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Measurement and decomposition of energy-saving and emissions reduction performance in Chinese cities

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HIGHLIGHTS

- We propose an energy-saving and emission reduction (ESER) performance index.
- Inefficient management and technology gap are the two main sources of ESER performance lose.
- The relationship between ESER performance and economic development is U-shaped.
- The heterogeneities of production technologies related to ESER are universal in Chinese cities.
- We propose four combinable strategies for improving ESER performance.

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ABSTRACT

Taking into account the heterogeneity of production technologies across Chinese cities, we adopted a meta-frontier function and a non-radial directional distance function to construct an index that comprehensively evaluates the performance achieved by coupling energy-saving and emissions reduction. We also analyzed the theoretical factors leading to performance loss in energy-saving and emissions reduction. An empirical analysis of 209 Chinese cities suggests the following. First, the energy-saving and emissions reduction performances of Chinese cities are generally low, and the relationship between these variables and the economic development level is U-shaped. The results also suggest that cities place more importance on energy-saving than on emissions reduction. Second, the technology gap and insufficient management are the two primary sources of latent capacity that could contribute to energy-saving and emissions reduction in Chinese cities; insufficient management is the dominant factor in both high-income and lower-middle income cities. Four combinable strategies for energy-saving and emissions reduction are proposed. Third, the heterogeneities of production technologies related to energy-saving and emissions reduction are universal; the technological gap between the current and the best production technologies is seen in the largest of the middle income cities, and the gap is smallest in high-income cities.

1. Introduction

Since China joined the *Kyoto Protocol*, central and local governments have paid great attention to the issue of greenhouse gas emissions, which are mainly caused by fossil energy consumption. A series of policies have been promulgated, including *China's National Climate Change Program* and *China's Policies and Actions in Response to Climate Change*. China's 11th Five-year Plan was the first to propose a binding target for reducing energy intensity (energy consumption per ten thousand Yuan of gross domestic product (GDP)). China's 12th Five-year Plan imposed the requirement that energy intensity and CO_2 emissions intensity (CO_2 emissions per ten thousand Yuan of GDP) should be reduced by 16% and 17%, respectively, by 2015. To increase the rate of construction of a resource-saving and environmentally friendly society, energy-saving and emissions reduction are among China's most important social and economic tasks.

To facilitate energy-saving and emissions reduction, the state's general objectives must be implemented at the provincial and city level. As the engine for the national and regional economic development, cities use a great deal of resources, consume a large

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amount of energy, and discharge significant environmental pollutants. As an example of a typical pollution-driven problem, in December 2013, hazy weather appeared in more than 100 large and medium-sized cities in China's north, southeast coastal area, and southwest, covering nearly half of China's land area. This indicates that cities are key areas for energy consumption and pollution control in China. Chinese cities, however, are large in number, widely distributed, and have significant differences. This makes it difficult to evaluate factors using a uniform city-level standard measurement, making policy formulation and implementation challenging.

Existing literature shows that energy-saving and emissions reduction research in China is mainly rooted in searching for ways to measure and improve energy efficiency, such as applying index decomposition and structure decomposition methods to theorize about energy intensity changes and trends at the country level [1–5]. Hu and Wang [6] first proposed a total factor energy efficiency index based on data envelopment analysis (DEA). Since then, many researchers, such as Wei et al. [7], Shi et al. [8], and Wu et al. [9], have measured China's energy efficiency using a variety of DEA models at the regional and industrial levels, and analyzed the latent capacity for energy-saving [10–14].

With the increasing international attention on greenhouse gas emissions, the focus on China has also increased, mainly concentrated on assessing the total amount of CO_2 emissions [15], CO_2 emissions intensity [16,17], trade-associated CO_2 emissions measurements [18,19], and the effects of technological progress and structural changes [20]. Similar to the total factor energy efficiency measurement roadmap, Zhou et al. [21] developed a measurement index for total factor CO_2 emissions performance using the environmental production technology. Later, Wang et al. [12] systematically analyzed the dynamic change, regional differences, and influencing factors of CO_2 emissions performance in Chinese provinces. Differently from studying energy-saving and emissions reduction separately, Zhou et al. [22], Zhang et al. [23], and Wang and Wei [14] considered these factors within a production framework, focusing on undesirable outputs.

Methodologically, the directional distance function is widely applied to assess energy and environmental performance [22,24,25]. In comparison to traditional DEA models, the directional distance function measures performance by increasing desirable outputs (e.g., GDP) and reducing undesirable outputs (e.g., CO_2 emissions) simultaneously. For example, Färe et al. [26] and Chiu et al. [27] employed the directional distance function to measure the environmental performance of coal-fired plants in the US and OECD countries. Picazo-Tadeo et al. [28] and Beltrán-Esteve et al. [29] further studied the eco-efficiency of farmers in Spain by combining the approaches of the directional distance function and the meta-frontier.

The conventional directional distance function measure is often regarded as a radial measure [10,26,30]. This measure requires policy-makers to reduce undesirable outputs and increase desirable outputs at the same rate. Färe et al. [26] and Fukuyama and Weber [31] proposed the non-radial directional distance function. This extended distance function can overcome slack in the efficiency measurement. Wang et al. [10] used the non-radial directional distance function to measure scenario-based energy efficiency and productivity in China. Using a similar method, Zhang et al. [32] analyzed the effect of the size-control policy on unified energy and carbon efficiency for Chinese fossil fuel power plants. More recently, Zhang and Choi [33] proposed a comprehensive literature review of the directional distance function and its development in energy and environmental studies.

Previous research has been marked by the following disadvantages. First, research objects have been used at the provincial or industrial level without sufficient data from relatively small individual cities. Second, these studies have looked at energy-saving and emissions reduction as two independent indices, without combined analysis. Third, studies have often omitted the impact of the heterogeneity of production technology in evaluating the efficacies of the DEA method, potentially magnifying undesirable deviations in results [34]. Fourth, heavily weighting latent energy-saving or emissions reduction while failing to adequately consider the latent capacity source decomposition does not adequately support the targeted policy development.

Using a non-radial directional distance function and DEA, this study proposes a comprehensive index to evaluate energy-saving and emissions reduction performance while also considering intrinsic differences among Chinese cities. Furthermore, we discuss and decompose latent capacity sources for energy-saving and emissions reduction, providing a reference for the 12th Five-year Plan and supporting efforts to achieve China's 2020 energy-saving and emissions reduction targets. The remainder of this paper is organized as follows. Section 2 introduces the derivation of the energy-saving and emissions reduction performance index with the non-radial directional distance function and DEA. Section 3 conducts an empirical study of Chinese cities. The results and discussions appear in this section. Section 4 concludes and provides some policy recommendations.

2. Methodology

2.1. Non-radial directional distance function

For this study, we assumed that in each city, there are J types of energy inputs ($E^j, j = 1, \ldots, J$) and K types of non-energy inputs ($NE^k, k = 1, \ldots K$). These variables are used to produce P types of desirable outputs ($Y^p, p = 1, \ldots, P$) with Q types of discharged environmental pollutants, namely, undesirable outputs ($B^q, q = 1, \ldots, Q$). Following Färe et al. [26] and Zhou et al. [21], the corresponding production technology set can be expressed as Eq. (1):

$$T = \left\{ (E^j, NE^k, Y^p, B^q) : (E^j, NE^k,) \text{ can produce } (Y^p, B^q) \right\} \tag{1}$$

The inputs and desirable outputs have strong disposability. The joint production of desirable and undesirable outputs has the properties of null-jointness and weak disposability [35]. The null-jointness indicates that desirable output is inevitably accompanied by undesirable output unless all production activities stop. That is, if $(E^j, NE^k, Y^p, B^q) \in T$ and $B^q = 0$, then $Y^p = 0$. Weak disposability indicates that it is possible to proportionally decrease the desirable and undesirable outputs. That is, if $(E^j, NE^k, Y^p, B^q) \in T$ and $0 \leqslant \theta \leqslant 1$, then there must be $(E^j, NE^k, \theta Y^p, \theta B^q) \in T$.

To isolate redundant inputs and undesirable outputs during the production process and to seek the possibility of expanding desirable outputs, a non-radial directional distance function (Eq. (2)) was constructed [36]. The goal of this equation is to obtain a linear and flexible combination of input and output factors for further optimization.

$$\begin{aligned} &\vec{D}(E^j, NE^k, Y^p, B^q : g) \\ &\qquad = \sup\left\{ \omega^T \beta : (E^j + g_{E^j}, NE^k + g_{NE^k}, Y^p + g_{Y^p}, B^q + g_{B^q}) \in T \right\} \end{aligned} \tag{2}$$

In Eq. (2), $\omega = (\omega_{E^j}, \omega_{NE^k}, \omega_{Y^p}, \omega_{B^q})$ represents the weight of energy inputs, non-energy inputs, desirable outputs, and undesirable outputs, indicating the degree of the city's decision-maker's attention to each factor. The variable $g = (-g_{E^j}, -g_{NE^k}, g_{Y^p}, -g_{B^q})$ is the direction vector, which requires reducing inputs and undesirable outputs and increasing desirable outputs. The corresponding proportion is expressed as $\beta = (\beta_{E^j}, \beta_{NE^k}, \beta_{Y^p}, \beta_{B^q})$. When $\beta = (\beta_{E^j}, \beta_{NE^k}, \beta_{Y^p}, \beta_{B^q}) = 0$, the input and output factors of the