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Measuring ecological total-factor energy efficiency incorporating regional heterogeneities in China

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ABSTRACT

This paper proposes a metafrontier slack-based efficiency measure (MSBM) approach to model ecological total-factor energy efficiency. This new advanced approach incorporates group heterogeneities of regions, total slacks, and undesirable outputs simultaneously into energy efficiency analysis. We incorporate global environmental technology into the proposed model so as to improve its discriminating power. We conduct an empirical analysis of regional ecological energy efficiency by incorporating carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions and the chemical oxygen demand (COD) of China during 2001-2010. The results indicate that most of the provinces are not performing at high ecological energy efficiency. Significant regional technology gaps in ecological energy efficiency exist in three areas. We present some policy suggestions based on the empirical results.

1. Introduction

Although China has achieved remarkable economic growth in recent times, it is also facing serious problems concerning energy usage and carbon emissions. Since 2007, China has been the world's largest contributor of carbon dioxide (CO_2) emissions. Moreover, according to BP (2011), it overtook the United States to become the world's largest energy user in 2010. Thus, improving China's energy efficiency is critical for reducing its energy consumption and related emissions.

Accordingly, China's 12th Five-Year Plan announced several new energy and CO_2 emissions targets for 2015, including reducing energy intensity by 16%, SO_2 emissions and COD by 8%, and CO_2 emissions (per unit of GDP) by 17%. Corresponding targets for energy usage and emissions have also been announced for each of China's provinces. Therefore, a provincial energy efficiency analysis can help determine whether each province can meet its energy and emissions reduction targets through energy efficiency improvements.

Data envelopment analysis (DEA) has been widely used in energy efficiency analysis because it can provide a total-factor energy efficiency index (Hu and Wang, 2006). Using DEA, a number of studies have conducted energy efficiency analyses for China. Hu and Wang (2006) first employed the basic DEA model to analyze China's total-factor energy efficiency. Wei et al. (2009) added regression to the DEA model to evaluate regional energy efficiency and its determinants. However, as both studies neglected to address the environmental impacts of undesirable outputs in the fuel combustion process, their results may not prove effective in assessing ecological energy efficiency (Li and Hu, 2012). To take into account the growing concern about environmental impacts, undesirable outputs of emissions should be incorporated into the environmental DEA framework. Some studies have tried to include undesirable outputs while conducting an energy efficiency analysis for China. For instance, Shi et al. (2010) treated undesirable outputs as inputs in the energy efficiency analysis, and Yeh et al. (2010) employed the data translation method to incorporate undesirable outputs in energy efficiency measurements. Wu et al. (2012) used the weak disposability concept for undesirable outputs in energy efficiency benchmarking.

However, the above papers were based on radial efficiency measures and suffered the limitation of overestimating energy efficiency, because they neglected the slack variables (Fukuyama and Weber, 2009). To overcome this problem, Tone (2001) first incorporated a slack-based efficiency measure (SBM) in DEA to measure technical efficiency. Zhou et al. (2006) incorporated undesirable outputs into the basic SBM to calculate environmental performance. Some recent studies have employed the SBM to calculate ecological total-factor energy or carbon efficiency for China

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(Bi et al., 2014; Chen and Zhang, 2014, Choi et al., 2012; Li and Hu, 2012; Song et al., 2013; Wei et al., 2012; Zhang and Choi, 2013a).[1]

Despite much progress in this area, some methodological limitations persist. A common limitation of previous studies is that they did not consider regional heterogeneities in production technology. If technological heterogeneities among provinces are not considered, the estimated energy efficiency score may be biased because group heterogeneity may lead to differences in production technologies (Battese et al., 2004). This is especially significant for China. There are large provincial differences in the production structure; some provinces house more service industries, while others have more rural or manufacturing industries. Thus, the single technology DEA approach, wherein the production technology is assumed to be the same, is relatively restrictive. The metafrontier approach incorporating technology heterogeneities may overcome this limitation. Some studies have used the metafrontier approach in the directional distance function framework (Chiu et al., 2012; Zhang and Choi, 2013b, Zhang and Choi, 2013c; Zhang et al., 2013). However, the metafrontier approach has not been combined with the SBM framework. Thus, this study proposes a metafrontier SBM incorporating regional heterogeneities to measure China's ecological total-factor energy efficiency (ETFEE). This new approach allows us to simultaneously incorporate group heterogeneities of regions, total input slacks, and undesirable outputs into energy efficiency analysis. To improve the discriminating power of the proposed model, we employ global environmental technology as the reference technology.

The rest of this paper is organized as follows. Section 2 presents the metafrontier slack-based efficiency measure (MSBM) approach, Section 3 presents an empirical study using the proposed approach for Chinese regions from 2001-2010, and Section 4 concludes with some policy suggestions.

2. Methodology

2.1. SBM model

Assume that there are $n = 1,\ldots,N$ regions in China, and each region uses input vector $x \in \Re_+^m$ to jointly produce outputs vector $y \in \Re_+^R$ and undesirable outputs $b \in \Re_+^J$. In this study, the output vector contains regional GDP (g) and SO_2 (s), CO_2 (c), and COD (d) as the by-products of GDP. The input vector contains capital (k), labor (l), and energy (e).

The multi-output production technology can be expressed as

$$T = \{(x, y, b) : x\, can\, produce\, (y, b)\}, \tag{1}$$

where T is often assumed to satisfy the standard axioms of the production theory (Färe and Grosskopf, 2005). For instance, inactivity is always possible, and finite amounts of inputs can produce only finite amounts of outputs. In addition, inputs and desirable outputs are often assumed to be strongly or freely disposable.

After defining the production technology T, we use the parametric distance function or the nonparametric DEA to construct the production technology in the presence of undesirable outputs. In this paper, we use a nonparametric DEA piecewise linear production frontier to construct the production technology. Then, we express T for N regions exhibiting constant returns to scale as follows:[2]

$$\begin{aligned} T = \{(x, y, b) \;:\; & \sum_{n=1}^{N} \lambda_n x_{mn} \le x_m, m = 1, \ldots, M, \\ & \sum_{n=1}^{N} \lambda_n y_{rn} \ge y_r, r = 1, \ldots, R, \\ & \sum_{n=1}^{N} \lambda_n b_{jn} \le b_j, j = 1, \ldots, J, \\ & \lambda_n \ge 0, n = 1, \cdots, N.\} \end{aligned} \tag{2}$$

Here, λ is a nonnegative multiplier vector for constructing the production technology through a convex combination. One can impose some constraints on the intensity vector, such as $\sum_{n=1}^{N} \lambda_n = 1$ for variable returns to scale (VRS). If the nonparametric production technology is well constructed, then the SBM model can be used to calculate energy efficiency. The conventional radial DEA method neglects slack variables that may overestimate efficiency when there is nonzero slack (Fukuyama and Weber, 2009). In order to overcome this limitation, some recent studies have tried to develop non-radial DEA approaches (Fukuyama and Weber, 2009; Zhou et al., 2007, 2012). The SBM developed by Tone (2001) is a non-radial approach with some desirable features. It directly accounts for input and output slacks in efficiency measurements, with the advantage of capturing the whole aspect of inefficiency. However, undesirable outputs are not incorporated in Tone's SBM model. Zhou et al. (2006) extended the SBM model to incorporate undesirable outputs. If we add the slacks for undesirable outputs into the objective function by modifying the constraint for undesirable outputs, the following undesirable output SBM model (Cooper et al., 2007) can be used:[3]

$$\rho^* = \min \frac{1 - \frac{1}{M}\sum_{m=1}^{M} \frac{s_{m0}^x}{x_{mo}}}{1 + \frac{1}{R+J}\left(\sum_{r=1}^{R} \frac{s_{r0}^y}{y_{r0}} + \sum_{j=1}^{J} \frac{s_{j0}^b}{b_{j0}}\right)}$$

$$\begin{aligned} & S.T. \\ & \sum_{n=1}^{N} \lambda_n x_{mn} = x_{mo} + s_{m0}^x \\ & \sum_{n=1}^{N} \lambda_n y_{rn} = y_{r0} - s_{r0}^y \\ & \sum_{n=1}^{N} \lambda_n b_{jn} = b_{j0} + s_{j0}^b \\ & s_{m0}^x \ge 0, s_{r0}^y \ge 0, s_{j0}^b \ge 0, \lambda_n \ge 0 \end{aligned} \tag{3}$$

where $m = 1,2\ldots,M$ Index of inputs;

[1] Among the non-radial efficiency approaches, the slacks-based measure (SBM) directly accounts for input and output slacks in efficiency measurements, with the advantage of capturing the whole aspect of inefficiency. This property is particularly suitable for the reduction of undesirable outputs and energy consumption (Zhang and Choi, 2013a).

[2] There are different methods to handle undesirable outputs in energy efficiency analysis, such as treating an undesirable output as an input (Shi et al., 2010), using the data translation method (Yeh et al., 2010), and employing weak disposability (Wu et al., 2012). In this study, we use a slack-based measure model to treat undesirable outputs, because the remaining methods pose certain limitations (Zhang and Choi, 2013a). Recently, some new methodologies have been proposed for modeling environmental technology, such as pollution generating technologies (Murty et al., 2012) or the nutrients balance approach (Hoang and Nguyen, 2013).

[3] Taking advantage of the Porter hypothesis, Sueyoshi and Goto (2012) introduced managerial disposability in DEA environmental assessment and proposed its usage for measuring energy and environmental efficiency in developed countries. However, this approach is not suitable for China, because China is still a developing country.