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Efficiency evaluation of China's provincial power systems based on the dynamic network slacks-based measure model

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ABSTRACT

A power system contains generation, transmission, and distribution divisions. Policy reforms and management mechanisms may affect the environmental efficiency of certain divisions or the integrated power system. This study applied the dynamic network slacks-based measure (DNSBM) model to analyze the environmental efficiency of both the power systems and their divisions of provincial administrative areas in China and investigated the effects of the external environmental factors. It employed scenario analysis to further explore the feasibility of separating the distribution from the transmission division. The results indicate that: 1) The DNSBM model takes the internal structure of the power system into account and provides a new perspective to seek the sources of the system and division efficiencies. 2) Customer density and energy consumption intensity have significant impacts on the system and division efficiencies, while the power generation structure only affects the environmental efficiency of the generation division. 3) The scenario analysis shows that the policy of "separating power plants from grids" improved the system efficiency to which the improvement in generation division is the main contributor and "separating distribution from transmission" may have great potential for enhancing the efficiencies of power systems.

1. Introduction

In China all of the transmission and distribution enterprises and the vast majority of the power generation enterprises are owned by the central or local government (Yan and Tao, 2014). To cope with the growing electricity demand, excessive administrative intervention, cross-subsidization, and distorted pricing mechanisms, China has implemented a wave of policy measures to accelerate power market reform in recent decades and to improve the efficiencies of the power system (Zhao et al., 2012). China started the unbundling reform from 2002, namely separating power plants from grids aiming at introducing competition in the generation division and exploring reform paths for other divisions (Ma and Zhao, 2015). It laid the basic framework for China's current power management mechanism. Together with the economic development, electricity consumption and investments increased dramatically after this reform. The national annual power consumption increased from 1903.16 TWh in 2003–5523.30 TWh in 2014, and the investment levels increased nearly tenfold over this period.[1] This reform was considered to be successful especially in breaking the monopoly in the generation division (Xie et al., 2012; Zeng et al., 2016; Zhou et al., 2012). It also hastened the separation of government administration and enterprise management in the electric power industry. The generation and grid companies began to formulate their production plans with the aim of optimizing resource allocations. Further reforms, including the "smart grid" policy in 2006 and the "smart energy" policy in 2009, accelerated the extra-high voltage and super-high voltage grid construction. The total assets quadrupled over the period 2003 to 2014 in both the generation and grid divisions[2] and posed great challenges to the power system. The generation sector became more competitive after the reforms and implemented more interregional transmissions while the distribution division faced more constraints caused by management mechanisms and local conditions. Issues such as cross-subsidization and unclear property rights increased

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[1] China National Statistics Yearbook, 2003–2015.
[2] The data are collected from the MacroChina Industries Database.

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the difficulties in improving the system efficiency. To counteract these issues, China's central government issued "*Instructions on further deepening the reform of the electric power system*" in March 2015 and launched a new round of power industry reform.

Improving the efficiency of an integrated power system needs the cooperation of all the divisions (Xie et al., 2012). Objectively investigating the reform effect needs to analyze its accumulation effects and the dynamic efficiency of the power system. In addition, considering the interrelationship of the divisions, it is irrational to determine the system's efficiency simply by summing the divisional efficiencies. The point in time for inputs will also affect the system efficiency. Only by taking the influences of these factors into consideration can we obtain reasonable environmental efficiency estimates. Therefore, analyzing the contributions of different divisions to system efficiency is urgent and important to find the critical factors of the environmental efficiency, fill the gap between the entities and their benchmarks, and optimize the resource allocations.

Network data envelopment analysis (DEA) provides an alternative to look inside the interaction of the divisions and present the inputs and outputs of each division (Bogetoft et al., 2017). Several studies have employed this approach in studying the production efficiency of power systems in the United States (Tone and Tsutsui, 2009, 2014; Tsutsui and Goto, 2009), but the experiences of the American power system cannot be directly applied to China because of the different management mechanism. This is what has motivated us to present this study. Currently, the business areas of China's grid companies are defined mainly according to the provincial administrative regions, and this is the case for power supervision. This study employs the dynamic network slacks-based measure (DNSBM) model to study the environmental efficiencies of China's provincial power systems from 2007 to 2014. It will analyze the efficiencies of the integrated power system and divisions wherein the impacts of inter-regional transmissions and the constraints of the variables are fully considered. In addition, we will conduct scenario analysis to investigate the impacts of the policy of "separating the power plants from the grids" and to explore the possibility of "separating the distribution from the transmission" in future reforms. The remainder is structured as follows. The second section reviews the relevant literature. The methodology is illustrated in the third section and the empirical analysis is given in the fourth section. The last section concludes this paper.

2. Literature review

DEA is the most widely used nonparametric method for efficiency evaluation. DEA, which was first proposed by Charnes et al. (1978), evaluates comparative efficiency of the decision-making units (DMUs) without predetermining production function. To study the influences of time factor and the internal structure, Färe and Grosskopf (1996, 2000) proposed a dynamic DEA model and a network DEA (NDEA) model. The DEA method has been widely applied in power industry (Abbott, 2006; Amado et al., 2013; Geymueller, 2009; Liu et al., 2017; Ramos-Real et al., 2009). These studies mainly include three categories: the production and environmental efficiency of the generation division, the production efficiency of transmission or distribution division, and the production efficiency analysis of the integrated power system.

At first, the DEA method was mainly used to study the production efficiency of generation division (Sueyoshi et al., 2017). Färe et al. (1983) and Lam and Shiu (2004) employed traditional DEA models to assess the efficiency of power plants in the United States and China, respectively. When applying the CCR and the BCC model to measure the relative performances of 32 power electric generation management companies in Iran, Fallahi et al. (2011) tested the stability of the model and the importance of each input variable. In evaluating the efficiency of power plants in the United States and Britain, Yaisawarng and Klein (1994) and Athanassopoulos et al. (1999) began to take undesirable outputs into consideration. Sueyoshi et al. (2010) put forward the range-adjusted measure (RAM) DEA method, which took the desirable and undesirable outputs under a selective framework to study the operation, environment, and comprehensive performance of power plants. Mou (2014) employed a SBM model to study China's coal-fired power disparity from the perspective of corporations, provinces, and power plants and found that the definition of the DMUs impacted the results significantly. The results indicated that reducing the slacks helped to narrow the disparity and enhance the efficiency.

Efficiency studies of grids first appeared in the 1990s (Weyman-Jones, 1991) and experienced a similar development trend to that of generation division. Li et al. (2014) employed a unified DEA model to analyze the efficiency of China's provincial power industry with undesirable outputs considered. Geymueller (2009) introduced the quasi-fixed input into the dynamic DEA framework and compared the empirical results of distribution companies in the United States with the static model. The results showed that the static model might reach misleading conclusions because of the neglect of short-term invariance variables such as transmission lines. In order to further study the effects of inputs and outputs on the efficiency of the dynamic model, Tone and Tsutsui (2010) combined it with the SBM to propose a slacks-based measure dynamic DEA (DSBM) model and divided the carry-overs into four types: fixed, free, expected, and unexpected. The concept of free and fixed links are recently used to investigate the effects of different tax policies on China's coal-fired power generation industry from a static view (Song et al., 2016). To solve the heterogeneity when evaluating efficiency, Xavier et al. (2015) combined the DEA technology with the unit network technology to propose a new two-stage DEA model. Amado et al. (2013) found that DEA technology had a big potential in depicting the internal process of distribution companies.

For the derivations of efficiency change, the study of Yadav et al. (2011) revealed that scale inefficiency rather than technical inefficiency was the source of the inefficiency for the distribution companies of Uttarakhand in India. Abbott (2006) and Munisamy and Arabi (2015) analyzed the influence of policy reforms on the operational efficiency or eco-efficiency of the power industry and both found a positive effect. When studying the production efficiency of coal-fired power plants in the United States, mainland China, and Taiwan, Olatubi and Dismukes (2000), Lam and Shiu (2004), and Liu et al. (2010) found that environmental variables had an important impact on efficiency. Then they adopted Tobit regression to analyze the influences of these factors on efficiency. The study of Mullarkey et al. (2015) showed that the restructuring and integration reforms of distribution networks helped to enhance the efficiency of distribution companies in Ireland without considering the undesirable indicators. Yan and Tao (2014) were pioneers in studying the performance of China's provincial grid companies. They employed the DNSBM model and deemed that the policy of "separating distribution from transmission" might further improve the efficiencies of the grid companies.

For the efficiency of the integrated power system, Nemoto and Goto (2003) employed a dynamic DEA model, including a quasi-fixed input, to evaluate the production efficiency of Japanese companies. As the divisions of the power system are closely linked, it is probable to reach misleading conclusions without considering the inter connections. Xie et al. (2012) found that the power generation structure had a significant impact on the environmental efficiency. In order to further study the influence of the internal