Renewable and Sustainable Energy Reviews 94 (2018) 565–575

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Analysis of energy efficiency in China's transportation sector

Chao Feng[a], Miao Wang[b,*]

[a] School of Economics and Business Administration, Chongqing University, Chongqing 400030, China
[b] School of Management, Xiamen University, Xiamen 361005, China

ARTICLE INFO

Keywords:
Meta-frontier
Data envelopment analysis
Technological heterogeneities
Energy-savings strategy
Malmquist index

ABSTRACT

Using a global meta-frontier approach, this paper analyzes energy efficiency and the savings potential in China's transportation sector from 2006 to 2014 from the perspectives of technological progress, technology gaps, and management efficiency. The results show that energy efficiency in China's transportation sector first decreased from 2006 to 2010, mainly due to a decline in management efficiency and an expansion of the regional technology gap. The energy efficiency then increased from 2011 to 2014 when management efficiency and the regional technology gap stabilized. The energy efficiency in China's transportation sector shows spatial differences, suggesting that the focus of future work on China's provincial transportation sectors should be quite varied. Most provinces in eastern China should commit to upgrading their management efficiency, while most provinces in central and western China should focus on both upgrading their management efficiency and narrowing the regional technology gap.

1. Introduction

Recently, China has begun to face increasing pressure to save energy and reduce CO_2 emissions. Considering the fact that the country's transportation sector utilizes a high level of energy and is CO_2 emissions-intensive, the promotion of energy savings and CO_2 emissions reduction is of considerable significance for China to address this serious challenge [1–4]. Statistics show that from 2000 to 2014, the energy consumption of China's transportation sector increased 3.75 times, from 95.77 to 359.60 million tons of standard coal. Meanwhile, its share of China's final energy consumption increased from 7.7% to 8.7%. In particular, high-speed rail has developed rapidly. However, this rapid development has been high in "energy consumption and CO_2 emissions" [5]. Fortunately, China has already recognized the significance of energy savings and emissions reduction in its transportation sector and has implemented a basket of policies and targets for energy savings and emissions reduction. However, although there have been some positive results (e.g., energy consumption growth has slowed), the absolute volume of energy consumption in the transportation sector is still growing, and the problem of high "energy consumption and CO_2 emissions" is far from being fundamentally solved [6]. In this context, calculating and analyzing the changes in energy efficiency and the current levels of energy efficiency, inefficiency, and savings in the transportation sector can help both scholars and policymakers clarify the gains and losses, form a feedback mechanism for adjustments and improvements in follow-up policies, and determine the appropriate direction and focus of future work.

This study aims to investigate the changes in energy efficiency and the current levels of energy efficiency, inefficiency, and savings in China's transportation sector during the period 2006–2014 by applying a global meta-frontier approach. The main contributions of this paper are (i) its introduction of a global meta-frontier DEA to measure the energy efficiency and savings potential in the transportation sector, in which regional heterogeneities are considered; (ii) its calculation and analysis of the changes in energy efficiency and the current levels of efficiency, inefficiency, and savings in China's transportation sector from the perspectives of technological progress (or innovation), technology gaps, and management efficiency, which can help international readers understand the sources and distribution of energy inefficiency and savings in China's transportation sector; and (iii) its formulation of strategies to promote energy efficiency improvements and realized savings in China's transportation sector, which can guide policymakers regarding future work in this sector.

The remainder of the paper proceeds as follows. Section 2 presents a literature review. Section 3 introduces the methodology. Section 4 describes the data. Section 5 presents the results. The main conclusions are provided in Section 6.

2. Literature review

In recent years, issues related to energy efficiency have been garnering increased attention. There are two main types of energy

* Corresponding author.
E-mail addresses: littlefc@126.com (C. Feng), bigmiao613@126.com (M. Wang).

https://doi.org/10.1016/j.rser.2018.06.037
Received 9 October 2017; Received in revised form 2 June 2018; Accepted 19 June 2018
1364-0321/

efficiency indicators: single- and total-factor indicators. For single-factor indicators such as energy intensity indicators, several energy efficiency accounting methodologies have been developed to track energy efficiency trends and their driving forces, such as index decomposition analysis (IDA) [7]. For example, Liao et al. [8], Ma and Stern [9], and Zha et al. [10] applied the logarithmic mean Divisia index (LMDI) to analyze the drivers of China's energy intensity. Inglesi-Lotz and Pouris [11] also adopted the LMDI approach to analyze the drivers of energy intensity in South Africa. González [12] explored the impact of sectoral composition changes on energy intensity in EU economies. Using the LMDI, Andrés and Padilla [13] examined the changes in energy intensity in Spanish road freight transportation. In addition, to allow for various energy inputs and product outputs, Wei et al. [14] utilized the Malmquist index approach to analyze the energy efficiency of China's iron and steel sector.

In a single-factor framework, many other key inputs are ignored. However, in reality, energy alone cannot produce any output [15]. Hence, single-factor indicators such as energy intensity indicators cannot measure the underlying substitution effects between energy and other inputs [16]. In addition, because a single-factor framework is not consistent with the actual production process, estimations based on it cannot measure actual energy-saving potential. In response to these issues, Hu and Wang [15] developed a total-factor framework that incorporates all the key inputs to measure energy efficiency. To date, numerous scholars have applied or extended the total-factor framework for energy efficiency measurements [17–20], and a number of scholars have attempted to adopt the total-factor framework to measure the energy efficiency of regions, countries, and industries (e.g. [21–24],). Because there are always undesirable outputs such as CO_2 emissions during production processes, many scholars have addressed the by-products within a total-factor framework for energy efficiency measurement [25–32]. In addition, to address the heterogeneities in production technology among decision-making units, scholars have applied the meta-frontier approach for energy efficiency measurement [33–44].

Because the transportation sector emits the most greenhouse gas and is the largest fuel consumer, its energy efficiency has attracted the attention of many international scholars. The existing energy efficiency indicators for the transportation sector can be classified into three types, i.e., indicators that measure the ratio between the output and energy input or the ratio of work to energy (e.g. [45–52],), indicators that measure the ratio between the energy in products and the energy input using energy and exergy analysis [53–57], and indicators that measure energy efficiency within a total-factor framework using stochastic frontier analysis (SFA) and DEA [58–60]. As noted above, in reality, energy alone cannot produce any output, and the same is true for the transportation sector. The transportation sector requires labor, capital, and energy inputs, although there may be substitutions between these input factors. Based on these considerations, the total-factor framework may be a suitable tool for investigating the energy efficiency of the transportation sector from an economy-wide perspective.

Specific to China's transportation energy efficiency, studies mainly utilize the total-factor framework. For example, Zhou et al. [2] applied output-oriented environmental DEA technology to analyze transportation energy efficiency and savings in China. To eliminate the effects of non-operational factors and to strengthen the effectiveness of the ranking system, Cui and Li [61] developed the virtual frontier DEA to measure the transportation energy efficiency in China. Lin et al. [62] employed DEA to analyze the energy efficiency of China's transportation sector. Combining non-radial and window DEA, Liu et al. [63] examined China's road and railway transportation energy and environmental efficiency. Applying a non-radial DEA, Bi et al. [64] investigated China's transportation energy and environmental efficiency for the period 2006–2010. Wu et al. [65] applied a parallel DEA to investigate China's transportation energy and environmental efficiency. Liu and Wu [66] examined China's transportation energy and environmental efficiency using a slacks-based DEA. In addition to these energy efficiency studies, there are also many environmental efficiency and transportation efficiency studies on China's transportation sector [67–73].

As reviewed above, several streams of literature have examined China's transportation energy efficiency. Unfortunately, however, the energy efficiency studies on China's transportation sector described above did not take heterogeneities in production technology among the regions of China into consideration. Due to the country's uneven economic development and differences in the economic structure and resource endowments, there are technological heterogeneities among China's regions [33]. In addition, not considering these heterogeneities might lead to a biased estimation. To fill this gap in the literature, this paper attempts to investigate the transportation energy efficiency in China by using a global meta-frontier DEA. This study chose DEA rather than SFA mainly because SFA requires a prior set of functional forms, and thus, the results have been questioned [74].

Using this global meta-frontier DEA, the study evaluates and analyzes China's transportation energy efficiency and savings potential by considering the heterogeneities among China's regions. Both energy efficiency and savings potential are decomposed into technology gaps and management efficiency. By analyzing China's transportation energy efficiency and the sources of its inefficiency, this study reveals the gains and losses in the performance of this sector with regard to energy utilization and provides guidance to adjust and improve policies. In addition, by revealing the sources for potential energy savings, this study can help policymakers and those implementing such policies determine the appropriate direction and focus of future work.

3. Methodologies

DEA was first proposed by Charnes et al. [75] to measure the efficiency of decision-making units (DMUs). In our study, DEA is used to measure China's transportation energy efficiency and savings potential. To take heterogeneities in production technology among regions into consideration and make the estimations comparable throughout the entire sample period, global meta-frontier DEA is proposed in this section.

3.1. The meta-frontier DEA measure

To take the heterogeneities in production technology among DMUs into consideration when estimating the DMUs' energy efficiency, the meta-frontier DEA approach is proposed here. Suppose that there are K DMUs, and there are G groups. The technologies of the DMUs within a group are considered to be the same but across groups to be heterogeneous [76]. Therefore, each group of DMUs constitutes a group frontier. In addition, all the group frontiers constitute the meta-frontier. Following Wang et al. [16] and Wang et al. [33], the procedure to determine the energy efficiency under the two types of frontiers can be obtained by solving the following:

$$\begin{cases} \min:\ \lambda^{meta}(x, e, y, c|CRS) \\ s.\ t.\ \sum_{k=1}^{K} z_k x_k \le x;\ \sum_{k=1}^{K} z_k y_k \ge y;\ \sum_{k=1}^{K} z_k e_k \le \lambda^{meta} e;\ \sum_{k=1}^{K} z_k c_k = \delta^{meta} c \\ 0 \le \delta^{meta} \le 1;\ \lambda^{meta} \ge 0;\ z_k \ge 0, fork = 1, \dots, K \end{cases} \tag{1}$$

$$\begin{cases} \min:\ \lambda^{g}(x, e, y, c|CRS) \\ s.\ t.\ \sum_{k=1}^{K_g} z_k x_k \le x;\ \sum_{k=1}^{K_g} z_k y_k \ge y;\ \sum_{k=1}^{K_g} z_k e_k \le \lambda^{g} e;\ \sum_{k=1}^{K_g} z_k c_k = \delta^{g} c \\ 0 \le \delta^{g} \le 1;\ \lambda^{g} \ge 0;\ z_k \ge 0, fork = 1, \dots, K_g \end{cases} \tag{2}$$

where (x, e, y, c) denote non-energy and energy inputs, desirable output, and CO_2 emissions, respectively; kg is the gth group's number of