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An analysis of Chinese provincial carbon dioxide emission efficiencies based on energy consumption structure

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HIGHLIGHTS

- Slacks Based Measure model is used to analyze the carbon dioxide emission efficiencies.
- Data from 30 provinces in China are analyzed.
- Unacceptable loss of energy is identified.
- Chinese provinces are divided into five groups to effectively control emissions.

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ABSTRACT

China plans to reduce carbon dioxide emissions from 2005 levels by 40–45% by 2020 and by 60–65% by 2030. This research project addresses this challenge by analyzing Chinese provincial carbon dioxide emission efficiencies and the energy consumption structure. The study applies the Slacks Based Measure (SBM) model to analyze the data from 30 regions in China from 2000 to 2011. The situation of provincial carbon dioxide emission efficiency, the characteristics of the energy consumption structure in each province, and the differences among these provinces are quantitatively analyzed. Based on the K-means cluster analysis, this research suggests that China be divided into five groups in the energy consumption structure: the inefficient and less reasonable group, the inefficient and more reasonable group, the efficient and less reasonable group, the efficient and more reasonable group, and the efficient and most reasonable group. The study offers recommendations for the government to develop policies to effectively and efficiently reduce carbon dioxide emission levels for each group. It also has profound implications for government administration in developing countries to guide the energy consumption and to control environmental pollution for the healthy development of the economy.

1. Introduction

With over 30 years of reform and development, China's economy has maintained remarkable growth and has become the world's second largest economy close behind the United States. Meanwhile, China has also paid a heavy price with resources and the environment. Such high input, high consumption, high pollution, and low efficiency (three-high and one-low) ways of economic development are a serious constraint to the economic and social sustainable development of China (Gregg et al., 2008; Lin and Du, 2015). In addition, global warming and carbon emission reduction issues have become the common focus of world attention and research (Kounetas, 2015). China, as the world's largest developing country and a country with the largest increment of carbon dioxide emissions, is facing the global low-carbon challenge as well as the pressure of domestic resource shortages and serious environmental deterioration (Li et al., 2013).

The Chinese government has set targets to reduce carbon dioxide emissions per unit of GDP from 2005 levels by 40–45% by 2020 and by 60–65% by 2030. Improving the efficiency of carbon dioxide emissions is vital to achieving the Chinese carbon dioxide emission intensity targets by 2020, as well as by 2030. Moreover, China covers a large territory, has different resource endowments and regional economic developments, and hence consists of a variety of regional energy consumption structures. Therefore, the carbon dioxide emission levels are significantly different across various regions (Meng et al., 2011). With the development of the

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economy, the pressure of emission reduction will become even greater, and the cost will become proportionally higher. Therefore, research is needed to efficiently and effectively achieve carbon dioxide emission reduction at low cost while understanding and grasping the Chinese regional differences between the carbon dioxide emission efficiency and the energy consumption structure. It is important to reasonably distribute the carbon dioxide emission reduction task on the regional level and to put forward a corresponding policy to maintain the stable economic and social development (Fridley, 2011; Gregg et al., 2008; Lin and Du, 2015).

Many models have been proposed to study the impact of carbon dioxide emissions (Kounetas, 2015). Charnes et al. (1978) used Data Envelopment Analysis (referred to as DEA) to evaluate the effectiveness of multiple-output/multiple-input systems. Nabavi-Pelesaraei et al. (2014) applied DEA to analyze the efficiency of orchardists based on the non-parametric method for multi-criteria decision making. DEA is an evaluation method based on relative efficiency and the concept of convex analysis by using linear programming. It applies the mathematical programming model to assess the object and to evaluate the relative efficiency of a decision-making unit (DMU) which is multiple-input and multiple-output. DEA has been proven to have an advantage in handling multiple-output/multiple-input. However, the undesirable output problem is not considered in the traditional efficiency evaluation. The DEA relative efficiency evaluation requires that the input be reduced as much as possible and the output be expanded as much as possible (Goto et al., 2014).

Scholars have made useful attempts to apply the DEA efficiency evaluation model including the undesirable output. Hailu and Veeman (2001) used the undesirable output variables as inputs to process. This method clearly did not correspond to the actual production process. Scheel (2001) and Zhu (2003) first converted the undesirable output value into the reciprocal form, and then treated it as the desirable output variable. This method goes against the real production process, and the efficiency evaluation is still biased. Seiford and Zhu (2002) processed the undesirable output as the desirable output by use of the inverse output model, yet this method can only be used on the variable-returns-to-scale condition to solve the efficiency; otherwise, there may be no solution. Khalili-Damghani et al. (2015) used DEA to assess the optimal scale size of a combined cycle power plant in the presence of uncertain data and undesirable outputs. Chung et al. (1997) proposed a DEA model based on the directional distance function considering the undesirable output reduction and the desirable output expansion. It is a better solution to the problem of undesirable output efficiency evaluation which has been widely applied by Hu et al. (2008), Tu (2008), and Chen (2009). Previous research primarily relied on the radial and angle DEA model.

Tone (2001) proposed the Slacks Based Measure (SBM) model based on the slack variables measure. The SBM model is an efficiency evaluation method considering the relaxation of input-output. It not only solves the input-output relaxation problem but also solves the problem of undesirable output efficiency evaluation. In addition, the SBM model is the non-radial and non-angle evaluation method among the DEA model. It can effectively avoid the bias and influence caused by the choice differences of radial and angle (Chang et al., 2013). It reflects the nature of the efficiency evaluation better than other models. Bi et al. (2014) applied a Slacks Based DEA model to study the relationship between fossil fuel consumption and the environmental policy of power generation in China. Li (2009) and Wang et al. (2010) calculated the environmental efficiency of various regions in China using the SBM model. Bi et al. (2015) conducted profound studies by applying the SBM model based on Data Envelopment Analysis. Wang et al. (2013) applied range-adjusted measures to evaluate the regional energy and environmental efficiency of China. They geographically categorized Chinese regions into different groups and provided recommendations to improve the production process so that the local government could use it for environmental protection.

This study extends the previous research in several ways. First, this study collects data from 2000 to 2011. It is derived from a variety of sources including 30 provinces, municipalities, and autonomous regions. The carbon dioxide emission efficiencies are respectively calculated and compared according to 30 provinces, municipalities, and autonomous regions in China by use of the SBM model considering relaxation of the input-output problem. Second, the grouping of different Chinese regions was traditionally based on geographic locations to analyze different energy consumption structures and production processes. However, they may lack specificity with respect to policy making. This study utilizes K-means cluster analysis to determine the number of groups. The grouping of different provinces, municipalities, and autonomous regions is based on the results of cluster analysis. Third, the situation of provincial carbon dioxide emission efficiencies and differences are quantitatively analyzed. By using the Geographic Information System (GIS) technology, the evolution rule of carbon dioxide emission efficiencies in the provinces and the characteristics of the energy consumption structure are also studied. On this basis, combined with the characteristics of different provinces in China, spatial division of carbon dioxide emission efficiency and energy consumption structure characteristics in China's 30 provinces (municipalities and autonomous regions) are analyzed by the K-means cluster analysis method to identify the different provincial low-carbon development models in China.

2. SBM model and data sources

2.1. SBM model based on the undesirable outputs

It is assumed that the production system has n decision making units. Each decision unit has m inputs and s outputs. The basic form of the traditional SBM fractional programming model is:

$$\min \rho_o^* = \frac{1-(1/m)\sum_{i=1}^{m} s_{it}^-/x_{iot}}{1+(1/s)\sum_{r=1}^{s} s_{rt}^+/y_{rot}} \tag{1}$$

$$st.\quad x_{iot} = X_{it}\Lambda_t + S_{it}^-\ \ (i=1,2,\dots,m;\ t=1,2,\dots,T);$$
$$y_{rot} = Y_{rt}\Lambda_t - S_{rt}^+\ \ (r=1,2,\dots,s;\ t=1,2,\dots,T);$$
$$\sum_{j=1}^{n}\lambda_{jt}=1\ \ (t=1,2,\dots,T);\ \lambda_{jt},\ S_{it}^-,\ S_{rt}^+ \ge 0$$

where, S_{it}^- and S_{rt}^+ represent the amount of slack input and output. λ_{jt} is the weight vector. The above definition corresponds to the variable returns-to-scale (VRS) situation. The subscript o represents the DMU under evaluation. The matrices X_{it}, Y_{rt} and Λ_t are defined as follows:

$$X_{it} = [x_{i1t}, x_{i2t}\cdots x_{int}] \in R^{m\times n},\qquad Y_{rt} = \left[y_{r1t}, y_{r2t}\cdots y_{rnt}\right] \in R^{s\times n}$$
$$\Lambda_t = [\lambda_{1t}, \lambda_{2t}\cdots\lambda_{nt}]' \in R^{n\times 1}\qquad \text{Where } X_{it}, Y_{rt}, \Lambda_t > 0$$

Considering the undesirable outputs, it is assumed that the production system has n decision making units. Each decision unit has m inputs, s_1 desirable outputs, and s_2 undesirable outputs. The three elements can be expressed as $X_{it}\in R^m$, $Y_{rt}^g\in R^{s1}$, $Y_{kt}^b\in R^{s2}$. Also, X_{it}, Y_{rt}^g, Y_{kt}^b, $\Lambda_t\in$ matrices are defined as follows: