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Carbon emission efficiency and spatial clustering analyses in China's thermal power industry: Evidence from the provincial level

Dan Yan [a, b], Yalin Lei [a, b, *], Li Li [a, b], Wen Song [c]

[a] School of Humanities and Economic Management, China University of Geosciences, Beijing, 100083, China
[b] Key Laboratory of Carrying Capacity Assessment for Resource and Environment, Ministry of Land and Resources, Beijing, 100083, China
[c] School of Land Science and Technology, China University of Geosciences, Beijing, 100083, China

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ABSTRACT

The power industry produces nearly 40% of China's carbon emission, thus, this sector should be regarded as priority for carbon emission reduction. Identifying the unevenness of regional development may be crucial for increasing the carbon emission efficiency of power plants. This work evaluates the carbon emission efficiency using the Undesirable-SBM (slacks-based measure) model and data from China's power industry in 30 provinces from 2003 to 2014. Moreover, the global Malmquist index, which consists of efficiency changes (ECs) and technical changes (TCs), is used to determine the driving factors of these changes. Finally, a spatial autocorrelation analysis that is based on Moran's index is performed to confirm the non-equilibrium spatial distribution of the carbon emission efficiency for the power industry. The main findings are as follows: (1) compared to economically underdeveloped provinces, the wealthy eastern coastal provinces exhibit higher carbon emission efficiency; (2) the positive effects of TCs on the efficiency changes are stronger, moreover, the provinces with lower efficiency are more likely to achieve greater improvements; and (3) significant spatial correlations exist among the power sectors of the 30 provinces in terms of carbon emission efficiency; the eastern regions have relatively high efficiency and tend to have a positive spillover effect on the neighboring provinces. Therefore, technological cooperation between various regions is beneficial to ameliorate carbon emission efficiency. Finally, policy implications are provided to address such spatial discrepancies.

1. Introduction

The massive exploitation and use of fossil fuels have caused serious environmental pollution, ecological damage and greenhouse gas emissions. China has replaced the United States as the world's largest country in terms of energy consumption and carbon emissions since 2007 (Lindner et al., 2013; Wang et al., 2013; Zhang et al., 2014). The environmental cost for this high-speed development has been huge, the economic losses associated with air and water pollution account for 3%–8% of China's GDP. In these circumstances, a greenhouse gas reduction agreement was reached between China and the United States in 2014, and China pledged to stop increasing CO_2 emissions by 2030. Therefore, determining methods to maintain stable economic development while reducing negative externalities form energy consumption has become a hot issue.

In terms of the distribution of carbon dioxide emissions from various industries, the global fossil fuel consumption is mainly concentrated in the electric power, transportation and industrial sectors. In China, approximately 50% of coal consumptions is used for power generation, as such, the power industry is the largest source of CO_2 emissions, accounting for about 40% of China's total carbon emissions (Yang and Lin, 2016; Zhao et al., 2015). Obviously, this sector should be regarded as priority for carbon emission reduction. In 2014, China's power generation exceeded that of the United States to become the world's largest power generator, with a total installed capacity of 1.37 billion kilowatts, of which thermal power comprises 67.4% (China Electric Power Yearbook 2015). The central government has promoted multiple policies to improve the energy efficiency of this sector. According to the 13th Five-Year Plan of Electric Power Development (2016–2020), China strives to decrease the national average coal consumption rate in coal units to 310 g tce/kWh by 2020 and achieve ultra-low emission at 300 MW

* Corresponding author. Rm.505, Administrative office building, China University of Geosciences, Beijing, 100083, China.
E-mail address: leiyalin@cugb.edu.cn (Y. Lei).

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or higher levels. Increasing the carbon emission efficiency may be an important task for the power industry in all regions of this country.

Estimation of carbon emission efficiency can be divided into single factors and multiple factors. Traditional single factors are termed as "partial indicators" because they can reflect only certain aspects. Ramanathan (2002) proposed that the total factor productivity (TFP) assessment would be more comprehensive and reasonable. Generally, two types of methods are used to determine the production frontier in TFP evaluations: parametric methods and non-parametric methods. Stochastic Frontier Analysis (SFA) is a classical parametric approach that measures the effectiveness according to random error terms. The most commonly used non-parametric method is Data Envelopment Analysis (DEA), which constructs a deterministic production frontier by linear programming and then compares the relative efficiency of decision making units (DMUs). It is especially suitable for the analysis of multi-input and multi-output situations, and its advantage is that it does not need to preset the production function and assumes the object is technically efficient. Thanks to the increasing awareness of environmental protection, numerous studies have incorporated undesirable outputs into environmental efficiency assessments by the DEA model (Chen et al., 2015; Jiang et al., 2016; Lin et al., 2015; Wu et al., 2014; Yang et al., 2015). Extensive literature analyzed the environmental efficiency of the industrial sector using DEA technology. Li and Shi (2014) measured the energy efficiencies of China's industrial sectors from 2001 to 2010 based on an improved super slacks-based measure (SBM) model. A non-radial DEA approach was proposed by Meng et al. (2013) for assessing the environmental performance of China's provincial industrial sectors, and one of the findings was that the environmental performance growth is mainly due to technological change. Wang and Wei (2014) also employed the DEA method to investigate the energy and emission efficiencies in Chinese cities from 2006 to 2010, and the results indicated that significant disparities existed in the efficiencies between regions, which have narrowed since 2006.

In terms of the power industry, Zhou et al. (2013) treated SO_2, NO_x and CO_2 emissions as undesirable outputs and calculated the environmental efficiency of power industry from 2005 to 2010 by using SBM model, and an entropy weight was introduced to improve reliability and rationality. The principal findings showed significant differences in environmental efficiency in the power industry among China's provinces. The proportion of power plants had a positive effect, while sewage charges and investment had a negative impact on the efficiency. Zhang and Choi (2013) extended the Malmquist CO_2 emission performance index (MCPI) that was proposed by Zhou et al. (2010) and developed a metafrontier non-radial Malmquist CO_2 emission performance index (MNMCPI) to dynamically measure the carbon emission performance for China's power plants with time. By using the Malmquist-Luenberger productivity index computed by DEA method, Arabi et al. (2014) evaluated the productivity changes of 48 Iranian thermal power plants from 2003 to 2010. Other similar studies since 2000 are shown in Table 1. The input-output indicators differed in the literature in Table 1, with some indicators based on data for micro-power companies and others based on the perspective of the power industry. Generally, most of this research included asset input, human input and energy input. The selection of undesirable outputs varied, depending on the purpose of the studies.

Furthermore, considerable research has discussed the factors that are essential for CO_2 emission control and efficiency improvement (Fan et al., 2015; Ma and Zhao, 2015). Notably, most of the related research shared the unspoken belief that DMUs are mutually independent and that their spatial interactions are neglected. However, the characteristics of a region may depend on its neighbors, and these regional differences and correlations must be considered (Anselin, 2013; LeSage, 2008). Geographical space has been gradually taking into account in the area of exhaust emission research (Dong and Liang, 2014; Hao and Liu, 2016; Zhao et al., 2014).

Improving the environmental efficiency is crucial to relieve the negative externalities that are associated with energy consumption in China. However, achieving this goal is complicated by technical limitations as well as by the considerable differences in economic development, geographical location and lifestyle in China's provinces (municipalities). The starting point of China's industrialization and modernization was the eastern region. This region's first priority was development to pull and drive the entire country's economic development, whereas the central and western regions provided energy-intensive but low-value-added products such as raw materials, fuels, and semi-finished products, which created serious environmental problems. In short, policymakers should take into account spatial characteristics and attempt to eliminate regional inequality. Compared to most developed countries, the regional disparity in China creates difficulties and uncertainties in policy implementation (Liang et al., 2016). The huge differences among provinces in terms of their socioeconomic conditions and geographical locations reflect that China is a heterogeneous country with many homogeneous urban agglomerations (Meng et al., 2011). Therefore, environmental efficiency changes are analyzed via spatial and temporal perspectives to provide targeted information for different provinces.

In summary, understanding regional development disparities is crucial to reduce carbon emissions; however, previous research seldom investigated the spatial characteristics of regional carbon emission efficiency. In light of this, the primary objectives of this study are listed as the following three aspects: (1) investigate the spatial and temporal changes in the carbon emission efficiency of the thermal power industry in China and demonstrate the unequal development of this sector, (2) identify the influencing factors with regard to efficiency changes through the Malmquist index decomposition, and (3) analyze the specific spatial aggregation effect of carbon emission efficiency in China's provincial thermal power industry. This study consists of four parts. The first part describes the background and significance of this study, as well as the primary objectives. Part 2 presents the data sources and methods, Part 3 presents the research results and discusses the results, and Part 4 provides a summary of the research and the corresponding policy enlightenments.

2. Methodology

2.1. Data

The dataset covered thirty provinces, except for Tibet, for the period 2003–2014. The State Council issued "the reformation of electric power systems" in 2002, and environmental efficiency in the power industry has since been the subject of greater attention. This study adopted the installed capacity, energy consumption and labor force of the thermal power industry in China's 30 provinces as the inputs, power generation as the desirable output, and carbon emissions as the undesirable output. Specifically, all the data were obtained from the China Electric Power Yearbook, China Labor Statistical Yearbook and China Statistical Yearbook. To be clear, since specific values were not available for the employment and carbon emissions of the power sector, thus, labor was represented