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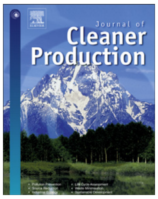

Low-carbon economy efficiency analysis of China's provinces based on a range-adjusted measure and data envelopment analysis model

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ABSTRACT

To guide the policy adjustment in the new normal economic mode, this study uses a range-adjusted measure and data envelopment analysis model to evaluate the provincial comprehensive efficiencies and explore the factors causing poor performance in China during 2001–2014. Empirical analysis draws the following conclusions. 1) The comprehensive efficiencies of most provinces present upward trends, which imply the positively contribution of previous efficiency-related policies. 2) Contrary to economic levels, the comprehensive efficiency of the central region is lower than that in the east but higher than that in the west. This result confirms the existence of extensive growth and implies that developed regions should be largely responsible for the low comprehensive efficiency of the country. 3) Except for a few outliers, the comprehensive efficiency level of a province is highly correlated to its climatic characteristics. This phenomenon offers new ideas for the central government to create differential efficiency-related policies. 4) For east provinces, labor input, energy input, gross domestic product (GDP) output, and CO_2 emissions are all important in improving the comprehensive efficiency. Efficiency-related policies should focus on technical progress. For west and central provinces, labor input and GDP output are the main contributors to inefficiency. The key policy direction of these provinces should be the improvement of human resource efficiency.

1. Introduction

China's economy has been developing rapidly in the past decades (NBS, 2017a). To support the gross domestic product (GDP) output, in addition to the input of necessary production factors, China has paid the price of massive carbon emissions, which are associated with severe local environment deterioration (BP, 2017). To realize sustainable development, China's economy is currently transforming to a new normal mode (Li and Zhang, 2017). This research aims to evaluate the low-carbon economy efficiency (Liu and Liu, 2016) of China's provinces and recognize the factors causing inefficiency in order to guide the current policy adjustment.

Since the implementation of reform and opening-up policies (Ao et al., 2016) at the end of 1978, China has witnessed remarkable economic development, with a mean annual growth rate of approximately 9.74% in real GDP (NBS, 2017a). Given that extensive growth is the main economic development mode in the past, China's energy consumption scale also increases considerably during this period. In 2015, China's primary energy consumption is 4305.96 million tons of coal equivalent (tce), which accounts for 22.9% of the world's total (BP, 2017). Fossil fuels are the major energy sources of China because of resource endowment (coal reserves are abundant) and historical overdevelopment; their share has never been less than 88% for the past 40 years (NBS, 2017a). China is presently facing considerable pressures in mitigating energy-related CO_2 emissions, which are considered the main cause of global greenhouse effect aggravation, because its emission share has ranked first in the world since 2006 (BP, 2017). In its intended nationally determined contributions (INDCs), China committed that its CO_2 emissions will reach the peak, and the CO_2 per unit of GDP will decrease by 60%–65% from its 2005 level by 2030; these INDCs were submitted to the 21st Conference of Parties of United Nations Framework Convention on Climate Change, which was held in Paris at the end of 2015 (CIIC, 2016). Moreover,

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Abbreviations

δ	Capital depreciation rate
θ_k	Unified efficiency of the *k*th decision-making unit
F	Capital formation
K	Capital stock
L	Number of decision-making units
$x=(x_1, x_2, \ldots, x_N)\in Rx\ N$	Non-energy inputs
$e=(e_1, e_2, \ldots, e_I)\in Re\ I$	Energy inputs
$y=(y_1, y_2, \ldots, y_M)\in Ry\ M$	GDP outputs
$u=(u_1, u_2, \ldots, u_J)\in Ru\ J$	CO_2 emissions
$sx\ n$, $se + i$, $se\text{-}i$, $sy\ m$, and $su\ j$	Slack variables representing excesses/shortages of input or output
NE_x, NE_e, NE_y, and NE_u	Contributions to inefficiency of x, e, y, and u

emitted pollutants that are accompanied with CO_2 have remarkably deteriorated the local environment of China. To date, less than 1% of the 500 largest cities in China satisfy the air quality standards recommended by the World Health Organization, and seven of these cities are ranked among the 10 most polluted cities in the world (ADB, 2012).

To prompt the sustainable development of economy and environment, China is presently transforming to a new normal mode. This development pattern is characterized with lowered economic growth, upgraded industrial structure, and converted driving force of economic growth from key input factors and investment to innovation (Li and Zhang, 2017). In this economic mode, the coordinated development of economy, energy, and environment is the main policy orientation. As a comprehensive indicator that considers input, output, and environmental impact, the low-carbon economy efficiency (Liu and Liu, 2016) is presently a core indicator being focused in the development policies of China. Considering that the macroeconomic policies of China are commonly formulated by the central government but implemented mainly by the provincial governments (Meng et al., 2015), this research performs the provincial-level analysis of the low-carbon economy efficiency of China.

Currently, some studies analyze the production, energy, and environmental efficiency of China. Most of these studies focus on three issues. The first issue is specific region analysis. Jiang et al. (2016) used a structural equation model to evaluate the relationship between output efficiency and environmental efficiency in Jiangsu province. Clarke–Sather et al. (2016) adopted the life cycle assessment method to assess the potential of improving the lighting efficiency in rural Anding district, Gansu province. Other similar studies were also conducted by Yu et al. (2015), Pradhan et al. (2017), and Ma et al. (2017). The conclusions of these existing studies are only applicable to their target regions, and they cannot be used for macropolicy adjustment in the whole country. The second issue is industrial sector evaluation. Yan et al. (2017) evaluated the carbon emission efficiency using the slack-based measurement (SBM) model and data from the power industry in 30 provinces of China. Fei and Lin (2017) explored the operational and environmental efficiencies of China's agricultural sector using a nonradial, directional distance function (DDF), and related data from 30 provinces. Similarly, Liu et al. (2016), Zhang (2017), and Chen et al. (2018) also measured the provincial-level efficiency of different industrial sectors. Considering the research subject, the existing literature is suitable for the specific industrial policy adjustment in China. The third issue is single aspect assessment. Wu et al. (2016), Yue et al. (2017), and Yang and Fukuyama (2018) assessed the environment, ecology, and production efficiency of China's provinces, respectively. The idea of the current new normal mode emphasizes the integrated efficiency improvement of economy, energy, and environment, not any of their individual aspects. Aiming at guiding the policy adjustment to adapt to the new normal economic mode, we use the low-carbon economy efficiency (Liu and Liu, 2016) in the present research to evaluate the comprehensive level of economic development, energy consumption, and environment protection. The objective indicator of this research is calculated by the following range-adjusted measure and data envelopment analysis (RAM-DEA) model.

The traditional DEA model, as a nonparametric programming technique, is an effective method in measuring the relative efficiencies of decision-making units (DMUs) (Charnes et al., 1978). In recent years, DEA methods have been largely extended and widely applied in the production and/or energy performance evaluation (Bretholt and Pan, 2013; Han et al., 2015). However, most of the traditional studies disregard the undesirable outputs (environmental contaminants, e.g. energy related CO_2), which may be not in accordance with the actual production process and result in biased efficiency results (Lozano and Gutiérrez, 2011). Results may be effected only when the undesirable outputs, which are often produced along with desirable outputs, have been taken into account during efficiency evaluation (Zhang et al., 2016). Researchers have proposed various methods to deal with undesirable problem so far. Most of these proposed approaches can be generally summarized as follows. Some undesirable outputs are directly treated as inputs for processing, but they cannot reflect the actual production process in some degrees yet (Zhou et al., 2013). Other researchers used a DDF to assess the efficiency of undesirable outputs by maximizing inputs and outputs simultaneously in a directional vector optimization (Zhang et al., 2012). Essentially, these DDF methods belong to radial and oriented DEA models. Without nonzero slacks in the efficiency measurement, these measures fail to reflect inefficiencies (Ramli and Munisamy, 2015); consequently, they may not provide the most suitable efficiency measure (Guo et al., 2017). To eliminate the deviation of radial and oriented DEA measures, Tone (2001) introduced the SBM model, in which the slack variables are directly added. Subsequently, Fukuyama and Weber (2009) developed a directional SBM model to rectify the drawbacks of DDF. Nevertheless, the SBM model standardizes the slack variables based on the inputs and outputs of the observed DMUs rather than the entire samples, and the evaluation may be subjective. On the basis of SBM model, Sueyoshi and Goto (2010) proposed the RAM model, where outputs are maximized, and inputs are minimized simultaneously; in addition, the radial expansions or contractions are not restricted, and the limitations found in other DEA measures are overcome. According to the difference of output-oriented optimization, the RAM model exhibits three types of performance measures, namely, operational, environmental, and unified performances (Sueyoshi and Goto, 2011). Operational performance only calculates the desirable outputs and ignores the environmental aspect in the measurement process; environmental performance only refers to the undesirable outputs; and unified performance combines operational efficiency on desirable outputs and environmental efficiency on undesirable outputs in a unified, analytical structure, which is referred to as low-carbon economy efficiency or unified efficiency (Wang et al., 2017).

The remainder of this paper is organized as follows. Section 2 introduces the models and data used in this research. Section 3 describes the modeling results that are discussed in Section 4. Section 5 concludes the study with some policy recommendations.