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The effect of size-control policy on unified energy and carbon efficiency for Chinese fossil fuel power plants

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HIGHLIGHTS

- Two non-radial directional distance functions are presented for energy/carbon efficiency analysis.
- An empirical study of 252 fossil fuel power plants in China is conducted.
- The five state-owned companies show lower unified efficiency and energy–environmental performance.

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ABSTRACT

This paper examines the effect of size control policy on the energy and carbon efficiency for Chinese fossil fuel power industry. For this purpose, we propose two non-radial directional distance functions for energy/carbon efficiency analysis of fossil fuel electricity generation. One is named a total-factor directional distance function that incorporates the inefficiency of all input and output factors to measure the unified (operational and environmental) efficiency of fossil fuel power plants, and the other is called an energy–environmental directional distance function that can be used to measure the energy–environmental performance of fossil fuel electric power plants. Several standardized indicators for measuring unified efficiency and energy–environmental performance are derived from the two directional distance functions. An empirical study of 252 fossil fuel power plants in China is conducted by using the proposed approach. Our empirical results show that there exists a significant positive relationship between the plant size and unified efficiency, the five state-owned companies show lower unified efficiency and energy–environmental performance than other companies. It is suggested that Chinese government might need to consider private incentives and deregulation for its state-owned enterprises to improve their performance proactively.

1. Introduction

Fossil fuel electricity generation accounts for more than 40% of global CO_2 emissions and thus is a core issue in environmental management and sustainable development International Energy Agency (IEA) (2011). In China, fossil fuel electricity generation accounted for about 50% of coal consumption and 48% of CO_2 emissions from fossil fuel combustion in 2010 (Liu and Wang, 2011). Clearly, this sector plays an important role in reducing China's total CO_2 emissions. In this regard, it is crucial for fossil fuel power plants in China to improve their energy and operational efficiency to reduce CO_2 emissions. By taking a proactive approach to improving energy efficiency, power generation companies cannot only reduce CO_2 regulation risks but also improve their economic competitiveness through decreasing their costs.

During the 11th five-year plan (2006–2010), China's fossil fuel power industry was under substantial pressure to reduce its emissions to meet emission reduction targets. The Chinese government introduced a selective concentration policy to meet these targets. The country's “promoting large and closing small” policy implies the closure of small fossil fuel power plants by 2010 and

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the total loss of 76,830 MW (10.8% of the total capacity). This selective concentration policy during the 11th five-year period was very effective in that, with 2005 as the base year, the fossil fuel power sector reduced its CO_2 emissions by 1.74 billion tons (China Electricity Council, 2011). The aim of this study is to investigate the effect of the carbon reduction policy on the energy and carbon efficiency for Chinese fossil fuel power industry.

Several studies have conducted simple benchmark analyses to estimate the emission reduction potential of global electricity generation (Maruyama and Eckelman, 2009; Ang et al., 2011). This approach assumes that the efficiency of fossil fuel electricity generation for any country is greater than or equal to a certain level established by sample countries or regions. Despite the usefulness of findings based on this approach, it typically considers only one indicator and thus may be considered a single-factor analysis. However, electricity generation is a multi-factor production process in which energy as well as non-energy inputs such as labor and capital are employed to produce electricity. As discussed in Sueyoshi and Goto (2011), measuring the unified efficiency of electricity generation within a total-factor production framework can provide better insights into power managers' decision making.

Many studies have benchmarked energy and environmental performance from a production efficiency point of view (Zhou et al., 2008a). Along this line of research, data envelopment analysis (DEA) technique has gained popularity in assessing energy and environmental performance (Song et al., 2012). See, for example, Zhou et al. (2006, 2010); Picazo-Tadeo et al. (2011) and Wang et al. (2013a). In the case of electric power industry, a number of studies have employed DEA to analyze the efficiency of fossil fuel electricity generation (e.g., Barros and Peypoch, 2008; Liu et al., 2010; Yang and Pollitt, 2010; Sozen et al., 2010; Sueyoshi et al., 2010; Jaraite and Maria, 2012; Sueyoshi and Goto, 2011, 2012a, 2012b; Zhou et al., 2012, 2013; Bi et al., 2014). However, few have focused on the use of the directional distance function (DDF) for efficiency measurement of electric power industry. In comparison to traditional DEA models, DDF measures efficiency by increasing desirable outputs (e.g., electricity) and reducing undesirable ones (e.g., CO_2 emissions) simultaneously. At power plant level, Färe et al. (2007) employ the DDF to measure the environmental efficiency of coal-fired plants in the US. Zhang et al. (2013) develop a metafrontier DDF for measuring energy and carbon emission efficiency of Korean fossil-fuel power plants. Zhang and Choi (2014) proposes a comprehensive literature review on DDF in energy and environmental studies.

The conventional DDF reduces undesirable outputs (inputs) and increases desirable outputs at the same rate and may be regarded as a radial efficiency measure with several limitations. One limitation is that a radial measure may overestimate efficiency when there exist some slacks (Fukuyama and Weber, 2009). In addition, as Sueyoshi and Goto (2011) argued, a radial efficiency measure cannot distinguish between environmental performance and operational performance for power plants. Several studies have extended the conventional DDF to the non-radial DDF (NDDF) by incorporating slacks into efficiency measurement (Fukuyama and Weber, 2009; Färe and Grosskopf, 2010; Barros et al., 2012). More recently, Zhou et al. (2012) define a NDDF with desirable mathematical properties by taking an axiomatic approach to efficiency measurement. Wang et al. (2013c) use the NDDF to measure the Scenario-based energy efficiency and productivity.

The present paper proposes two NDDFs based on Zhou et al. (2012) to measure the unified efficiency (operational and environmental efficiency) and energy–environmental performance of fossil fuel power plants in China. Unlike Zhou et al. (2012), however, the paper considers not only energy inputs but also non-energy ones (capital and labor) because it focuses on benchmarking unified performance within a total-factor production framework. Another contribution is that this paper employs plant-level data, whereas country-level data are used by Zhou et al. (2012). To measure unified efficiency, we propose a total-factor NDDF (TNDDF) that incorporates inefficiencies for all the input and output factors. To measure energy–environmental performance, we introduce an energy–environmental NDDF (ENDDF) by fixing non-energy inputs. To the best of our knowledge, this paper is the first to empirically measure the unified efficiency of fossil fuel power plants in China. Some studies analyzed other environmental characteristics of Chinese fossil fuel power plants such as productivity growth (Zhang and Choi, 2013a) and shadow price of CO_2 emissions (Wei et al., 2013).

The rest of this paper is organized as follows: Section 2 describes the material and methods. Section 3 empirically estimates the unified efficiency and energy–environmental performance of fossil fuel power plants in China and presents the results, Section 4 presents the related discussions, and Section 5 concludes and proposes some policy suggestions.

2. Material and methods

2.1. Methods

Suppose that there are N fossil fuel power plants and that each plant uses capital (K), labor (L), and fossil fuel (F) as inputs to generate electricity (E), the desirable output, and CO_2 emissions (C), the undesirable output. The multi-output production technology can be described as follows:

$$T=\{(K,L,F,E,C):(K,L,F)\text{ can produce }(E,C)\},\tag{1}$$

where T is often assumed to satisfy the standard axioms of production theory (Färe and Grosskopf, 2005). For instance, inactivity is always possible, and finite amounts of inputs can only produce finite amounts of outputs. In addition, inputs and desirable output are often assumed to be strongly or freely disposable. For a reasonable modeling of joint-production technology, as described in Färe et al. (1989), the weak-disposability and null-jointness assumptions should be imposed on T. Technically, these two assumptions can be expressed as follows:

(i) If $(K,L,F,E,C)\in T$ and $0\le\theta\le 1$, then $(K,L,F,\theta E,\theta C)\in T$,
(ii) If $(K,L,F,E,C)\in T$ and $C=0$, then $E=0$.

The weak-disposability assumption indicates that reducing CO_2 emissions is costly in terms of a proportional reduction in electricity generation, and the null-jointness assumption implies that CO_2 emissions are unavoidable in fossil fuel electricity generation and that the only way to remove all CO_2 emissions is to stop operating electric power plants.

Once the environmental production technology T is specified, the parametric translog/quadratic function or the nonparametric DEA method can be used to specify the environmental production technology. Based on Färe et al. (2007) and Zhou et al. (2012), the environmental production technology T for N power plants exhibiting constant returns to scale can be expressed as follows[2]:

$$T=\left\{\begin{array}{l}(K,L,F,E,C):\sum\limits_{n=1}^{N}z_nK_n\le K,\ \sum\limits_{n=1}^{N}z_nL_n\le L,\\ \sum\limits_{n=1}^{N}z_nF_n\le F,\ \sum\limits_{n=1}^{N}z_nE_n\ge E,\ \sum\limits_{n=1}^{N}z_nC_n=C,z_n\ge 0,n=1,2,\ldots,N\end{array}\right\}\tag{2}$$

[2] The environmental technology is based on the assumption that exhibiting constant returns to scale. Although the assumption is widely adopted in literature, other cases like variable returns to scale could occur in real cases. Zhou et al. (2008b) discussed the characterization of environmental production exhibiting variable returns to scale.