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Efficiency assessment of wind farms in China using two-stage data envelopment analysis

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ABSTRACT

China has been the world's leader in wind power capacity due to the promotion of favorable policies. Given the rare research on the efficiency of China's wind farms, this study analyzes the productive efficiency of 42 large-scale wind farms in China using a two-stage analysis. In the first stage, efficiency scores of wind farms are determined with data envelopment analysis and the sensitivity analysis is conducted to verify the robustness of efficiency calculation results. In the second stage, the Tobit regression is employed to explore the relationship between the efficiency scores and the environment variables that are beyond the control of wind farms. According to the results, all wind farms studied operate at an acceptable level. However, 50% of them overinvest in the installed capacity and about 48% have the electricity-saving potential. The most important factors affecting the efficiency of wind farms are the installed capacity and the wind power density. In addition, the age of the wind farm and the wind curtailment rate have a negative effect on productive efficiency, whereas the ownership of the wind farm has no significant effect. Findings from this study may be helpful for stakeholders in the wind industry to select wind power projects, optimize operational strategies and make related policies.

1. Introduction

With the further aggravation of global energy crisis, growing attention has been paid to the development of renewable energy. The share of renewable energy generation in overall generation is predicted to increase from 21% in 2012 to 33% in 2040 [1]. Wind energy is one of the most promising renewable energy sources because of its availability, low cost and relatively advanced technology [2]. According to the report of World Wind Energy Association (WWEA) [3], the average growth rate in the global wind power capacity over the last 10 years reached almost 23% and the cumulative wind power capacity in 2014 ended up with 369.6 GW.

China has abundant wind energy resources, with the huge potential to develop wind power generation. Meanwhile, the development of wind power serves the Chinese resource-saving sustainable development path and also can be conducive for improving energy structure. Therefore, wind power plays a key role in the Chinese energy industry. Since the enactment of the *Renewable Energy Law* in 2006, wind power in China has entered a stage of high-speed growth. Fig. 1 shows the change of the installed wind power capacity in China from 2004 to the first half of 2015. During 2006–2009, Chinese wind power capacity expansions surpassed 100% per year. In 2010, the new installed capacity reached 18.9 GW [4], which made Chinese wind power capacity rank first in the world [5]. Subsequently, in order to accomplish the Chinese government's pledge for climate change that non-fossil energy accounts for 15% of primary energy consumption, a series of favorable policies and regulations have been introduced, including feed-in tariff and tax incentives [6]. By the end of June 2015, the cumulative installed capacity of wind power amounted to 124.7 GW [7].

Behind the rapid expansion, the Chinese wind power sector is faced with problems of blind investment and noneconomic operation. Pei et al. [8] show that the utilization hours of wind power equipment began to drop abruptly since 2011 and the wind curtailment problem has deteriorated year by year. Lo et al. [9] find that the wind farms have developed out of harmony with the electricity grid construction, which has resulted in a large proportion of the electricity generated by wind turbines being wasted. Liu [10] also demonstrates that about 30% of the installed wind capacity sits idle owing to overinvestment. In such situations, how to enhance performance of wind farms becomes the primary concern of developers, operators and policymakers. Evaluating the productive efficiency of existing wind farms is beneficial to identify key factors affecting the performance and develop optimal operation strategies. Therefore, efficiency assessment is meaningful

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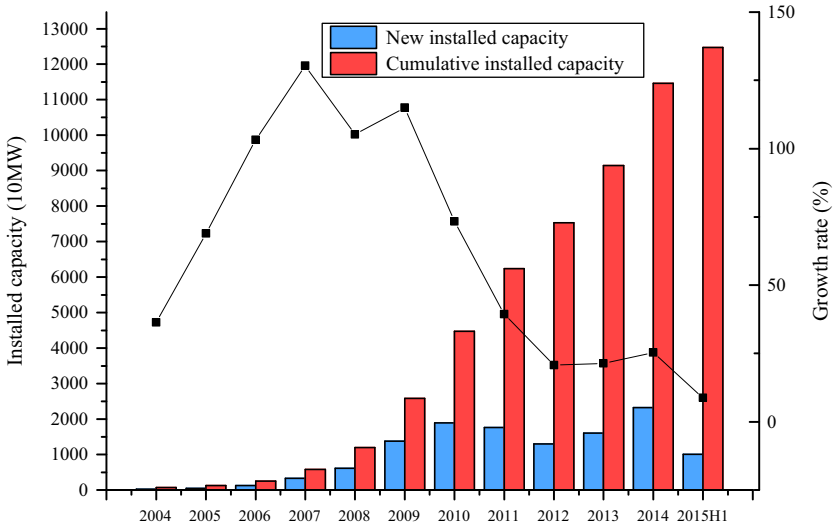

Fig. 1. Wind power capacity in China (2004–2015 H1). *Note:* 2015 H1 represents the first half of 2015. *Source*: CWEA.

and essential for the wind power industry, which can provide guidance for the installation of new wind farms and the repowering processes of existing ones.

Efficiency analysis can be conducted by different techniques, among which stochastic frontier analysis (SFA) and data envelopment analysis (DEA) are the most popular. The main advantage of SFA is that it can separate measurement error and other random factors from the sources of variation in technical efficiency [11]. However, it requires assumptions on the functional form of the frontier and the underlying distribution of the inefficiency term. DEA, in contrast, requires no prior functional assumptions on inherent relationship between multiple inputs and outputs. It also can provide insights into the reasons for the inefficiency based on slack and radial adjustment [12]. The limitation of DEA is that random factors are included in the efficiency score rather than accounted for directly [13]. Efficiency analysis of wind farms needs to consider many influencing factors, such as annual generation, installed capacity and availability. It is also difficult to reasonably assume the form of the frontier and inefficiency term due to the lack of relevant statistics of Chinese wind farms. Moreover, Iglesias et al. [14] point out that the effect of random factors is limited for efficiency analysis of wind farms. Therefore, this study selects the DEA approach to analyze the efficiency of Chinese wind farms.

The purpose of this study is, on the one hand, to quantitatively evaluate what level existing Chinese wind farms operate at and, on the other hand, to identify potential inefficient factors and seek out the best practices that will contribute to performance improvement of wind farms. The innovations of this study are as follows: first, the productive efficiency of China's wind farms are measured from the perspective of the extended production process, which includes the development phase and the operation phase. Second, the two-stage DEA model is employed to take uncontrollable factors into consideration and explain efficiency scores. Third, the analysis of variance is introduced to analyze the relationship between wind farms' efficiency scores and resource areas. Owing to the lack of relevant research on Chinese wind farms' efficiency, stakeholders suffer from poor reference data when evaluating their efficiency. This study fills this gap by presenting representative efficiency figures of Chinese wind farms for stakeholders. Assessment variables are specially selected based on the practices of the Chinese wind power sector. The results of efficiency assessment can be helpful for managers to select appropriate wind power projects and design effective management strategies. Meanwhile, the assessment can also provide reliable recommendations for policy formulation.

The remainder of this study is organized as follows: Section 2 provides a brief review of the DEA applications in the wind power field. Section 3 introduces the two-stage (DEA & Tobit) analysis. Section 4 explains variables and data. Section 5 demonstrates efficiency calculation results and corresponding discussions. Section 6 concludes this study and presents suggestions about improving the efficiency of wind farms.

2. Literature review

DEA has been developed as an important data-driven approach for benchmarking and measuring the efficiency of some homogenous entities [15]. Due to its practicability and simplicity, this method has been extensively applied to efficiency evaluation of different decision making units (DMUs) in the energy sector [16]. Zhou et al. [17] present a detailed literature survey on DEA utilized in energy studies.

As the high-speed development of the wind power industry, DEA has increasingly gained popularity in the field of wind power. Those literatures can be divided into two themes: efficiency analysis of wind power technology and efficiency analysis of wind farms. The former category is usually about the comparison between wind power technology and other power generation technologies to provide guidelines for power planning. San Cristóbal [18] compares the efficiency of 13 renewable energy technologies (including wind power, solar thermo-electric and other energy technologies) with a multiple criteria data envelopment analysis (MCDEA) model. The results show that only the wind power $10 < P < 50$ MW technology is efficient and it can be deemed the only non-dominated solution. Lins et al. [19] comprehensively assess the performance of Brazilian alternative energy resources (including wind, photovoltaic and others) from the perspective of environment, society and economy. The findings demonstrate that the government ought to give priority to the development of technologies using solid wastes to generate energy. Kim et al. [20] estimate the investment efficiency of three renewable energy technologies including wind power, photovoltaic, and fuel cells with the DEA in Korea. They conclude that wind power is the most efficient renewable energy technology in Korea from the perspective of government investment.