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Environmental efficiency evaluation of thermal power generation in China based on a slack-based endogenous directional distance function model

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A B S T R A C T

This study proposes a slack-based endogenous directional distance function model (SBEDDF) to assess the environmental impact of China's power generation industry. By selecting directional vectors according to slack values and endowing them with norms, this model guarantees that unit invariance and efficiency value measures are suitable for economic interpretation. The results of this study indicate that the environmental efficiency of China's power generation industry is low and varies considerably from one region to another. The optimal approach to reduction of emissions is unique for each region. For example, in Guangxi, reducing SO_2 emissions is the priority, while in Shanxi, NO_x emissions need to be targeted. The results of the Tobit regression analysis indicate that the power function of unit elasticity fits the environmental Kuznets curve of the power industry well. These results demonstrate that it is prudent for environmental administrators to tailor emission reduction standards and incentive policies to the prevailing circumstances in a region.

1. Introduction

In recent years, smog and related air quality issues have been in the forefront across China. Air pollution has become the focus of attention across all social sectors and is directly related to energy production and distribution in China [1]. As the largest coal producer and consumer in the world, China's coal consumption is almost half of that across the globe [2]. Compared with other energy sources, such as petroleum and natural gas, coal is an unclean source of energy because coal-burning produces pollutants like SO_2, NO_x, and soot that are released into the environment. Thermal power generators are the main industrial consumers of coal resources, up to half of the total coal yield, and the single greatest contributors to air pollution. To combat such problems, China has gradually strived to restrict the toxic emissions of the thermal power generation industry. The first of these regulations to restrict the emissions was the Tentative Standard for Industrial "Three Wastes" Emission Rule (GBJ4-73), published in 1973 and specific to air pollution contributions by thermal power generation was the Emission Standards of Air Pollutants for Coal-Fired Power Plants (GB13223-1991), published in 1991. After several amendments, the latest Emission Standard of Air Pollutants for Thermal Power Plants, 2011 (GB13223-2011) was implemented in 2012. This standard is the strictest standard in China's history. The emission limit for soot was lowered to 30 mg/m^3, while the emission limit for key areas was lowered to 20 mg/m^3. SO_2 emission tolerance was lowered to 200 mg/m^3, while the emission limit for some boilers in key areas was lowered to 50 mg/m^3. The emission limit for NO_x was lowered to 100 mg/m^3. This newest emission standard for air pollutants is comparable to EU, American, and Japanese standards, whose emission limits for soot, SO_2, and NO_x are, respectively, 30 mg/m^3, 200 mg/m^3, and 100 mg/m^3. To satisfy the requirements in GB13223-2011 as described above, China incurs a great deal of expenditure on environmental protection. There has been no breakthrough in low-cost low-emission power generation technology in China. To reduce the emission, the only choice for the power generation enterprises is adding more desulphurization and dust-removing equipment, which would consume energy and increase the cost of power generation. The estimate for short-term pollution control expenditure on current thermal power

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generating units is as high as 200 billion to 250 billion Yuan. This would put a great financial burden on power generation enterprises unless the price of electricity is significantly increased.

Strict emission limits are no doubt beneficial to improve the quality of air, human health, and the environment. However, it is not an optimal practice to set one single quantitative standard for all areas. From the economic perspective, the lower the level of pollution emission, the higher the marginal cost of further reducing them [3]. There is a huge diversity in economic development, population conditions, and resource endowments across China. According to the data from the sixth census, Shanghai had 3650.36 people per square kilometer, while in Heilongjiang Province, this number was 85.12. In the western region, the population density is even lower. It is reasonable to believe that there exist diversities in the emission level of thermal power plants across the country. In addition, thermal power plant pollutant emission is also multidimensional. Given that the production conditions and emission levels in different areas of China vary greatly, emission policies should be formulated considering this diversity.

If the objective of the final policy is to reduce the total amount of country-wide emissions, a better method would be to find out the production frontier curve of thermal power generation plants, and calculate the environmental efficiency as a function of the deviation of the actual condition of these plants with respect to their efficiency frontiers. The next step would be to formulate the designated emission reduction standards for different areas. The development of an understanding of production frontiers fundamentally relies on how each contaminant of concern is treated within the reduction goal. Depending on how these pollution emissions are reduced, we have to determine the optimal emission reduction direction.

To evaluate the environmental performance and calculate the optimal emissions reduction direction for each area of concern, we propose a directional distance function model, namely, the slack-based endogenous directional distance function (SBEDDF) model, which has three main advantages as compared to the existing models:(i) it objectively provides the optimal direction along which the decision-making unit moves towards the frontier, (ii) it supports unit invariance once the optimal direction vector is given, and (iii) the results provide a more robust economic interpretation. Applying this model to data from 2006 to 2012, we studied the thermal power generation in each area of China and defined the optimal direction for emission reduction for each, under the principle of slack maximization.

This study commences with a review of existing literature that describes the development of the directional distance function model and previous environmental efficiency evaluation of China's thermal power industry. On this basis, the research introduces the SBEDDF model, in which directional vectors are selected according to slack values. Finally, we completed an analysis of environmental efficiency and directional vectors for thermal industries in 30 areas and compared the results with those of other models.

2. Literature review

Charnes et al. [4] first introduced the Data Envelopment Analysis (DEA) method for measuring the efficiency of decision-making units. Traditional DEA models are radial; each input or output factor must be adjusted proportionally and the direction of movement is towards the original point in the coordinate system. The directional distance function (DDF) models proposed by Luenberger [5]; Chambers et al. [6] and [7] and Chung et al. [8] broke the restrictions of radial models, allowing decision-making units to move along liberally-defined directions, which greatly increased the flexibility of efficiency evaluation.

Undesirable outputs occur frequently during efficiency evaluations, yet these can be suitably resolved using the directional distance function, which designates the direction of desirable output as positive, while the direction of undesirable output is negative. Thus, decision-making units can simultaneously expand desirable outputs and compress undesirable outputs, rendering greater accuracy in both evaluations and explanations. Due of these advantages, directional distance functions are widely used to evaluate environmental performance, eco-efficiency, and total factor energy efficiency. Zha and Zhou [9] applied the directional distance function to the Chinese industry at the provincial level with the consideration of undesirable outputs. They found that Shanghai, Fujian, and Guangxi were always environmentally efficient. Besides the directional distance function, the slack-based measure (SBM) proposed by Tone [10] is also suitable for managing undesirable output. Mei et al. [11] combined the SBM model with Meta-frontier to evaluate the regional environmental efficiency in China, also incorporating sulfur dioxide emissions and the chemical oxygen demand (COD).

This paper is mainly focused on directional distance function models, where an alternative directional vector is proposed. Researchers need to define directional vectors themselves when dealing with undesirable outputs, except for a few based on a priori information. These decisions are often subjective. Chung et al. [8] put forward an approach that was followed by similar studies [12,13]. Their approach directly borrows the observed values of decision-making units as directions, which maintains the unit variance. However, direct use of observed values as directional vectors has no theoretical basis and efficiency values may be overestimated in practice.

In Fig. 1, the vertical axis represents the desirable output while the horizontal axis, the undesirable output and the observed values of unit "A" are (y_0, b_0). According to the approach of Chung et al. [8]; the directional vector is selected as $(y_0, - b_0)$, which is represented by OC, and along which the projection point of A is D; AD is parallel to OC. In this condition, slack exists. However, along the direction of AE, undesirable outputs can be further reduced without changing the desirable outputs. The region represented by ED is called "slack deviation" [14].

Considering the described defect in directional distance function, some researchers attempted to combine the directional distance function and slack-based models. Fukuyama and Weber [14] introduced the directional distance function in the SBM model, and thus constructed an inefficiency measurement approach, known as directional slack-based inefficiency (SBI) measurement. Such a measurement approach considers the slack between the input and output. The model by Barros et al. [15] also considers slack and allows for adjustment in the desirable and undesirable outputs to varied degrees. Zhou et al. [13] and Wang et al. [16] used this approach in their research, generally called the non-radial

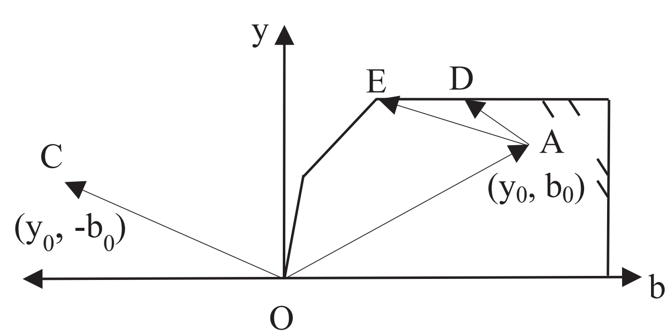

Fig. 1. Directional distance function.