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China's regional energy and environmental efficiency: A Range-Adjusted Measure based analysis

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Abstract: Energy and environmental efficiency evaluation has recently attracted increasing interest in China. In this study, we utilize the Range-Adjusted Measure (RAM) based nonparametric approach to evaluate the regional energy and environmental efficiency of China over the period of 2006-2010. The desirable/good and undesirable/bad outputs, as well as the energy and non-energy inputs are considered in the efficiency evaluation so as to characterize the energy consumption, economic production, and CO_2 emission process of different China's regions. In addition, the economic concepts of natural disposability and managerial disposability are incorporated in the evaluation instead of the strong and weak disposability in conventional environmental efficiency evaluation. Therefore, the types of returns to scale and damages to scale of different China's regions are measured and correspondingly the strategy and policy implications are proposed for guiding the future improvement of regional energy and environmental efficiency. This study finds that: i) Beijing, Shanghai, and Guangdong had the highest integrated energy and environmental efficiency during the study period, which could be seen as the benchmarks of inefficient China's regions. ii) On average, east China had the highest integrated efficiency under natural disposability, and west China had the highest integrated efficiency under managerial disposability. iii) During 2006-2010, the average production efficiency of China slightly decreased and the average emission efficiency of China slightly increased. v) Among China's 30 regions, 19 regions exhibited decreasing returns to scale, 4 regions shown increasing returns to scale, and 7 regions have mixed returns to scale types under natural disposability in our study period. In addition, under managerial disposability, there are 18, 3 and 9 regions respectively exhibited increasing, decreasing and mixed damages to scale types over time. v) For most Chinese regions, it is not recommended to simply increase or maintain their current scales of production, but alternatively, they should pay more attentions on technology innovation of energy utilization efficiency improvement, since up to 2010, China still had large energy conservation and emission reduction potentials.

Keywords: Energy and environmental efficiency, Range-Adjusted Measure (RAM), Returns to scale, Damages to scale

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1 Introduction

In recent years, energy performance and environmental performance evaluation issues has attracted increasing interest since they are considered a crucial approach to save energy, reduce greenhouse gas emissions, protect environment and mitigate global climate change. Despite the major energy performance improvements achieved by China during the last two decades, the rapid development of economy has substantially increased China's primary energy consumption and leaded to serious environmental problems due to the yearly increasing emissions of CO_2 and other pollutants [1]. In addition, since different regions of China have different energy consumption structures, different economic growth modes, and different energy saving and environment protection policies, the regional energy and environmental performance of China may vary significantly across different regions. Hence, it is meaningful to evaluate China's regional energy and environmental efficiency, which can assist the energy and environmental policy making for Chinese government both at the national and regional levels.

The evaluation of energy and environmental performance is often in the form of energy or environmental efficiency indices which can be constructed through mathematics programming methods such as conventional data envelopment analysis (DEA) models [2,3], non-radial DEA models [4], range-adjusted measure based DEA (RAM-DEA) models [5], and directional distance function (DDF) models [6,7].

At the macro-economy level, DEA approach has recently been widely applied to studying the energy and environmental efficiency for it provides an appropriate method to deal with multiple inputs and outputs in examining relative efficiency [3]. For instance, Hu and Wang [8] proposed a total-factor energy efficiency evaluation DEA model and measured the energy efficiency of 29 regions in China. Zhou et al. [9] developed several environmental DEA technologies and measured the carbon emission efficiency of eight world regions. Yeh et al. [10] calculated the technical efficiency of energy utilization in Chinese mainland and Taiwan by using the traditional BCC model [11]. Wang et al. [12] developed a mixed energy economic-environmental efficiency model to measure the environmental efficiency, economic efficiency, and economic-environmental efficiency of 28 provinces in China for the period of 2001-2007. Bian and Yang [13] proposed several DEA models to simultaneously measure resource and environmental efficiency and applied their models in efficiency evaluation of 30 Chinese provinces. Shi et al. [14] presented three extended DEA model to calculate the energy and environmental overall technical efficiency, pure technical efficiency, and scale efficiency of 28 administrative regions in China. Wang et al. [4] established several DEA window analysis models to measure the energy and environmental efficiency of 29 administrative regions of China using cross-sectional and time-varying data and proposed a dynamic evaluation result.

Since Färe and Grosskopf [15] and Zhou and Ang [16] incorporated undesirable outputs in measuring efficiency, many researchers have considered undesirable outputs in energy efficiency evaluation. Here, we point out that most of the previous researches are built upon the concept of weak and strong disposability in environmental performance evaluation [17]. If we consider $\boldsymbol{X}$ as an input vector and $\boldsymbol{G}$ as a desirable output vector, then production technology can be considered as P: $\boldsymbol{X} \rightarrow P(\boldsymbol{X})$, where the set $P(\boldsymbol{X})$ denotes that the output vector $\boldsymbol{G}$ is producible by the input vector $\boldsymbol{X}$. The weak disposability on $\boldsymbol{G}$

can be specified by $G \in P(X) \Rightarrow \theta G \in P(X)$ for all $0 \le \theta \le 1$, and the strong disposability on $\boldsymbol{G}$ can be specified by $G' \le G \in P(X) \Rightarrow G' \in P(X)$. However, this concept, associated with radial DEA model, is not sufficient, since the weak disposability assumes that all the decision making units (DMUs) yield a unified abatement on input factors for using only one efficiency score [18]. In addition, the previous researches never measured the returns to scale and damages to scale under the energy and environmental efficiency evaluation framework. Therefore, in this study, following Sueyoshi and Goto [19-21], we evaluate the regional energy and environmental efficiency of China by applying Range-Adjusted measure based DEA models. The RAM-DEA models are non-radial models and they measure the energy and environmental efficiency by slacks, therefore, the evaluation framework in this study is different from the previous ones and not only the regional efficiency levels for China are measured, but the types of returns to scale and damages to scale for each region are explored, which is considered more meaningful for policy-making regarding how to improve the effect of energy conservation, greenhouse gas emission reduction, and environment protection for each region of China.

The rest of this paper is organized as follows: Section 2 proposes the RAM-DEA model and several indicators for integrated energy and environmental efficiency measurement under natural disposability and managerial disposability, respectively. The related approaches for determining returns to scale and damages to scale are also presented in Section 2. In Section 3, the regional energy and environmental efficiency, the types of returns and damages to scale, as well as the RAM-DEA based energy conservations and CO_2 emissions reduction potentials for China's 30 regions during 2006-2010 are evaluated and analyzed. Furthermore, the strategies and policy implications for integrated energy and environmental efficiency improvement are also discussed in Section 3. Section 4 concludes this paper.

2 Methodology

In this study, we apply the range-adjusted measure based DEA (RAM-DEA) models, which is first proposed by Cooper et al. [22] and then further developed by Sueyoshi and Goto [20] in environmental strategy, to measure China's regional energy and environmental efficiency. Since the RAM-DEA models can easily combine both energy performance and environmental performance for each DMU under a unified treatment, this non-radial method is considered to be more appropriate than the traditional radial DEA models which have difficulty is combining the above two performances. In addition, as discussed by Sueyoshi and Goto [20], there are two concerns on the definitions of strong and weak disposability. The first concern is that the above two concepts of disposability are proposed for environmental efficiency evaluation under radial DEA framework, in which a single efficiency measure (score) need to be incorporated and thus the assumption of weak disposability is needed. However, under non-radial DEA framework, to distinguish between weak and strong disposability is not necessary, since there is no need to incorporate a unified efficiency measure (score) in the non-radial model. The second concern is that the directional vector of inputs is not specified under strong and weak disposability within radial DEA model, but can be defined under

RAM-DEA model and give rise to several new concepts on disposability from operational and environmental strategy point of view, and thus provide deeper insight into energy and environmental efficiency measure of China, which, to our knowledge, has been never discussed in previous studies on China's regional energy and environmental efficiency evaluation. Therefore, in this study, we apply the RAM-DEA models proposed in Sueyoshi and Goto [20] for evaluation.

In applying RAM-DEA models, we first give the interpretation of two concepts proposed in Sueyoshi and Goto [20]: natural disposability and managerial disposability. Natural disposability indicates that a DMU can decrease its directional vector of inputs so as to decrease the directional vector of bad outputs. Then, given a decreased vector of inputs, the DMU tries to increase its directional vector of good outputs as much as possible. As an opposite concept to the natural disposability, the managerial disposability indicates that a DMU increases its directional vector of inputs to decrease the directional vector of bad outputs. Then, given the increased vector of inputs, the DMU tries to increase the directional vector of good outputs as much as possible.

2.1 Integrated energy and environmental efficiency under natural disposability

Following [20], we consider there are n regions (DMUs) in this study. Each region (DMU$_j$, j=1,…,n) uses m inputs $\boldsymbol{X}_j=(x_{1j},\dots,x_{mj})$, such as energy, capital and labor, to produce both s desirable (good) outputs $\boldsymbol{G}_j=(g_{1j},\dots,g_{sj})$, like industrial added value or GDP, and f undesirable (bad) outputs $\boldsymbol{B}_j=(b_{1j},\dots,b_{fj})$, like CO_2 emissions and other pollutions as byproducts. We first present the following RAM-DEA model for evaluating the energy and environmental efficiency of a specific region (DMU$_k$) under natural disposability:

$$
\begin{aligned}
\max\ & \sum\nolimits_{i=1}^{m} R_i^x d_i^x + \sum\nolimits_{r=1}^{s} R_r^g d_r^g + \sum\nolimits_{f=1}^{h} R_f^b d_f^b \\
s.t.\ \ & \sum\nolimits_{j=1}^{n} x_{ij}\lambda_j + d_i^x = x_{ik},\ i=1,\dots,m, \\
& \sum\nolimits_{j=1}^{n} g_{rj}\lambda_j - d_r^g = g_{rk},\ r=1,\dots,s, \\
& \sum\nolimits_{j=1}^{n} b_{fj}\lambda_j + d_f^b = b_{fk},\ f=1,\dots,h, \qquad\qquad (1) \\
& \sum\nolimits_{j=1}^{n} \lambda_j = 1, \\
& \lambda_j \ge 0,\ j=1,\dots,n,\quad d_i^x \ge 0,\ i=1,\dots,m, \\
& d_r^g \ge 0,\ r=1,\dots,s,\quad d_f^b \ge 0,\ f=1,\dots,h.
\end{aligned}
$$

In Model (1), $\lambda_j\,(j=1,\dots,n)$ is the intensity variables associated with each DMU$_j$. $d_i^x\,(i=1,\dots,m)$, $d_r^g\,(r=1,\dots,s)$, and $d_f^b\,(f=1,\dots,h)$ are all slack variables. R are the ranges determined by the upper and lower bounds of inputs and both good and bad outputs. The upper and lower bounds of the ith inputs are calculated as $\overline{x}_i = \max_j\{x_{ij}\}$ and $\underline{x}_i = \min_j\{x_{ij}\}$. The range for the ith input then becomes $R_i^x = 1/[(m+s+h)(\overline{x}_i - \underline{x}_i)]$.

Similarly, the range for the rth good output is $R_r^g = 1/[(m+s+h)(\overline{g}_r - \underline{g}_r)]$ and the range for the fth bad output is $R_f^b = 1/[(m+s+h)(\overline{b}_f - \underline{b}_f)]$.

We point out that, in Model (1), the undesirable outputs are treated like inputs, which has no essential difference with strong disposability concept. Under the concept of natural disposability associated with Model (1), an integrated energy and environmental efficiency indicator and a production efficiency indicator could be defined as:

Integrated Efficiency under Natural Disposability (*IEND*) =
$1-\left(\sum_{i=1}^{m} R_i^x d_i^{x*} + \sum_{r=1}^{s} R_r^g d_r^{g*} + \sum_{f=1}^{h} R_f^b d_f^{b*}\right)$.

Production Efficiency (*PE*) = $1-\left(\sum_{i=1}^{m} R_i^x d_i^{x*} + \sum_{r=1}^{s} R_r^g d_r^{g*}\right)$.

All slacks here are determined through optimizing the objective value of Model (1), and the optimized objective value indicates the level of inefficiency under natural disposability. The efficiency measure of *IEND* incorporates the inputs and both the good and bad outputs; however *PE* does not incorporate the bad outputs. Therefore *PE* mainly measures the energy and other inputs utilization, and desirable output production performance but ignores the environmental or emission factor.

Model (1) has the following dual programming:

$$\begin{aligned}
&\min \sum_{i=1}^{m} v_i x_{ik} - \sum_{r=1}^{s} u_r g_{rk} + \sum_{f=1}^{h} w_f b_{fk} + \sigma \\
&s.t.\quad \sum_{i=1}^{m} v_i x_{ij} - \sum_{r=1}^{s} u_r g_{rj} + \sum_{f=1}^{h} w_f b_{fj} + \sigma \geq 0, \\
&\qquad v_i \geq R_i^x,\ i=1,\ldots,m,\ u_r \geq R_r^g,\ r=1,\ldots,s, \\
&w_f \geq R_f^b,\ f=1,\ldots,h,\ j=1,\ldots,n.
\end{aligned} \tag{2}$$

In Model (2), $v_i(i=1,\ldots,m)$, $u_r(r=1,\ldots,s)$, $w_f(f=1,\ldots,h)$ and σ are dual variables that need to be optimized, and σ is an unrestricted variable.

For efficient DMU, whose *IEND* is unit 1, indicated from Model (1) or (2), its type of returns to scale can be determined by solving the following Model (3), and for inefficient DMU, whose *IEND* is less than unit 1, the type of returns to scale should be determined through solving Model (4). Here, the concept of returns to scale represents the marginal and proportional changes of a good output due to a unit increase in an input.

$$
\begin{aligned}
&\max/\min \sigma \\
&s.t. \quad \sum_{j=1}^{n} x_{ij}\lambda_j + d_i^x = x_{ik}, i = 1,\ldots,m, \\
&\qquad \sum_{j=1}^{n} g_{rj}\lambda_j - d_i^g = g_{rk}, r = 1,\ldots,s, \\
&\qquad \sum_{j=1}^{n} \lambda_j = 1, \\
&\qquad \sum_{i=1}^{m} v_i x_{ij} - \sum_{r=1}^{s} u_r g_{rj} + \sigma \geq 0, \\
&\qquad \sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g = \sum_{i=1}^{m} v_i x_{ik} - \sum_{r=1}^{s} u_r g_{rk} + \sigma, \\
&\qquad v_i \geq R_i^x, i = 1,\ldots,m, \quad u_r \geq R_r^g, r = 1,\ldots,s, \\
&\qquad \lambda_j \geq 0, j = 1,\ldots,n, \quad d_i^x \geq 0, i = 1,\ldots,m, \\
&\qquad d_r^g \geq 0, r = 1,\ldots,s, \quad j = 1,\ldots,n.
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
&\max/\min \mu = \sigma + \sum_{f=1}^{h} w_f b_{fj} \\
&s.t. \quad \sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b = \sum_{i=1}^{m} v_i x_{ik} - \sum_{r=1}^{s} u_r g_{rk} + \sum_{f=1}^{h} w_f b_{kj} + \sigma, \\
&\qquad \text{all constraints in Model (1) and (2).}
\end{aligned} \tag{4}
$$

In Model (3) and (4), the definitions of all three ranges are same as those in Model (1), and all the constraints in Model (4) are due to the constraints and objective functions of both Model (1) and (2). The upper bounds and the lower bound of the objective value are obtained from the maximization and minimization of Model (3) and (4), respectively. Then based on the optimal upper bounds and lower bounds, we could determine the returns to scale regarding DMU$_k$: (a) $\underline{\mu}^*(\underline{\sigma}^*) \leq \overline{\mu}^*(\overline{\sigma}^*) < 0$: DMU$_k$ under increasing returns to scale; (b) $\underline{\mu}^*(\underline{\sigma}^*) \leq 0 \leq \overline{\mu}^*(\overline{\sigma}^*)$: DMU$_k$ under constant returns to scale; (c) $\overline{\mu}^*(\overline{\sigma}^*) \geq \underline{\mu}^*(\underline{\sigma}^*) > 0$: DMU$_k$ under decreasing returns to scale.

2.2 Integrated energy and environmental efficiency under managerial disposability

In addition, following [20] we present the following RAM-DEA models for evaluating the energy and environmental efficiency of a specific region (DMU$_k$) under managerial disposability:

$$
\begin{aligned}
&\max \sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b \\
&s.t. \quad \sum_{j=1}^{n} x_{ij}\lambda_j - d_i^x = x_{ik}, i = 1,\ldots,m, \\
&\qquad \sum_{j=1}^{n} g_{rj}\lambda_j - d_r^g = g_{rk}, r = 1,\ldots,s, \\
&\qquad \sum_{j=1}^{n} b_{fj}\lambda_j + d_f^b = b_{fk}, f = 1,\ldots,h, \\
&\qquad \sum_{j=1}^{n} \lambda_j = 1, \\
&\qquad \lambda_j \geq 0, j = 1,\ldots,n, \quad d_i^x \geq 0, i = 1,\ldots,m, \\
&\qquad d_r^g \geq 0, r = 1,\ldots,s, \quad d_f^b \geq 0, f = 1,\ldots,h.
\end{aligned} \tag{5}
$$

We point out that, the meanings of variables and parameters in Model (5) are same as those in Model (1), and the only difference between these two models of (1) and (5) is the sign of slack d_i^x related to inputs. In addition, in Model (5), the undesirable outputs are treated like inputs while inputs like outputs in mathematics. Similarly, with the managerial disposability concept associated with Model (5), an integrated energy and environmental efficiency indicator and an emission efficiency indicator could be defined as:

Integrated Efficiency under Managerial Disposability (*IEMD*) =
$1-\left(\sum_{i=1}^{m} R_i^x d_i^{x*} + \sum_{r=1}^{s} R_r^g d_r^{g*} + \sum_{f=1}^{h} R_f^b d_f^{b*}\right)$.

Emission Efficiency (*EE*) = $1-\left(\sum_{i=1}^{m} R_i^x d_i^{x*} + \sum_{f=1}^{h} R_f^b d_f^{b*}\right)$.

All slacks above are determined through optimizing the objective value of Model (5), and the optimized objective value indicates the level of inefficiency under managerial disposability. The efficiency measure of *IEMD* incorporates the inputs and both the good and bad outputs; however *EE* does not incorporate the good outputs. Therefore *EE* mainly measures the energy and other input consumption, and undesirable output production or emission performance without considering the economic factor.

Model (5) has the following dual programming:

$$\begin{aligned} &\min -\sum_{i=1}^{m} v_i x_{ik} - \sum_{r=1}^{s} u_r g_{rk} + \sum_{f=1}^{h} w_f b_{fk} + \sigma \\ &s.t. \quad -\sum_{i=1}^{m} v_i x_{ij} - \sum_{r=1}^{s} u_r g_{rj} + \sum_{f=1}^{h} w_f b_{fj} + \sigma \ge 0, \\ &\qquad v_i \ge R_i^x, i = 1,\ldots,m, u_r \ge R_r^g, r = 1,\ldots,s, w_f \ge R_f^b, \\ &\qquad f = 1,\ldots,h, \; j = 1,\ldots,n. \end{aligned} \tag{6}$$

The meanings of variables and parameters in Model (6) are same as those in Model (2), and also, the only difference between these two models of (2) and (6) is the sign of variable v_i related to inputs.

For efficient DMU, whose *IEMD* is unit 1, indicated from Model (5) or (6), its type of damages to scale can be determined by solving the following Model (7), and for inefficient DMU, whose *IEMD* is less than unit 1, the type damages to scale should be determined through solving Model (8). Here, the concept of damages to scale is corresponds to the concept of returns to scale in the case of undesirable outputs, which represents the marginal and proportional changes of a bad output due to a unit increase in an input.

$$
\begin{aligned}
& \max/\min \sigma \\
s.t. \quad & \sum_{j=1}^{n} x_{ij}\lambda_j - d_i^x = x_{ik},\ i = 1,...,m, \\
& \sum_{j=1}^{n} b_{fj}\lambda_j + d_f^b = b_{fk},\ f = 1,...,h, \\
& \sum_{j=1}^{n} \lambda_j = 1, \\
& -\sum_{i=1}^{m} v_i x_{ij} - \sum_{f=1}^{h} w_f b_{fj} + \sigma \ge 0, \\
& \sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_f^b d_f^b = -\sum_{i=1}^{m} v_i x_{ik} - \sum_{f=1}^{h} w_f b_{fk} + \sigma, \\
& v_i \ge R_i^x,\ i = 1,...,m, \quad w_f \ge R_f^b,\ f = 1,...,h, \\
& \lambda_j \ge 0,\ j = 1,...,n, \quad d_i^x \ge 0, i = 1,...,m, \\
& d_f^b \ge 0,\ f = 1,...,h, \quad j = 1,...,n.
\end{aligned} \tag{7}
$$

$$
\begin{aligned}
& \max/\min \tau = \sigma - \sum_{r=1}^{s} u_r g_{rk} \\
s.t. \quad & \sum_{i=1}^{m} R_i^x d_i^x + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b = -\sum_{i=1}^{m} v_i x_{ik} - \sum_{r=1}^{s} u_r g_{rk} + \sum_{f=1}^{h} w_f b_{fk} + \sigma, \\
& \text{all constraints in (5) and (6).}
\end{aligned} \tag{8}
$$

In Model (7) and (8), the definitions of all three ranges are same as those in Model (1) and (5), and all the constraints in Model (8) are due to the constraints and objective functions of both Model (5) and (6). The upper bounds and the lower bound of the objective value are obtained from the maximization and minimization of Model (7) and (8), respectively. Then based on the optimal upper bounds and lower bounds, we could determine the damages to scale regarding DMU$_k$: (a) $\underline{\tau}^*(\underline{\sigma}^*) \le \overline{\tau}^*(\overline{\sigma}^*) < 0$: DMU$_k$ under decreasing damages to scale; (b) $\underline{\tau}^*(\underline{\sigma}^*) \le 0 \le \overline{\tau}^*(\overline{\sigma}^*)$: DMU$_k$ under constant damages to scale; (c) $\overline{\tau}^*(\overline{\sigma}^*) \ge \underline{\tau}^*(\underline{\sigma}^*) > 0$: DMU$_k$ under increasing damages to scale.

3 Empirical studies

In this section, we first describe the regions and areas of China, the input and output variables selected, and the associated data for integrated energy and environmental efficiency measurement. Then, the RAM-DEA models are applied and the indicators of *IEND*, *PE*, *IEMD*, and *EE* are calculated and analyzed for China's 30 regions. In addition, the types of returns to scale and damages to scale, as well as the energy saving potential and CO_2 emissions reduction potential for each of these regions are determined or measured and the strategies and policy implications for efficiency improvement are discussed.

3.1 Data and variables for efficiency evaluation of China's regions and areas

In this study, we examined 30 regions in mainland China during the 11th Five-Year plan period (2006-2010). 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 China [8, 23]. Detailed information on the areas and regions is shown in Table 1.

[Insert Table 1 here]

The east area is constituted by 11 regions including eight well-developed coastal provinces (Hebei, Liaoning, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan) and three municipalities (Beijing, Tianjin, and Shanghai). The central area consists of 10 regions which are inland provinces: Heilongjiang, Jilin, Inner Mongolia, Henan, Shanxi, Anhui, Hubei, Hunan, Jiangxi, and Guangxi. The west area includes one municipality of Chongqing and nine less developed provinces: Gansu, Guizhou, Ningxia, Qinghai, Shaanxi, Tibet, Yunnan, Xinjiang, and Sichuan.

Four regions of Tibet, Taiwan, Hong Kong and Macau are not included in this study due to the data absence. Table 2 summarizes the data set on the energy and environmental performance of China's regions that consists of three inputs, one desirable output, and one undesirable output. The input variables are i) Total energy consumption which mainly involves the consumption of coal, oil, and natural gas. They are all converted to the standard coal equivalent (million tonnes of coal equivalent, tce). ii) Labor (thousand employees). iii) Capital stock (billion RMB). The desirable/good output variable is gross domestic product (GDP) (billion RMB). The undesirable/bad output variable is CO_2 emissions (million tonnes of CO_2). The data of labor, energy consumption, GDP are obtained from China Statistical Yearbook and China Energy Statistical Yearbook of 2007-2011. The CO_2 emissions data come from our calculations [24, 25]. In the case of China, since there has been no large scale survey or census on capital assets in the post-1949 period, the data on capital stock of each region of China could not be obtained from the Statistical Yearbook. We use the data proposed by [26] and our estimation [27, 28]. All the prices used in the evaluation are converted into constant price.

[Insert Table 2 here]

3.2 Regional energy and environmental efficiency levels

Table 3 and 4 respectively documents the production efficiency (*PE*), emission efficiency (*EE*), integrated energy and environmental efficiency both under natural disposability and managerial disposability (*IEND* and *IEMD*), and the types of returns to scale (RTS) and damages to scale (DTS) for China's 30 regions. The first column shows each region's name. The second to the eleventh columns indicate each region's efficiency scores measured through the above RAM-DEA model and related indicators.

[**Insert Table 3 and Table 4 here**]

The *IEND* and *PE* documented in Table 3 indicate the integrated efficiency under natural disposability and production efficiency for each region of China. Table 3 shows that there are 10 regions exhibited efficient in *IEND* for at least one year during 2006-2010. These regions are Beijing, Tianjin, Liaoning, Shanghai, Jiangsu, Fujian, Guangdong, Hainan, Anhui, and Yunnan. We noticed that among these regions, Hainan performed best for keeping efficient over the whole study period. Yunnan also performed well and was measured as efficient region for four years except 2009. Most of these highly performed regions are east China coastal provinces and municipalities, and just two regions come from west and central areas of China. Here, the efficient *IEND* means that, under the assumption of natural disposability, these 10 regions have the best performance both on energy utilization related GDP production and environment protection for specific years during 2006-2010. Furthermore, according to the relation between the definitions of integrated efficiency and energy efficiency, these 10 regions also have unity *PE*, which mean that, without considering the undesirable output of CO_2 emissions, these regions also performed best in energy and other inputs utilization and GDP production. However, the other 20 regions of China never been measured as efficient during this period. On average, three regions (Hebei, Henan, and Shandong) are clustered into the worst performed regions whose *IEND* are all below 0.8; eight regions (Inner Mongolia, Shanxi, Sichuan, Chongqing, Hubei, Guizhou, Hunan, and Jiangxi) are clustered into the worse performed regions with *IEND* between 0.8 and 0.9; and the remaining nine regions (Guangxi, Xinjiang, Gansu, Shaanxi, Heilongjiang, Jilin, Zhejiang, Qinghai, and Ningxia) are all grouped in the highly performed and closed to efficient regions with *IEND* between 0.9 and 0.95. The cluster map of integrated efficiency under natural disposability for China's 30 regions is illustrated in Figure 1.

[Insert Figure 1 here]

The annual average *PE* scores and the coefficient of variation (CV) of *PE* for China and its three major areas during 2006-2010 are calculated and illustrated in Figure 2. From an area perspective, the regions in east China have the highest production efficiency, followed by the regions in west China, and the regions in central China have the lowest production efficiency. The efficiency scores of the central and west areas kept stable during this period, but that of the east area continuously decreased since 2006, which lead the average production efficiency of China slightly decreased over time. The regional production efficiency differences (denoted by CV in Figure 2) among east China regions are the smallest and those among west China regions are the largest, but the differences among the central areas sharply enlarged since 2007 and its CV began to exceed that of the west areas in 2008.

[Insert Figure 2 here]

The *IEMD* and *EE* documented in Table 4 indicate the integrated efficiency under managerial disposability and emission efficiency for each region of China. Eight regions exhibited efficient in *IEMD* for one to three years over our study period. In 2006, Beijing, Shanghai, Jiangsu, Shandong, Guangdong, Henan, Sichuan and Qinghai performed best with unit *IEMD* scores, but just two regions (Henan and Qinghai) kept efficient *IEMD* after that in one or two years of 2007, 2009 or 2010, respectively. On average, Beijing, Shanghai, Guangdong, Hainan, Sichuan, Qinghai, Henan and Jiangxi are considered the best performed provinces and municipalities for their average efficiency scores are higher than other Chinese regions over the whole study period. We noticed that more central and west Chinese regions are measured efficiency under *IEMD* compared to under *IEND*. Among the above eight regions, four come from east China, two are central China regions and another two regions are from the west area. Here, the efficient *IEMD* indicates that, under the assumption of managerial disposability, these efficient regions have the best performance both on energy utilization related GDP production and environment protection. Furthermore, these *IEMD* efficient regions also have unit *EE* scores, which mean that, without considering the desirable output production of GDP, these regions also performed best in CO_2 emissions caused by energy consumption.

Except the above eight best performed regions, the remaining 22 regions could be further clustered into several groups. Xinjiang, Gansu, Ningxia, Shaanxi, Chongqing, Yunnan, Hunan, Guangxi, Tianjin, Shandong, Jiangsu, Anhui, Zhejiang and Fujian are clustered into the worse performed regions whose *IEMD* are between 0.8 and 0.9; Inner Mongolia, Heilongjiang, Jilin, Liaoning, Hebei, Shanxi and Hubei are clustered into the worst performed regions with *IEMD* below 0.8. The cluster map of integrated efficiency under managerial disposability for China's 30 regions is illustrated in Figure 3.

[Insert Figure 3 here]

Figure 4 illustrates the annual average *EE* scores and the CV of *EE* for China and its three major areas during 2006-2010. Contrary to the *IEND* and *PE* comparison results, from an area perspective and on average, the regions in west China have the highest *IEMD* followed by east China regions, and both west and east China outperform central China on *IEMD*. Furthermore, the average *EE* of west and central China almost continuously increased during 2006-2010, but the *EE* of east China significantly decreased over the same period. The average emission efficiency of whole China slightly fluctuated during 2006-2009 and began to increase in the very last year of our study period, which was mainly caused by the significant efficiency increase of central China started in 2009. The CVs are again utilized to denote the emission efficiency differences for Chinese regions and areas. It can be seen from Figure 4 that, the efficiency difference among the less efficient west China regions is largest and its CV is much higher than the average level of China. However, the efficiency difference among west China regions kept stable over the study period. The CVs of both central and east China areas are comparatively lower than west China area, but they slightly increased during this study period which indicates that the efficiency differences among central and east China regions enlarged over time.

[Insert Figure 4 here]

To sum up, three out of thirty China's regions highly performed both on *IEND* and *IEMD*: Beijing, Shanghai, and Guangdong. These three regions are all east China province or municipalities, and measured efficiently on production efficiency and emission efficiency simultaneously for at least one year during our study period. Furthermore, these three regions all lie on or quite close to both the desirable and undesirable output frontiers and perform best both under the natural disposability and managerial disposability assumptions. Therefore, they could be seen as the benchmarks for other inefficient China's regions for integrated energy and environmental efficiency improvement. Since Beijing, Shanghai, and Guangdong are all economically and socially well-developed regions of China, their economic patterns, natural resource endowments, and energy utilization structures are considered quite different with regions in west China area. Therefore, we also indicate that one western Chinese province of Qinghai should be benchmarked for other inefficient China's regions, especially for west China regions. Because Qinghai also performed quite well on energy utilization, economic output production, and environment production, and measured quite close to unit *IEND* and *IEMD*.

The differences between the integrated efficiencies under natural disposability and managerial disposability and their changes over time during our study period for Chinese 30 regions were further analyzed in Figure 5.

[Insert Figure 5 here]

Firstly, the integrated efficiency under natural disposability is more balanced than that under managerial disposability, and on average, *IEND* is higher than *IEMD* (both in 2006 and 2010), which indicates that the integrated efficiency difference among China's 30 regions is more significant from the perspective of managerial disposability, and the integrated efficiency improvement potential through managerial effort is larger than that through natural decrease of energy consumption for most Chinese regions. For example, the regions of Liaoning, Jilin, Shanxi, and Inner Mongolia have large gaps between *IEND* and *IEMD*, and the efficiencies under managerial disposability for them are all below those under natural disposability. This implies that these regions should pay more attention on enhancing their energy utilization management instead of energy consumption control. However, there are also several regions, such as Sichuan, Henan Jiangxi, and Shandong, whose integrated efficiencies under natural disposability are lower than those under managerial disability. Therefore, in order to increase the integrated efficiency, it will be more effective for these regions to focus on total energy consumption control and naturally decreasing energy utilization instead of just relies on management improvement.

Secondly, both of the two integrated efficiency (*IEND* and *IEMD*) scores are more balanced in 2010 than in 2006, and for most Chinese regions, the integrated efficiencies increased over time from 2006 to 2010, which indicates that most less developed and lowly performed regions has accelerated their energy and environmental efficiency promotion process and began to catch up with the benchmark regions during this period. However, there are also several regions experienced integrated efficiency decreasing process during this period, especially the integrated efficiency under managerial disposability for Jiangsu, Shandong, and Inner Mongolia, whose *IEMD* significantly decreased from 2006 to 2010. This implies that compared with other Chinese regions, the efficiency improvement efforts through management improvement of Jiangsu, Shandong, and Inner Mongolia were considered less effective and should be paid more attentions in the future.

3.3 Measurement of returns to scale and damages to scale

Table 3 and 4 also respectively summarizes the types of returns to scale and damages to scale of China's 30 regions and three different types of increasing, constant and decreasing returns to scale and damages to scale during 2006-2010 are indicated in the last five columns.

As shown in Table 3, among China's 30 regions, 19 regions such as Hebei, Jilin, Shanxi, Inner Mongolia, Guizhou and Gansu etc., exhibited decreasing returns to scale over the whole study period from 2006 to 2010. Decreasing returns to scale under natural disposability implies that increases in inputs of energy, labor and capital stock will bring less percentage increase in desirable output of GDP and vice versa. Therefore, for these

19 regions, it is not recommended for them to simply increase their scales of production because that will not improve their integrated energy and environmental efficiency any more. We noticed that all of these 19 regions came from east and central China areas. In addition, there are four regions (Hainan, Yunnan, Qinghai, and Ningxia) have increasing returns to scale over the whole study period. Except Hainan, the other three regions are all west China areas. Increasing returns to scale under natural disposability indicates that one unit increase of input will produce desirable output more proportionally than the input increase and vice versa. Therefore, if the above four regions increases their production scale, then they will be more productive on GDP. In another word, among China's 30 regions, Hainan, Yunnan, Qinghai and Ningxia are recommended to increase their scales of production to enhance their integrated energy and environmental efficiency.

The remaining seven regions have mixed returns to scale types which can be further divided into two groups. Four regions of Beijing, Jiangsu, Guangdong, and Anhui performed constant returns to scale in the early years during 2006-2010, and then became decreasing returns to scale. Constant returns to scale under natural disposability means that increasing or decreasing input will result in the same percentage increase or decrease in desirable output. Thus, at the beginning of our study period, these four regions are recommended to maintain their current scale of production so as to keep their integrated energy and environmental efficiency unchanged, and stabilize their energy consumptions and CO_2 emissions. However, at the later years of the study period, these four regions are not recommended for maintaining or simply increasing their production scales any longer. Other three regions of Tianjin, Liaoning, and Fujian experienced all three types of returns to scale over the period of 2006-2010. They performed constant returns to scale in 2006, shifted to decreasing returns to scale in 2007, and then became increasing returns to scale since 2009 or 2010. The shifting processes of returns to scale types for these 3 regions indicates that not only the integrated efficiency levels of Tianjin, Liaoning, and Fujian were improved, but their energy utilization and economic production structures were optimized and became more productive in the last one or two years of our study period.

Furthermore, three types of damages to scale of China's 30 regions during 2006-2010 are summarized in the last five columns of Table 4. There are 18 regions (e.g. Hebei, Shanghai, Hunan, Yunnan etc.) exhibited increasing damages to scale over the whole study period of 2006-2010, and three regions (Hainan, Qinghai, and Ningxia) shown decreasing damages to scale during the same period. Increasing damages to scale under managerial disposability indicates that the undesirable outputs of CO_2 emissions are produced more proportionally than the unit increase in inputs of energy, labor and capital stock. That is to say, if the above 18 regions increase their scales of production, then they will produce more CO_2 and cause more damages than those before the inputs increase. Therefore, these 18 regions are not recommended to simply increase their production scales since that will have nothing to do with their integrated energy and environmental efficiency promotion. Alternatively, it is highly recommended that these 18 regions should rely on technology innovation, such as physical based energy efficiency improvement technology, carbon capture and storage (CCS) technology, which could enlarge their scales of production and improve their integrated energy and environmental efficiency simultaneously. To the contrary, decreasing damages to scale under managerial disposability implies that the undesirable outputs are yielded less proportionally than the unit increase in inputs. Hence, for the above three regions of Hainan, Qinghai, and Ningxia, it is not recommended, but acceptable that they can increase their scales of production to improve their integrated energy and environmental efficiency, however this will also lead to CO_2 emissions increase. Therefore, they should not ignore the efforts on technology innovation of high efficient energy utilization and emission control when enlarging their scales of production.

The remaining nine regions have mixed types of damages to scale. Firstly, seven regions of Tianjin, Guangdong, Jiangxi, Shaanxi, Guangxi, Chongqing, and Gansu exhibited increasing damages to scale at the beginning and then shifted to decreasing damages to scale in later years during 2006-2010. This type shifting of damages to scale indicates that the energy utilization structures of the above seven regions have been optimized, and their emission mitigation efforts are considered effective over the study period. Secondly, Sichuan experienced increasing damages to scale for four years from 2006 to 2009, but then changed into constant damages to scale in the very last year of 2010. Constant damages to scale under managerial disposability means that increasing or decreasing inputs will result in the same percentage increase or decrease in undesirable outputs. Thus, for Sichuan, it is not recommended, but acceptable to maintain its production scale so as to keep its integrated energy and environmental efficiency stable. Also there is an alternative recommendation that, Sichuan should pay more attention on technology innovation of energy utilization. Thirdly, Beijing experienced all three types of damages to scale during 2006-2010. It exhibited constant damages to scale in 2006 and changed into decreasing damages to scale since 2007, which indicates that Beijing's effort on optimizing its energy utilization structure was effective. However, this effort was temporarily broken off in 2009, which was mainly caused by the investment boom and related energy consumption increase around 2008 and 2009. Fortunately, this situation did not last for long and, in 2010, Beijing shifted back to decreasing damages to scale.

3.4 Regional energy conservation and emission reduction potentials

Since the RAM-DEA model utilizes slacks on input or output variables to measure the energy and environmental efficiency for each Chinese region, and according to the DEA theory, the inefficient regions can become efficient through adjust their input and output variables so as to reach the benchmark. Therefore, in this section, we further use the RAM-DEA to survey the energy conservation potential, emission reduction potential, and GDP increase potential for different Chinese regions during our study period.

Under the natural disposability, the slacks of d^x and d^b in model (1) indicate the potential redundancy on energy input variable and emission output variable, respectively, which could be seen as the theoretical maximum energy conservation potential and emission reduction potential for each region through naturally reducing its energy consumption and scale of production. In addition, under the managerial disposability, the slacks of d^g and d^x in model (5) denote the potential increase on GDP production and related energy consumption for each region through management promotion and technology innovation. Table 5 and 6 respectively document the energy conservation potential and related emission reduction potential, as well as the GDP increase potential and related energy consumption increase for Chinese 30 regions during 2006-2010. Figure 6 and 7 further illustrate the cumulate reduction potentials of energy saving and emission reduction and cumulate increase potentials of economic production and energy consumption of three Chinese areas from 2006 to 2010, respectively.

[**Insert Table 5 and Table 6 here**]

Since 2010 is the latest year in our study period, here we take the data in 2010 as an example to analysis the regional potentials on energy conservation, emission reduction, and economic production increase of China. From Table 5 we could find that, under the natural disposability assumption, the theoretical maximum energy conservation potentials of six regions are more than 60 million tce in 2010. In these six regions, Hebei has the largest energy conservation potential, followed by Shandong, Shanxi, Inner Mongolia, Henan, and Sichuan. Seven regions such as Liaoning and Ningxia had zero potential on energy conservation for they were measured as efficient Chinese regions in 2010. Among the integrated energy and environmental inefficient regions, Beijing has the lowest energy conservation potential in 2010, followed by Jiangxi, Tianjin, and Shanghai, whose energy conservation potentials were all less than 10 million tce. It can be noticed that although Hebei has the largest energy conservation potential, its energy conservation potential rate (energy conservation potential / total energy consumption) was not the highest, furthermore, its integrated efficiency score was not the lowest. On the contrary, Guizhou and Gansu had higher energy conservation potential rates than Hebei. In addition, the energy conservation potential rate of Xinjiang was also quite high in 2010. The above results indicate that those regions with large energy conservation potentials or high energy conservation potential rates should pay more attentions on their energy consumption control policy implementations and energy efficiency promotion managements, so as to reduce their energy redundancies under natural disposability and promote their energy utilization performances.

Table 5 also documents similar evaluation results on theoretical maximum emission reduction potentials for China's 30 regions in 2010. Shandong took over Hebei and became the region with the largest emission reduction potential in 2010. The emission reduction potentials of Hebei, Shanxi, and Inner Mongolia were following which were all above 200 million tonnes of CO_2. Among the integrated energy and environmental inefficient regions, Shanghai has the lowest emission reduction potential in 2010, followed by Chongqing and Tianjin whose emission reduction potentials were below 20 million tonnes of CO_2. According to the emission reduction potential rate (emission reduction potential / total CO_2 emissions), Guizhou was raked first and followed by Shanxi, Inner Mongolia, Hebei and Gansu (in decreasing ranking). Therefore, the above regions with large emission reduction potentials or high emission reduction potential rates played the most important role in China's effort on emission mitigation and integrated efficiency promotion, thus should pay more attentions on their energy utilization based emission controls and energy redundancy reductions under natural disposability.

Table 6 shows the GDP increase potentials and related energy consumption increases of China's 30 regions under managerial disposability. Here we take the data in 2010 as an example for analyzing. Hebei, Liaoning, Shanxi, Inner Mongolia, and Shandong were ranked top 5 for their theoretical maximum economic production increase potentials through managerial efforts were around 2500 billion RMB in 2010. However, if these

GDP increase potentials could be achieved by adjusting the input variables, the related energy consumptions of the above regions would also experience remarkable increases. Therefore, when these regions try to improve their integrated efficiencies through enlarge their scales of production, they should also strictly implement their energy saving policies and promote their energy efficiency managements, so as to avoid their energy consumption increases out of control. Three regions of Hainan, Henan, and Sichuan shown zero GDP increase potentials and zero energy consumption increases in 2010, because their integrated efficiency under managerial disposability were all unit. We noticed that although Qinghai's GDP increase potential in 2010 was the lowest in China, its related energy consumption increase was zero, which means that Qinghai could appropriately increase its scale of production and improve its integrated efficiency under managerial disposability simultaneously, but keep their energy consumption unchanged.

To sum up, as shown in Figure 6, the total energy conservation potentials of China and its central and west areas kept approximately stable within our study period, and the energy conservation potential of the east area slightly increased during 2006-2008. The total emission reduction potential of China decreased about 500 million tonnes of CO_2 over 2006-2010, which was mainly caused by the decrease of emission reduction potential in the central area. In addition, Figure 7 illustrates that the GDP increase potential of east China continuously increased during our study period, but the potentials of central and west China began to decrease in the very last year of the study period, which led China's total GDP increase potential sharply decreased in 2010. The related energy consumption increase of China exhibited the similar variation trend as the GDP increase potential during the study period. In general, the east area of China had the largest energy conservation and emission reduction potentials, as well as the GDP increase potential, and the potentials of the west area were the smallest.

[Insert Figure 6 and Figure 7 here]

3.5 Discussions on China's regional energy and environmental efficiency

The policy of economic reform and open up has successfully made China to achieve remarkable economic and social development progress during the latest three decades. However, China's energy-intensive and scale-oriented economic growth mode has led to a series problems related to large total energy consumption, rapid greenhouse gas emission increase, and serious environmental pollutions. In order to realize sustainable development, Chinese government has proposed and implemented numbers of energy conservation and efficiency improvement policies and programs.

During the period of 1980s and 1990s, the effect of these policies and programs was significant that the energy intensity (energy consumption per unit of GDP) continuously declined from 1980 to 2001. However, the continuously energy intensity decrease situation was broken off during 2002-2005, that China's energy intensity annually increased by 1.6% on average and its energy demand also remarkably increased by 57% during this period. In recognition of the unsustainable economic growth, the out of control energy demand increase, and the related CO_2 emission problems, the Chinese government announced a national energy conservation goal in 2006 that the energy intensity of China had to be reduced by 20% within five years from 2006 to 2010 based on the 2005 level. Since then, a series of energy saving and emission reduction laws, regulations, policies and programs were proposed to support the realization of the 20% reduction goal.

It seems that China has been on track to meet this energy intensity reduction goal since 2006, for its energy intensity decreased by 19.1% during 2006-2010 according to the latest report issued by the Chinese central government in 2011. In this study, our evaluation results further confirmed that the implementations of strict energy saving and emission reduction policies and programs contributed the performance promotion of China's energy utilization and emission reduction, for the energy conservation potential and emission reduction potential kept stable or even declined during 2006-2010, and at the same period, the integrated energy and environmental efficiency under managerial disposability obviously increased over time.

4 Conclusions

In recent years, increasing studies have focused on the measurement of energy efficiency or environmental efficiency applying DEA based approaches. In this paper, we applied the RAM-DEA approach to evaluate the integrated energy and environmental efficiency and determine the types of returns to scale and damages to scale, under the economic concepts of natural disposability and managerial disposability, respectively, for China's 30 regions during the period of 2006-2010. Then, we proposed several strategies and policy implications for the integrated efficiency improvement of each Chinese region. In addition, the regional energy conservation potential and emission reduction potential for each Chinese region during 2006-2010 were calculated and analyzed in this study.

The major results of this study show that: i) Three regions of Beijing, Shanghai, and Guangdong had the highest integrated energy and environmental efficiency both under the natural disposability and the managerial disposability. Thus, they could be seen as the benchmarks for other inefficient Chinese regions for energy efficiency and environmental efficiency improvement. ii) From an area perspective, east China had the highest integrated efficiency under natural disposability, followed by west China, and the efficiency of central China was the lowest. In addition, west China had the highest integrated efficiency under managerial disposability, followed by east China, and again, central China had the lowest efficiency. iii) Both the regional production efficiency difference and the regional emission efficiency difference among west China regions were the largest. iv) During 2006-2010, the average production efficiency of China slightly decreased over time, and the average emission efficiency of China fluctuated during the early years of the study period and then began to increase since 2009. v) Among China's 30 regions, under the natural disposability assumption, 19 regions exhibited decreasing returns to scale and 4 regions shown increasing returns to scale over the whole study period, and another 7 regions have mixed returns to scale types. In addition, under the managerial disposability, 18 regions exhibited increasing damages to scale and 3 regions shown decreasing damages to scale over the whole study period, and another 9 regions have mixed damages to scale types. vi) In order to maintain or increase integrated energy and environmental efficiency, for the regions under increasing damages to scale, it is recommended to reduce their scales of production; for the regions under decreasing damages to scale, it is acceptable, but not recommended that they could increase their scales of production; and for the regions of constant damages to scale, it is also acceptable but not recommended that they could maintain their scales of production. As an alternative way for the regions exhibited increasing or constant damages to scale, technology innovation on physical based energy efficiency improvement will be more effective for their efficiency promotion efforts. vii) Up to 2010, China still had large energy conservation potential and emission reduction potential which could be further achieved through implementing strict energy efficiency improvement energy consumption control policies and programs.

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Table and figure captions

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Figure 2 Regional production efficiency levels and differences

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Tables and Figures

Table 1 Regions and areas of China (excluding Tibet, Taiwan, Hong Kong and Macau)

Areas	Regions (provinces, autonomous regions, and municipalities) included
East area	Beijing, Tianjin, Shanghai, Hebei, Liaoning, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan
Central area	Shanxi, Inner Mongolia, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan, Guangxi
West area	Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang
Whole country	30 regions clustered into 3 areas

Table 2 Descriptive statistics of inputs and outputs

Year	Input & Output variables	Input 1 Energy consumption	Input 2 Capital stock	Input 3 Labor	Desirable output GDP	Undesirable output CO_2 emissions
	Statistics\ Units	Million tce	Billion RMB	Thousand people	Billion RMB	Million tonnes CO_2
2006	Average	96.8	395.5	23059.6	897.1	220.5
	St. dev.	62.7	374.2	15313.9	714.6	151.4
	Max.	267.6	1287.0	56897.4	2941.8	632.1
	Min.	9.2	27.6	2708.3	82.6	17.7
2008	Average	112.6	531.0	24263.6	1151.8	261.6
	St. dev.	71.9	482.0	16202.2	910.2	177.7
	Max.	305.7	1699.7	58354.5	3731.7	739.1
	Min.	11.4	35.7	2767.9	106.4	24.3
2010	Average	129.8	724.1	25553.1	1455.1	313.3
	St. dev.	81.7	666.4	17009.0	1130.9	217.8
	Max.	348.1	2326.7	60415.6	4601.3	856.8
	Min.	13.6	49.5	2941.0	135.0	26.5

Note: tce indicates tonnes of coal equivalent

Table 3 Regional production efficiency, integrated efficiency under natural disposability and types of returns to scale of China (2006-2010)

	PE					*IEND*					RTS				
Year	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010
Beijing	1.000	1.000	0.991	0.977	0.969	1.000	1.000	0.991	0.977	0.969	C	C	D	D	D
Tianjin	1.000	0.997	0.997	1.000	0.997	1.000	0.994	0.993	1.000	0.993	C	D	D	I	I
Hebei	0.839	0.833	0.840	0.839	0.840	0.703	0.737	0.747	0.748	0.759	D	D	D	D	D
Liaoning	1.000	0.986	0.981	1.000	1.000	1.000	0.979	0.974	1.000	1.000	C	D	D	I	I
Jilin	0.955	0.952	0.956	0.961	0.963	0.935	0.933	0.934	0.937	0.939	D	D	D	D	D
Heilongjiang	0.946	0.945	0.949	0.949	0.949	0.929	0.929	0.928	0.928	0.927	D	D	D	D	D
Shanghai	1.000	0.998	0.979	0.958	0.929	1.000	0.998	0.978	0.956	0.927	C	D	D	D	D
Jiangsu	1.000	0.953	0.942	0.931	0.921	1.000	0.918	0.902	0.891	0.878	D	D	D	D	D
Zhejiang	0.972	0.974	0.967	0.956	0.947	0.961	0.964	0.954	0.940	0.934	D	D	D	D	D
Fujian	1.000	0.988	0.989	0.993	1.000	1.000	0.985	0.989	0.993	1.000	C	D	D	D	I
Shandong	0.865	0.861	0.853	0.842	0.834	0.765	0.773	0.763	0.755	0.754	D	D	D	D	D
Guangdong	1.000	1.000	1.000	0.984	0.964	1.000	1.000	1.000	0.979	0.955	C	D	D	D	D
Hainan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	I	I	I	I	I
Shanxi	0.900	0.903	0.908	0.910	0.915	0.831	0.838	0.842	0.851	0.858	D	D	D	D	D
Inner Mongolia	0.903	0.895	0.905	0.914	0.925	0.815	0.812	0.826	0.851	0.876	D	D	D	D	D
Anhui	1.000	0.982	0.970	0.958	0.947	1.000	0.981	0.970	0.958	0.947	C	D	D	D	D
Jiangxi	0.902	0.903	0.905	0.908	0.914	0.898	0.894	0.899	0.898	0.908	D	D	D	D	D
Henan	0.814	0.802	0.806	0.806	0.806	0.745	0.745	0.750	0.747	0.763	D	D	D	D	D
Hubei	0.931	0.925	0.921	0.918	0.918	0.892	0.903	0.901	0.895	0.895	D	D	D	D	D
Hunan	0.918	0.909	0.907	0.903	0.899	0.903	0.893	0.888	0.884	0.882	D	D	D	D	D
Shaanxi	0.926	0.923	0.925	0.928	0.929	0.911	0.913	0.915	0.918	0.922	D	D	D	D	D
Guangxi	0.926	0.919	0.926	0.928	0.928	0.915	0.912	0.918	0.917	0.918	D	D	D	D	D
Chongqing	0.963	0.960	0.957	0.956	0.954	0.960	0.950	0.946	0.952	0.950	D	D	D	D	D
Sichuan	0.875	0.863	0.854	0.857	0.856	0.855	0.850	0.843	0.847	0.849	D	D	D	D	D
Guizhou	0.902	0.906	0.909	0.910	0.913	0.869	0.873	0.879	0.876	0.879	D	D	D	D	D
Yunnan	1.000	1.000	1.000	0.999	1.000	1.000	1.000	1.000	0.997	1.000	I	I	I	I	I
Gansu	0.925	0.930	0.933	0.936	0.939	0.904	0.918	0.918	0.922	0.925	D	D	D	D	D
Qinghai	0.996	0.998	1.000	0.999	1.000	0.996	0.997	1.000	0.999	1.000	I	I	I	I	I
Ningxia	0.990	0.990	0.993	0.994	1.000	0.975	0.977	0.982	0.984	1.000	I	I	I	I	I
Xinjiang	0.947	0.955	0.958	0.959	0.962	0.925	0.933	0.939	0.942	0.945	D	D	D	D	D

Note: D, C, and I indicate decreasing, constant and increasing returns to scale.

Table 4 Regional emission efficiency, integrated efficiency under managerial disposability and types of damages to scale of China (2006-2010)

	EE					IEMD					DTS				
Year	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010
Beijing	1.000	0.976	0.966	0.946	0.940	1.000	0.973	0.958	0.929	0.920	C	D	D	I	D
Tianjin	0.853	0.852	0.858	0.861	0.872	0.817	0.814	0.821	0.826	0.838	I	I	I	D	D
Hebei	0.777	0.799	0.778	0.766	0.759	0.666	0.675	0.648	0.628	0.614	I	I	I	I	I
Liaoning	0.679	0.677	0.702	0.693	0.722	0.557	0.545	0.578	0.563	0.604	I	I	I	I	I
Jilin	0.829	0.843	0.834	0.829	0.831	0.764	0.781	0.770	0.764	0.766	I	I	I	I	I
Heilongjiang	0.854	0.859	0.853	0.857	0.856	0.793	0.801	0.792	0.797	0.795	I	I	I	I	I
Shanghai	1.000	0.964	0.943	0.931	0.924	1.000	0.946	0.914	0.897	0.886	I	I	I	I	I
Jiangsu	1.000	0.921	0.887	0.863	0.844	1.000	0.880	0.829	0.787	0.759	I	I	I	I	I
Zhejiang	0.916	0.907	0.898	0.889	0.898	0.881	0.869	0.854	0.839	0.851	I	I	I	I	I
Fujian	0.883	0.884	0.889	0.883	0.894	0.852	0.849	0.856	0.845	0.864	I	I	I	I	I
Shandong	1.000	0.965	0.925	0.901	0.873	1.000	0.937	0.873	0.829	0.777	I	I	I	I	I
Guangdong	1.000	0.991	0.976	0.958	0.946	1.000	0.990	0.969	0.938	0.920	I	I	D	D	D
Hainan	0.990	0.989	0.990	0.995	1.000	0.989	0.986	0.987	0.994	1.000	D	D	D	D	D
Shanxi	0.706	0.722	0.723	0.753	0.763	0.565	0.588	0.590	0.631	0.647	I	I	I	I	I
Inner Mongolia	0.673	0.671	0.670	0.725	0.773	0.521	0.513	0.514	0.596	0.669	I	I	I	I	I
Anhui	0.866	0.873	0.884	0.900	0.907	0.809	0.819	0.836	0.861	0.874	I	I	I	I	I
Jiangxi	0.964	0.936	0.937	0.926	0.956	0.939	0.898	0.904	0.888	0.933	I	I	I	I	D
Henan	1.000	1.000	0.945	0.901	1.000	1.000	1.000	0.898	0.820	1.000	I	I	I	I	I
Hubei	0.810	0.875	0.877	0.868	0.877	0.718	0.810	0.813	0.799	0.812	I	I	I	I	I
Hunan	0.913	0.913	0.907	0.907	0.916	0.869	0.870	0.860	0.859	0.875	I	I	I	I	I
Shaanxi	0.875	0.895	0.898	0.904	0.921	0.816	0.845	0.849	0.861	0.889	I	I	I	I	D
Guangxi	0.904	0.919	0.925	0.922	0.945	0.866	0.890	0.902	0.897	0.927	I	I	I	D	D
Chongqing	0.906	0.892	0.891	0.943	0.955	0.876	0.853	0.851	0.924	0.938	I	I	I	D	D
Sichuan	0.945	0.971	0.983	0.987	1.000	0.906	0.949	0.970	0.977	1.000	I	I	I	I	C
Guizhou	0.862	0.862	0.874	0.863	0.862	0.785	0.786	0.808	0.790	0.791	I	I	I	I	I
Yunnan	0.862	0.861	0.878	0.875	0.881	0.799	0.798	0.827	0.820	0.832	I	I	I	I	I
Gansu	0.890	0.929	0.916	0.922	0.934	0.834	0.892	0.874	0.884	0.900	I	D	D	D	D
Qinghai	1.000	0.985	0.985	1.000	0.999	1.000	0.979	0.979	1.000	0.998	D	D	D	D	D
Ningxia	0.866	0.888	0.900	0.909	0.927	0.822	0.849	0.866	0.877	0.901	D	D	D	D	D
Xinjiang	0.849	0.847	0.860	0.865	0.869	0.786	0.787	0.806	0.813	0.820	I	I	I	I	I

Note: D, C, and I indicate decreasing, constant and increasing damages to scale.

Table 5 Regional energy conservation potential and related emission reduction potential of China under natural disposability (2006-2010)

	Energy conservation potential (Million tce)					Emission reduction potential (Million tonnes CO_2)				
Year	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010
Beijing	0.00	0.00	0.75	0.18	1.39	0.00	0.00	0.00	0.00	0.00
Tianjin	0.00	0.98	4.37	0.00	5.54	0.00	14.60	17.14	0.00	17.64
Hebei	146.13	137.12	135.18	136.08	127.47	568.27	401.28	389.38	382.51	340.07
Liaoning	0.00	12.27	17.01	0.00	0.00	0.00	32.85	28.46	0.00	0.00
Jilin	19.04	21.06	23.24	23.65	23.27	84.20	80.67	92.72	99.86	102.01
Heilongjiang	37.94	38.37	41.65	42.22	41.62	69.26	67.67	84.79	86.77	93.29
Shanghai	0.00	2.54	5.49	7.17	8.80	0.00	0.00	1.82	8.08	10.14
Jiangsu	0.00	18.56	25.93	33.21	34.69	0.00	146.61	167.45	167.64	177.45
Zhejiang	0.00	2.66	9.13	14.69	16.08	48.39	44.43	54.59	67.65	54.29
Fujian	0.00	2.51	1.44	0.00	0.00	0.00	12.58	0.00	0.00	0.00
Shandong	116.37	115.92	118.13	122.39	117.06	421.05	369.96	379.46	366.16	336.25
Guangdong	0.00	0.00	0.00	7.45	16.55	0.00	0.00	0.00	19.13	36.26
Hainan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shanxi	100.08	96.32	101.44	106.03	98.14	288.41	274.55	277.53	250.72	239.59
Inner Mongolia	86.65	80.21	76.95	73.73	67.22	367.09	345.97	329.60	264.51	204.84
Anhui	0.00	0.00	0.00	0.00	0.00	0.00	4.02	0.54	0.00	0.00
Jiangxi	0.00	0.00	0.09	3.31	5.14	17.79	38.75	26.43	42.21	25.18
Henan	70.47	67.61	70.88	70.41	65.83	290.98	240.17	237.26	246.49	181.31
Hubei	46.48	43.41	43.81	45.98	44.86	167.46	89.02	82.74	97.52	93.70
Hunan	42.25	39.24	41.42	40.56	39.24	63.74	64.99	81.26	78.22	72.33
Shaanxi	15.73	15.24	17.03	18.97	19.46	64.92	42.91	44.91	43.59	32.02
Guangxi	11.95	10.18	13.72	15.27	15.57	45.77	29.74	32.01	44.06	43.21
Chongqing	22.94	22.40	22.42	21.11	20.28	16.36	39.23	44.20	14.81	16.69
Sichuan	66.41	64.04	63.04	63.45	61.29	82.12	52.45	44.33	42.46	30.44
Guizhou	48.81	46.70	45.07	45.06	42.02	139.42	139.29	124.76	140.22	140.46
Yunnan	0.00	0.00	0.00	0.98	0.00	0.00	0.00	0.00	7.83	0.00
Gansu	29.96	28.87	30.13	30.10	28.97	84.82	51.07	61.01	60.11	57.48
Qinghai	4.46	2.93	0.00	1.51	0.00	0.61	4.20	0.00	0.10	0.00
Ningxia	16.10	15.33	12.07	10.46	0.00	63.84	55.31	45.79	40.49	0.00
Xinjiang	43.59	39.93	38.17	36.67	34.78	96.04	92.94	77.52	73.72	69.43

Note: tce indicates tonnes of coal equivalent

Table 6 Regional GDP increase potential and related energy consumption increase of China under managerial disposability (2006-2010)

	GDP increase potential (Billion RMB)					Related energy consumption increase (Million tce)				
	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010
Beijing	0.00	71.22	179.77	373.77	449.11	0.00	1.00	2.97	8.36	8.96
Tianjin	803.32	859.06	826.73	810.66	777.70	21.03	25.40	21.52	19.09	18.33
Hebei	2507.91	2783.64	2948.88	3100.46	3270.77	0.00	14.89	25.86	33.23	51.14
Liaoning	2755.58	2985.08	2803.67	2932.16	2677.82	59.61	77.96	68.01	78.06	67.44
Jilin	1476.17	1396.45	1452.78	1467.77	1447.16	44.84	39.27	41.86	43.65	43.84
Heilongjiang	1358.21	1315.56	1385.43	1362.99	1385.30	18.73	16.43	19.79	18.95	21.86
Shanghai	0.00	401.63	671.30	766.57	840.42	0.00	6.76	11.15	14.52	16.26
Jiangsu	0.00	925.58	1331.08	1699.60	1927.60	0.00	31.99	46.76	59.60	69.39
Zhejiang	783.82	845.01	975.45	1129.34	1067.96	35.05	33.41	33.51	35.91	29.05
Fujian	710.45	796.57	750.55	843.62	677.12	19.79	22.86	19.37	23.01	19.43
Shandong	0.00	635.87	1175.39	1629.13	2170.80	0.00	0.00	0.00	0.00	1.49
Guangdong	0.00	11.60	169.07	441.05	585.69	0.00	3.61	5.29	11.30	15.39
Hainan	33.34	53.17	51.42	22.78	0.00	1.01	1.86	1.88	0.62	0.00
Shanxi	3198.40	3029.40	3008.34	2735.91	2605.39	70.80	65.52	60.63	40.57	41.37
Inner Mongolia	3434.11	3586.35	3515.76	2912.04	2359.27	100.88	115.64	114.49	81.75	55.30
Anhui	1287.73	1210.29	1073.04	864.87	763.55	63.23	60.37	55.63	51.40	49.88
Jiangxi	561.16	864.19	746.83	848.38	506.65	30.53	40.62	37.60	40.82	30.06
Henan	0.00	0.00	1051.10	1818.99	0.00	0.00	0.00	28.24	54.11	0.00
Hubei	2061.46	1453.07	1436.81	1549.00	1472.63	58.71	22.07	19.34	24.32	21.87
Hunan	1001.40	979.25	1055.94	1078.04	931.28	17.62	23.65	28.35	30.15	30.04
Shaanxi	1323.08	1141.10	1107.00	981.33	723.34	38.52	27.45	24.97	22.58	17.69
Guangxi	851.21	647.89	511.37	561.51	397.98	38.50	34.77	31.67	34.59	32.15
Chongqing	686.65	890.76	910.04	440.24	372.79	6.09	16.46	18.93	5.99	6.60
Sichuan	887.51	491.67	297.25	227.63	0.00	9.04	3.62	1.40	2.35	0.00
Guizhou	1739.91	1703.59	1490.33	1641.72	1609.76	37.13	38.65	34.41	40.52	43.44
Yunnan	1403.55	1413.99	1164.82	1226.70	1124.66	38.32	40.70	34.56	36.85	35.16
Gansu	1263.17	839.07	946.13	874.45	765.65	26.82	10.27	13.51	12.37	11.39
Qinghai	0.00	124.80	125.00	0.00	17.11	0.00	0.00	0.00	0.00	0.00
Ningxia	1014.54	868.19	774.64	721.47	585.80	22.04	17.17	13.63	11.96	7.44
Xinjiang	1419.53	1368.79	1223.00	1169.81	1112.78	21.16	22.37	15.52	14.30	13.24

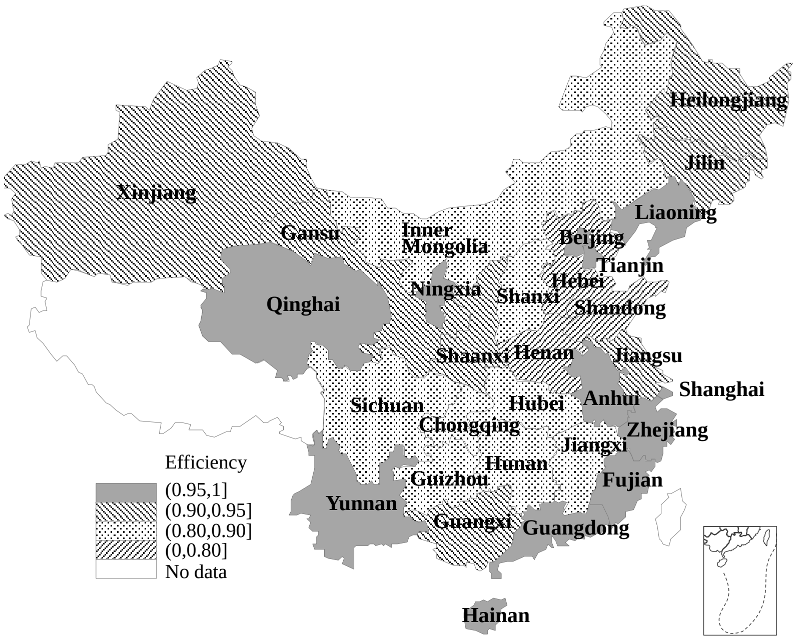

Figure 1 Average regional integrated efficiency under natural disposability of China (2006-2010)

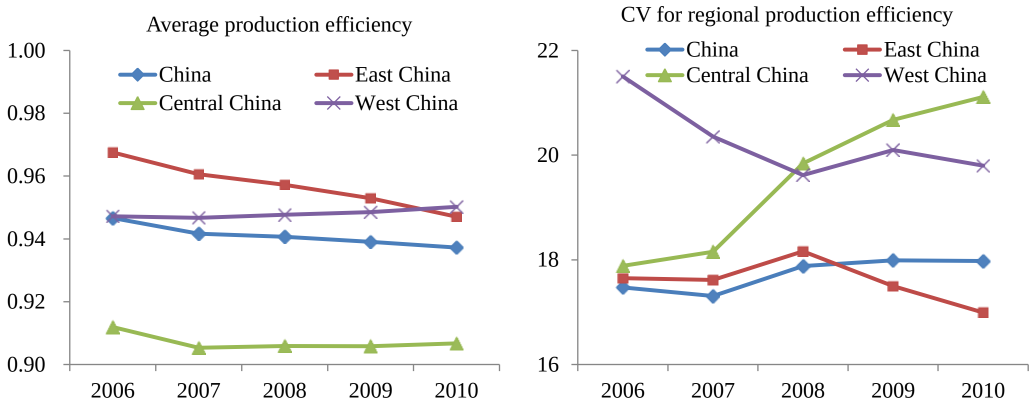

Figure 2 Regional production efficiency levels and differences

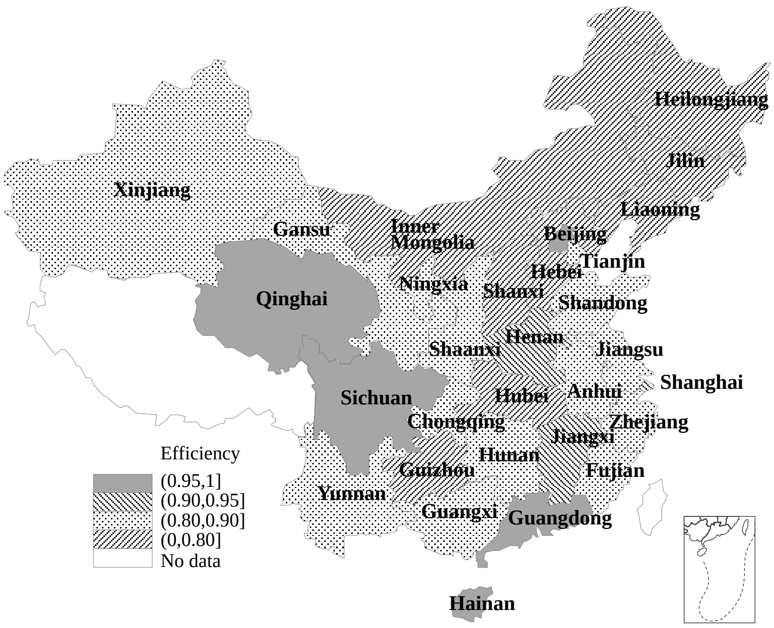

Figure 3 Average regional integrated efficiency under managerial disposability of China (2006-2010)

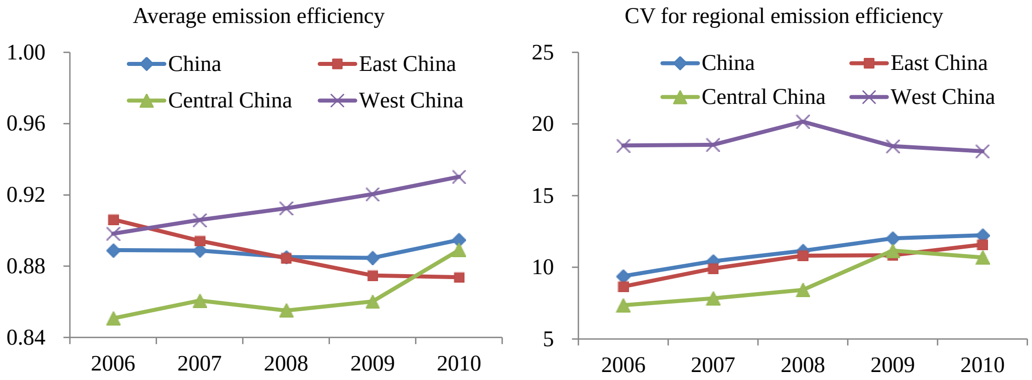

Figure 4 Regional emission efficiency levels and differences

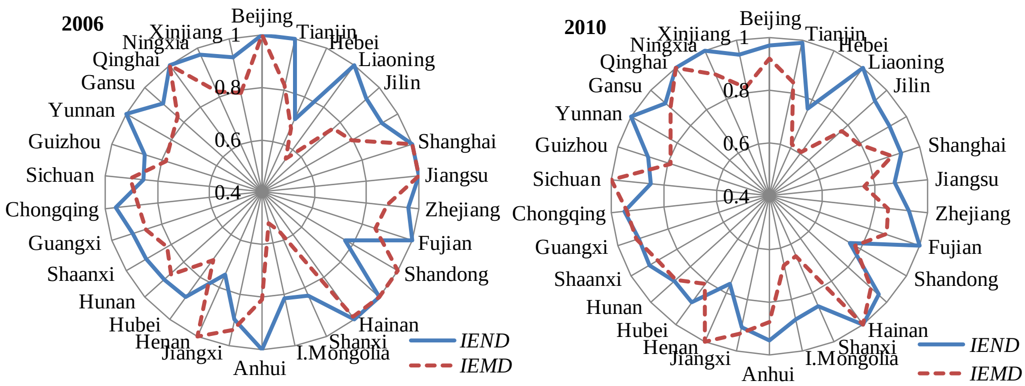

Figure 5 Regional integrated efficiency comparisons (2006 and 2010)

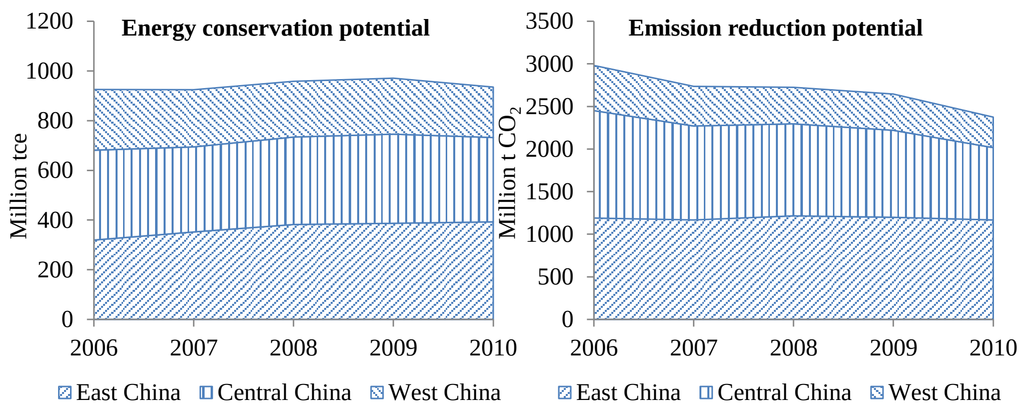

Figure 6 Energy conservation potential and emission reduction potential under natural disposability

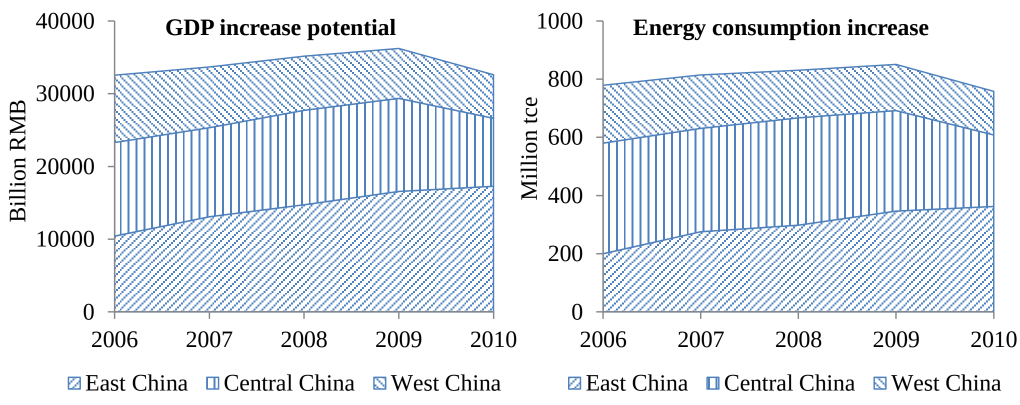

Figure 7 GDP increase potential and related energy consumption increase under managerial disposability