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Research paper

Composite eco-efficiency indicators for China based on data envelopment analysis

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ABSTRACT

Eco-efficiency is of great significance in facilitating a region's sustainable development. However, there are some inconsistencies among the concepts and also relationships of eco-efficiency and its relevant efficiencies in recent studies. This paper integrates eco-efficiency and three related-efficiencies (economic efficiency, energy efficiency, and environmental efficiencies) into a total-factor analysis framework, regarding them as composite eco-efficiency indicators. Employing a new data envelopment analysis approach, named Meta-US-SBM, which considers meta-frontier, undesirable outputs, super efficiency, and slacks simultaneously, the measure system of these four efficiencies is established. An empirical study is conducted using Chinese provincial data from 2001 to 2014. Results indicate that, overall, the regional economic efficiency is better than other related efficiency indicators. Furthermore, different provinces are adopting different development modes, as denoted by significant heterogeneity among eco-efficiency indicators.

1. Introduction

The concepts of "sustainability" and "eco-efficiency" are increasingly being considered with great importance in relation to their potential to delay the trend of resource exhaustion and environmental degradation. Eco-efficiency is a measure of a firm, an industry, or a region's performance in sustainable development, which involves economic, resource, environmental, and social aspects simultaneously (Huppes and Ishikawa, 2005; Seppäläa et al., 2005). In China, high resource inputs, especially energy, have supported rapid economic growth during the last three decades. Consequently, ecological crises, including desertification and pollution, have intensified within China because of extensive construction, inadequate clean production technology, and blind GDP growth.

Given the urgent issue of human survival, many researchers have devoted their efforts to facilitating studies of eco-efficiency (Schaltegger and Sturm, 1990; Mickwitz et al., 2006; Wang et al., 2011; Huang et al., 2014; Wang and Feng, 2015; Gómez-Calvet et al., 2016; Yue et al., 2017), environmental efficiency (Zhou et al., 2007; Halkos and Tzeremes, 2009; Chiu et al., 2012; Zhang et al., 2016; Wu et al., 2016; Moutinho et al., 2017) and energy efficiency (Hu and Wang, 2006; Honma and Hu, 2008; Shi et al., 2010; Li and Hu, 2012; Zhang and Choi, 2013; Apergis et al., 2015; Zhang et al., 2015; Al-Refaie et al., 2016; Huang et al., 2017). However, inconsistencies among concepts and also relationships of eco-efficiency and other relevant efficiencies have been presented. Some scholars label input-output efficiency in relation to pollutant emission as either "environmental efficiency" (Zhou et al., 2007; Halkos and Tzeremes, 2009; Chiu et al., 2012; Zhang et al., 2016), "total-factor energy and environmental efficiency" (Wang et al., 2013) or "resource and environmental efficiency" (Bian and Feng, 2010), the meanings of which are essentially synonymous with that of eco-efficiency. The discrepancy among efficiency terms in related theoretical and empirical studies is detrimental to the process of comparing and summarizing relevant research achievements. Moreover, some biased measurements of relevant efficiencies due to the unsuitable orientation of measure models still exist in recent related studies (Bi et al., 2014; Zhang et al., 2015).

Clarifying the relationships between eco-efficiency and other pertinent efficiencies, and then measuring these efficiencies suitably are crucial to the promotion of further research. Diagnosing problems with correlations between indicators to sustainable performance could support analysts in discovering patterns within and across units of analysis (De Leo and Miglietta, 2015). Eco-efficiency is a relatively comprehensive concept and sub-efficiencies could reflect the development characteristics of a decision-making unit (hereafter, DMU) from specific perspectives. Therefore, recognizing sub-efficiencies of eco-efficiency is sensible in terms of enhancing the sustainable development level of a DMU effectively. For this purpose, a total-factor framework is necessary

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as sub-efficiencies are measured when other respects are all assumed to be the same. For example, economic efficiency should be applied in assessment of a DMU's ability to maximize economic outputs, when every DMU's inputs and undesirable outputs are set at the same level. Although Wang and Feng (2015) proposed a total-factor framework, including eco-, energy, environmental, and economic efficiencies, they did not illustrate the inner relationships between these four efficiencies theoretically. In this paper, we present the composite eco-efficiency indicators, where eco-efficiency is the forefather of the family, and then it derives total-factor economic, total-factor resource, and total-factor environmental efficiencies with different points of focus.

Considering varying orientations according to different connotations of the considered efficiencies, we construct a measure system for composite eco-efficiency indicators. The proposed system is based a new data envelopment analysis (DEA) approach, named Meta-US-SBM, taking meta-frontier, undesirable outputs, super efficiency, and slacks-based measure into consideration simultaneously. As the *meta*-frontier approach envelops technology heterogeneity among groups (Li and Lin, 2015), Meta-US-SBM can compare efficiencies of any DMUs, regardless of whether they belong to distinct groups. Moreover, it can recognize and rank DMUs on the technological frontier, taking super efficiency into account. Using a provincial panel of China from 2001 to 2014, the proposed measure system is applied to assess the performance of Chinese provinces in terms of economic growth, energy consumption, and environmental impact.

The remainder of this paper proceeds as follows. In Section 2, we identify each member of the composite eco-efficiency indicators under a total-factor theoretical framework. In Section 3, we propose the measure models of these composite eco-efficiency indicators, based on Meta-US-SBM. Section 4 applies the proposed models using Chinese provincial data. Finally, Section 5 presents some conclusions.

2. Theoretical framework

2.1. Literature review

The concept of eco-efficiency was initially described by Schaltegger and Sturm (1990). The widely-accepted definition of eco-efficiency made by the world business council for sustainable development (WBCSD, 2000) illustrates that eco-efficiency means progressively reducing environmental impact and resource intensity in the process of satisfying human needs and bringing quality of life.

Eco-efficiency is an instrument for sustainability analysis, indicating an empirical relationship in economic activities between economic value and environmental impact (Huppes and Ishikawa, 2005). The definition introduced by the WBCSD demonstrates that sustainable development encompasses four dimensions: economy, resource, environment, and society (Seppäläa et al., 2005). Although the social aspect is an essential part of sustainability, it has not yet been embedded in the concept of eco-efficiency in practical applications (Mickwitz et al., 2006). Thus far, many scholars have contributed to the progress of eco-efficiency measure by using single or multiple inputs and outputs, and some scholars have just used synonyms of eco-efficiency, such as "environmental efficiency" (Zhou et al., 2007; Halkos and Tzeremes, 2009; Chiu et al., 2012; Zhang et al., 2016), "total-factor energy and environmental efficiency" (Wang et al., 2013) and "resource and environmental efficiency" (Bian and Feng, 2010).

After summarizing and refining the extant studies, we find that most researchers essentially make this point: eco-efficiency, or its synonyms, is a total-factor productivity that considers the negative externalities, such as environmental pollutants (ZofíO and Prieto, 2001; Korhonen and Luptacik, 2004; Seppäläa et al., 2005; Mickwitz et al., 2006; Zhou et al., 2007; Zhang et al., 2008; Halkos and Tzeremes, 2009; Wursthorn et al., 2011; Picazo-Tadeo et al., 2012; Chang et al., 2013; Huang et al., 2014; Liu et al., 2017). GDP is always treated as the only desirable output in most involved studies, and labor force, capital stock, and energy consumption are the regular inputs. Carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions, chemical oxygen demand (COD), and some other concrete forms of pollutant emission are the options for undesirable outputs in these researches. DEA is a method that can accommodate various desirable and undesirable effects of production in a single efficiency index (Zhang et al., 2008). With the advantage of handling multiple inputs and outputs simultaneously, plus nonparametric treatment of the frontier and calculating the relative efficiency of the data (Toma et al., 2017), DEA has become the most common approach for efficiency measure. Moreover, neither the imposition of a functional form on the underlying technology nor explicit weights to aggregate the indicators are required (Hailu and Veeman, 2000; Huang et al., 2014). As the radial DEA cannot take the possible slacks of variables into account, the SBM model proposed by Tone (2001) has focused gradually on the measure of either eco-efficiency or some related efficiencies. In much of the extant literature, eco-efficiency or environmental efficiency is always directly measured as the relative technical efficiency through DEA models (ZofíO and Prieto, 2001; Korhonen and Luptacik, 2004; Seppäläa et al., 2005; Mickwitz et al., 2006; Zhou et al., 2007; Zhang et al., 2008; Halkos and Tzeremes, 2009; Wursthorn et al., 2011; Picazo-Tadeo et al., 2012; Chang et al., 2013; Huang et al., 2014; Liu et al., 2017). Zhou et al. (2013) evaluated the environmental efficiency of the Chinese power industry by an entropy SBM model. Zhang et al. (2016) used SBM to evaluate the environmental efficiency of 30 provinces in China. Additionally, to overcome the shortage of deterministic frontier models which are sensitive to outliers, Simar and Wilson, (2000, 2008) developed a bootstrap DEA method for obtaining confidence intervals of efficiency scores. Recently, Toma et al. (2017) examine the agricultural efficiency of EU countries through the bootstrap DEA approach. For robustness analysis, we also implement this method to validate our results.

In the relevant efficiency measure literature, theoretical and empirical achievements in relation to "energy efficiency" cannot be ignored. Built upon the earliest work of Hu and Wang (2006), "total-factor energy efficiency," which not only includes energy consumption but also embraces non-energy inputs in its measure system, has been one of the core research topics in ecological economics. Subsequent researchers have often followed the main study procedure of Hu and Wang (2006), *i.e.*, obtaining the target energy input suggested from the input-oriented DEA model and then defining the total-factor energy efficiency as being the ratio of target energy input to actual energy input (Wei and Shen, 2007; Honma and Hu, 2008; Hu and Chang, 2016; Ma et al., 2017; Zhou et al., 2017). However, considerable studies present biased measurements of the total-factor energy efficiency. Some analysts defined energy efficiency as the ratio of target energy input to actual energy input, while the target energy input was suggested from a non-oriented DEA model (Li and Hu, 2012; Zhang and Choi, 2013; Zhang et al., 2015). Some other researchers yet used the technical efficiency directly as the total-factor energy efficiency, even though they consider the input-oriented model (Wang et al., 2012; Bi et al., 2014). For the reason that energy efficiency reflects the capability of minimizing the energy input under a fixed output level (Wei and Shen, 2007), we believe the suitable measurement of the total-factor energy efficiency as the ratio of target to actual energy input from an input-oriented viewpoint.

As the concept of sustainability has strengthened in the human consciousness over the decades, there have been quite a few research achievements concerning the impact of economic activities on ecology. However, several inadequacies in these studies have been presented. First, there is no exact consensus about the intension and extension of eco-efficiency, which results in the status quo that diverse terms are attached to the same object. Therefore, the essential