Sustainable Cities and Society 36 (2018) 157–168

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Eco-efficiency measurement of coal-fired power plants in China using super efficiency data envelopment analysis

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ARTICLE INFO

Keywords:
Coal-fired power plant
Eco-efficiency analysis
Super efficiency data envelopment analysis
External factors
Tobit regression

ABSTRACT

The measurement of coal-fired power plant eco-efficiency and identification of influencing variables are of great importance for the government to develop relative policy decisions. In this article, an improved two-stage analysis model is employed to analyze eco-efficiency of 58 Chinese coal-fired power plants: firstly, principal component analysis is selected for pre-treatment of variables in order to reduce dimensionality and distinguish prioritized factors; secondly, the super efficiency data envelopment analysis is chosen to assess eco-efficiency with overall ranking; thirdly, Kruskal-Wallis rank sum tests are adopted to figure out macro-environmental factors; finally, considering interactions in the coal power industry chain, plus time effect, we apply the Tobit regression to determine direct external factors. According to the result, over 60% of the coal-fired power plants work in an acceptable productive condition, while some still face improper investment problems. Plants with large installed capacity tend to stably operate. Then, macro-environmental factors like policy preference and economic situation can greatly affect local plants' performance, while resource distribution has few impacts because of the perfect transport condition. In addition, the increasing thermal coal price help improve eco-efficiency while the high power unit age and feed-in tariff do harm to production performance. Based on the analysis, this paper also proposes some effective suggestions for the government.

1. Introduction

Because of its large energy consumption and pollutant gas emissions, coal-fired power generation is under highly supervision by both the government and the public. Coal power takes a proportion of 40.8% in electricity generation in 2014 (Agency, 2016a). Fig. 1 shows the annual electricity produced by coal in the top four coal-fired countries from 2000 to 2014 (Bureau, 2016). China, ranking the first in electricity generation, owns a significant proportion of coal-fired power plants (CFPPs). With the resource endowment of coal, China still has a long way to go in changing the dominant position of coal in electricity generation. CFPPs' cumulative installed capacity in China has reached up to 920 GW until June 2016, accounting for 60.2% of the total generating installed capacity (Shui, 2016). However, inefficient fuel combustion is one of most important man-made sources of air pollutant emissions in energy production and utilization (Agency, 2016b). To meet the demand of energy conservation and emission reduction, it is imperative to measure the CFPPs' eco-efficiency and analyze the real influencing factors.

Some academic researches concerning CFPP's efficiency are carried out and the stochastic frontier analysis is one of most frequently used techniques in measuring efficiency. Based on the data of Indian power plants in 1986 and 1987, Singh (Singh, 1991) measures their technical efficiency by estimating a deterministic frontier production function. Furthermore, he points out that the size and capacity of power plants have positive effects on their technical efficiency. Later, Khanna and Zilberman (Khanna and Zilberman, 1999) use the stochastic frontier analysis to calculate CFPPs' technical efficiency and draw a conclusion that inefficient operations, imperfect facilities and high coal fees take great responsibilities for power plants' inefficiency.

Compared with the stochastic frontier analysis, another popular analysis method the data envelopment analysis (DEA) has an advantage of working out the result without knowing the specific form of production frontier (Vyas and Jha, 2017), for which DEA methods are more preferable in the coal-fired field. Sarıca and Or (Sarıca and Or, 2007) use DEA to evaluate both investment performance and operational performance of 65 Turkish power plants. They stress the environment cost negatively affect both the AR-IC efficiency and scale efficiency. Yang and Pollitt (Yang and Pollitt, 2009) propose six DEA-based performance evaluation models to deal with undesirable outputs and

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http://dx.doi.org/10.1016/j.scs.2017.10.011
Received 30 March 2017; Received in revised form 9 September 2017; Accepted 8 October 2017
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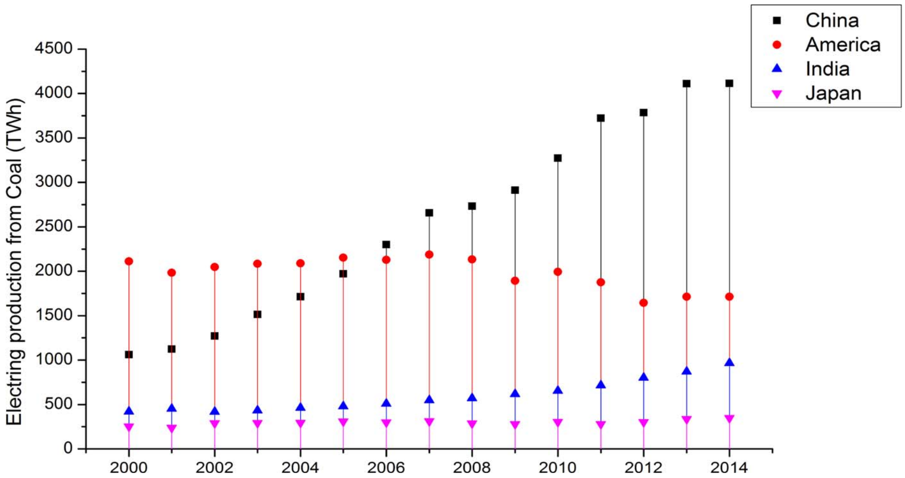

Fig. 1. Annual coal-fired power in China, America, India and Japan (2000–2014).

uncontrollable variables by calculating sample data of Chinese CFPPs. Based on the analysis of influencing factors, they claim that uncontrollable variables which result from the market and regulatory mechanisms have relatively significant impacts. Comparing American CFPP performance efficiency in the market liberalization and deregulation state, Sueyoshi et al. (Sueyoshi, Goto, & Ueno, 2010) arrive at the conclusion that plants in regulated states have more energy to ensure the long-term efficient operation and electricity stable supply. Selecting the coal consumption, the fuel oil consumption, the auxiliary power consumption as inputs and the generated electricity as an output, Shrivastava et al. (Shrivastava, Sharma, & Chauhan, 2012) assess relative technical efficiency of 60 CFPPs and work out the relationship between the plant size and efficiency. Zhou et al. (Zhou, Xing, Fang, Liang, & Xu, 2013) study the environmental efficiency of Chinese power industrial by integrating the entropy weight and the Slack Based Measure method. Moreover, by using the Tobit regression analysis, they point out the positive correlation between environmental efficiency and three uncontrollable factors, including enterprises' innovation ability, coal power proportion and generation capacity. Song et al. (Song, Li, Zhang, He, & Tao, 2015) analyze both the special and generalized energy efficiency of 34 Chinese coal-fired power units. They also find out the relation between energy efficiency and non-comparable factors, namely coal quality, load factor, capacity factor, main Steam parameters and cooling method.

However, some problems still exist in the CFPP efficiency measurement and related analysis of influencing variables.

Firstly, the independence of inputs can't be protected and no obvious linear relationships among inputs and outputs are permitted in DEA models. In previous studies, inputs from all aspects have ever been taken into consideration. However, things are generally linked, which increases difficulty in weighing between quantity and independence of variables. The correlation among input indicators will have significant influence on the accuracy of the efficiency measurement result.

Secondly, few researches on CFPP eco-efficiency measurement provide overall ranking. Most of them focus on selecting the efficient decision making unit (DMU) and neglect further research on efficient DMUs However, the whole CFPP ranking is paid great attention to by the society. Based on the ranking, the government can reasonably determine which plants should be shut down or rectified in the case of excess capacity.

Thirdly, it is difficult for the government to understand the analysis results because few researches are conducted from the governmental perspective. In a majority of researches, suggestions are offered mainly towards enterprises rather than the government.

The purpose of this research is to quantitatively measure the eco-efficiency of existing Chinese CFPPs on one hand and to identify the real influencing factors and make some effective suggestions on the other hand. The possible innovations are as follows: firstly, principal component analysis (PCA) is selected for pre-treatment of variables in evaluating CFPPs' eco-efficiency, so the dimensionality of inputs/outputs can be reduced and prioritized factors are distinguished. Moreover, it helps to cut the computational workload in the analysis by reflecting the original multidimensional variables with several synthetic variables; secondly, the super efficiency data envelopment analysis model (SE-DEA) is chosen to assess CFPPs' eco-efficiency with overall ranking including both efficient and inefficient DMUs. Then, environmental factors from resources, policies and economy aspects are involved in the Kruskal-Wallis (K-W) test, which can comprehensively reflect the relationship between CFPPs' locations and eco-efficiency; thirdly, under the consideration of an interaction between upstream and downstream enterprises in the coal power generation industry chain, three uncontrollable factors including thermal coal prices, utility ages and feed-in tariffs are tested in the Tobit regression model plus the time effect. Main contributions of the paper can be concluded as three aspects. First and foremost, the overall ranking in eco-efficiency can not only help the government get rid of massive and disorganized CFPP operation information, but also figure out troubled and well-performed CFPPs. In addition, based on the environmental analysis, policy makers can easily keep scientific coordination of regional development and CFPP supervision. Last but not least, the research on uncontrollable variables can help the government adjust macro-control policies in accordance with the development law of CFPPs' eco-efficiency, coal prices and power prices.

The remainder of this study is organized as follows: Section 2 provides a brief introduction of PCA, SE-DEA, K-W test and Tobit regression model. Section 3 conducts a variable pre-treatment and explains the data source. Section 4 analyzes a concrete case in China and tries to figure out environmental factors and uncontrollable variables. Section 5 draws a conclusion and make some recommendations.

2. Methodology

2.1. Research framework

A four-phase analysis model is proposed to analyze CFPPs' eco-efficiency and the concrete procedures are as follows. Fig. 2 is a specific flow chart of research methodologies.

2.1.1. Phase I: pre-treatment of variables

The pretreatments of variables, mainly including index selection and data processing, identifying input and output variables, which will directly affect the accuracy of subsequent analysis. Firstly, original analysis indexes are figured out by literature arrangement, data availability analysis and expert advice. Next, Pearson correlation coefficient