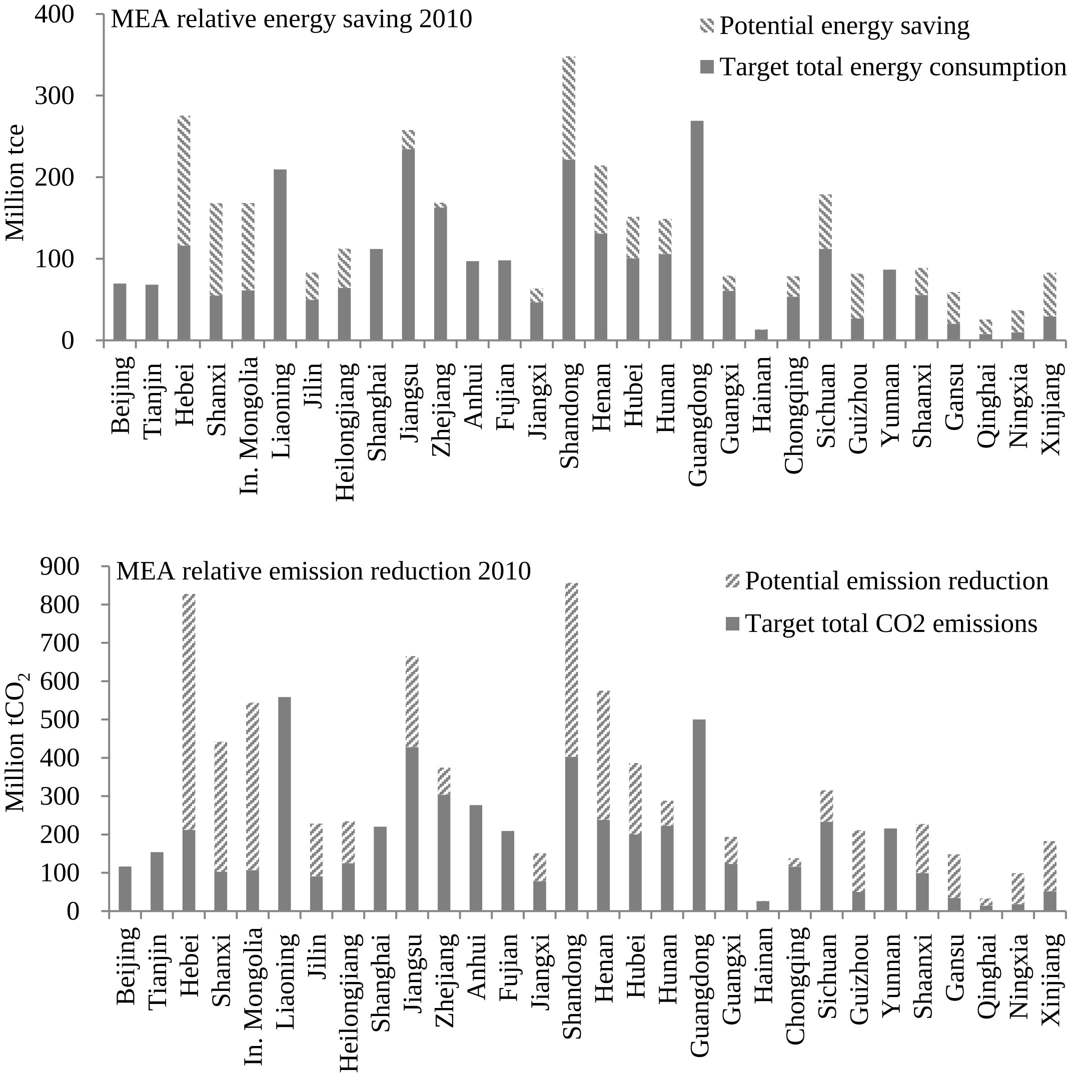

Figure 4 MEA relative energy saving and emissions reduction potentials of 30 Chinese regions (2010)

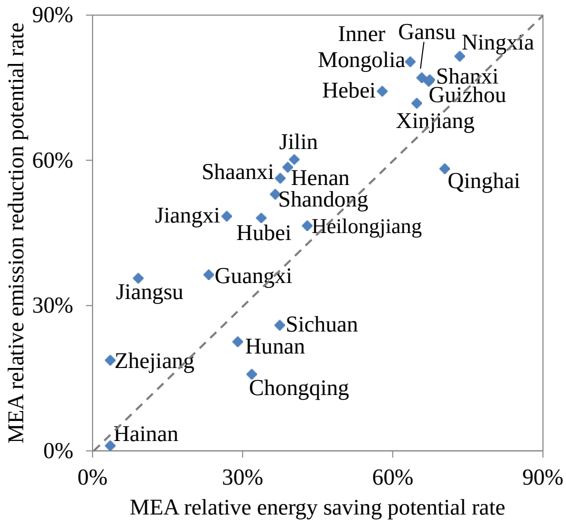

Figure 5 MEA relative energy saving and emissions reduction potential rates of 30 Chinese regions (2010)

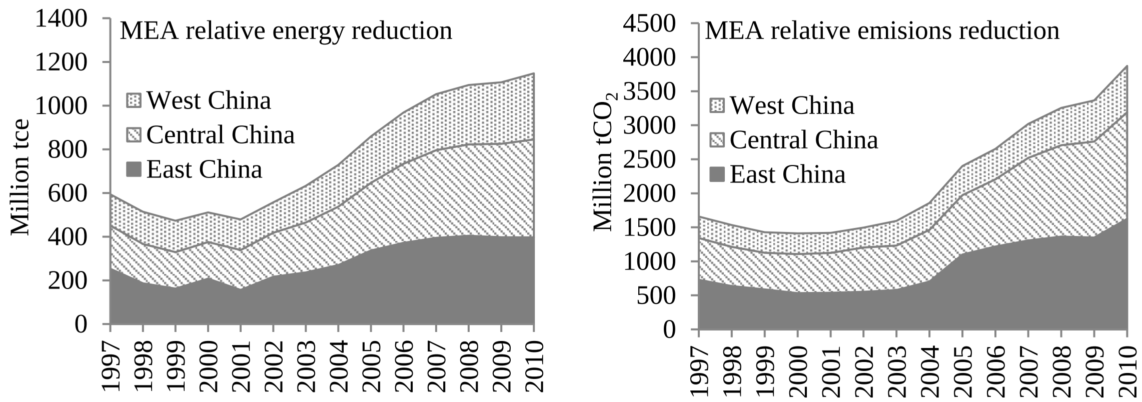

Figure 6 MEA relative energy saving and emissions reduction potentials of three areas of China (1997-2010)