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Scenario-based energy efficiency and productivity in China: A non-radial directional distance function analysis

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ABSTRACT

Improving energy efficiency and productivity is one of the most cost-effective ways for achieving the sustainable development target in China. This paper employs non-radial directional distance function approach to empirically investigate energy efficiency and energy productivity by including CO_2 emissions as an undesirable output. Three production scenarios, namely energy conservation (EC), energy conservation and emission reduction (ECER), and energy conservation, emission reduction and economic growth (ECEREG), are specified to assess China's energy efficiency and productivity growth during the period of Eleventh Five-Year Plan. Our empirical results show that there exist substantial differences in China's total-factor energy efficiency and productivity under different scenarios. Under the ECEREG scenario, the national average total-factor energy efficiency score was 0.6306 in 2005–2010, while the national average total-factor energy productivity increased by 0.27% annually during the period. The main driving force for energy productivity growth in China was energy technological change rather than energy efficiency change.

1. Introduction

China has achieved tremendous success in economic development during the past several decades, which was supported by huge energy consumption. Fig. 1 shows the changes in China's energy consumption and CO_2 emissions expanded uninterruptedly and considerably since 2005. With the increasing concern on climate change mainly arising from CO_2 emissions, Chinese government has strived to control its energy consumption and greenhouse gas emissions. Of the alternative ways for reducing energy consumption, improving energy efficiency and energy productivity has been regarded as one of the most cost-effective ways (Ang et al., 2010).[1] In China, improving energy efficiency has also been treated as an important policy strategy for controlling energy consumption and promoting low-carbon development. In its Eleventh Five-Year Plan, Chinese central government has set the target of decreasing national energy intensity, i.e. energy use per unit GDP, by 20% with 2005 as the base year. Through various proactive actions, China has almost achieved the target by the end of 2010. In the Twelfth Five-Year Plan, China has further set the target of reducing its national energy intensity by 16% till the end of 2015.

Monitoring economy-wide energy efficiency performance can provide useful information for assessing the effectiveness of energy efficiency policies and measures (Ang, 2006). Despite the usefulness of energy intensity indicator in performance monitoring, it takes energy consumption as the only input for conducting economic activities and is therefore a single-factor energy efficiency indicator. Given the uneven levels of regional economic development as well as diverse economy structure and energy consumption patterns in China, only energy intensity indicator is insufficient to depict the overall picture of energy use performance precisely. Since the production of any economic outputs requires both energy and non-energy inputs and there may exist substitution effects between different inputs, it seems to be more meaningful to assess energy efficiency and productivity performance within a total-factor production framework.[2]

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[1] It should be pointed out that the two terminologies, energy efficiency and energy productivity, are clearly distinguished in this paper, while they have been used interchangeably and implicitly in many previous studies. Here energy efficiency is considered as a kind of technical efficiency, which is defined as the ratio of expected energy consumption to actual energy consumption for an entity during a period of time. On the other hand, energy productivity refers to the ratio of desirable output to energy consumption, which incorporates both efficiency change and technological change.

[2] Another line of research in energy efficiency assessment is to use index decomposition analysis to isolate the impacts of energy intensity at sub-sector level on the change of energy use, which are further aggregated into a composite index for energy efficiency assessment (Ang, 2006; Ang et al., 2010). This practice has been adopted by many national energy agencies for tracking their economy-wide energy efficiency trends.

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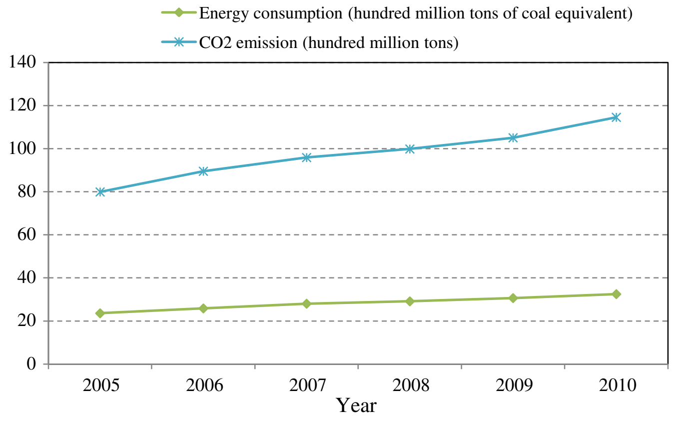

Fig. 1. Energy consumption and CO_2 emissions in China, 2005–2010.

Hu and Wang (2006) defined the first total-factor energy efficiency index with data envelopment analysis (DEA) for assessing the provincial energy efficiency performance in China. Since then, a number of researchers have devoted to use DEA to model energy efficiency performance at different aggregate levels.[3] Examples of such studies include Wei et al. (2007), Barros (2008), Mukherjee (2008, 2010), Barros and Assaf (2009) and Chang and Hu (2010).[4] These studies evaluate energy efficiency performance within a total-factor production framework without undesirable outputs. Since fossil energy consumption will inevitably produce undesirable outputs such as CO_2 emissions, evaluating total-factor energy efficiency without considering undesirable outputs may create biases in the resulting efficiency scores. As such, Zhou and Ang (2008) first proposed several DEA models with undesirable outputs for evaluating total-factor energy efficiency performance, which was followed by a number of studies such as Mandal (2010), Wang et al. (2012) and Wu et al. (2012). Several researchers also studied national and regional energy efficiency in China. Shi et al. (2010) investigated China's regional industrial energy efficiency during 2000–2006, which found significant differences between different regions. Yeh et al. (2010) evaluated China mainland's energy efficiency and compared it with that of Taiwan.

In the broad area of performance measurement, the inclusion of undesirable outputs has also become popular since most production processes will generate undesirable outputs as byproducts. An up-to-date development is to employ the directional distance function developed by Chambers et al. (1996), which is capable of expanding desirable outputs and contracting undesirable outputs simultaneously in performance measurement. Clearly, the utilization of fossil energy will inevitably produce undesirable outputs such as CO_2 emissions. A large number of studies have therefore employed directional distance function to model energy and environmental performance. See, for example, Färe et al. (2007), Kumar and Managi (2010), Oh (2010), Oh and Heshmati (2010), Mukherjee (2010), Zhang et al. (2011), Riccardi et al. (2012), Chiu et al. (2012) and Picazo-Tadeo et al. (2012). In methodology, Fukuyama and Weber (2009) and Färe and Grosskopf (2010) expanded directional distance function into a more general form that is able to identify and incorporate slacks as much as possible. Built upon the non-radial directional distance inefficiency measure, Mahlberg and Sahoo (2011) developed the non-radial Luenberger indicator for estimating total-factor productivity growth. Fukuyama et al. (2011) and Barros et al. (2012) conduct further investigation on how to derive non-radial directional distance efficiency measure in the presence of undesirable outputs. More recently, Zhou et al. (2012a) provided a formal characterization of non-radial directional distance function from the axiomatic production theory for measuring energy and CO_2 emission performance in electricity generation.[5]

In the context of energy efficiency measurement, Mukherjee (2010) explored the use of directional distance function for achieving the joint goals of energy conservation and economic growth. Chang and Hu (2010) defined a total-factor energy productivity index with non-radial directional distance function, which was used to evaluate the energy productivity change of Chinese provinces. However, these studies did not consider undesirable outputs in their modeling framework. The purpose of this study is to employ non-radial directional distance function described in Zhou et al. (2012a) to define total-factor energy efficiency and energy productivity indexes by considering CO_2 emissions, which are further used to assess the provincial and national energy efficiency and energy productivity changes during the period of 2005–2010 in China. As China has set the targets of reducing energy and CO_2 emission intensities, it is necessary for China to promote its economic growth while considering energy conservation and emission reduction constraints. In this study, several different production scenarios are specified to assess China's energy efficiency and productivity growth in a more comprehensive manner.

The rest of this paper is organized as follows. Section 2 introduces the derivation of total-factor energy efficiency and productivity indexes with non-radial directional distance function. Section 3 presents the data used and the results obtained. Section 4 further examines the driving forces behind energy productivity growth in China. Section 5 concludes this study.

2. Methodology

2.1. Environmental production technology

We first formulate the production technology for regions in China. As Hu and Wang (2006) as well as many other studies did, this study assumes that there are three inputs, i.e. capital (K), labor (L) and energy (E). Further assume that GDP (Y) and CO_2 emissions (C) are specified as desirable and undesirable outputs, respectively.[6] Then the production technology can be described as

$$\mathrm{T} = \{(K, L, E, Y, C) : (K, L, E) \text{ can produce } (Y, C)\}. \tag{1}$$

According to Färe et al. (2007), the output set corresponding to T is often assumed to be a closed set. It means that finite amount of inputs can only produce finite amount of outputs. Moreover, inputs (K, L, E) and desirable output (Y) are assumed to be strongly or freely disposable.

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[3] Zhou et al. (2008) conducted a survey of DEA in energy and environmental studies in which energy efficiency model was identified as one major area. The recent study by Chen (2013) examined the DEA models for environmental performance measurement published in this journal and other energy-related outlets, with emphasis on the appropriateness of weak disposability assumption. For more detailed information on DEA methodological development, please refer to a comprehensive review by Glover and Sueyoshi (2009).

[4] In addition to DEA, stochastic frontier analysis has also been employed to measure sectoral or economy-wide energy efficiency performance, e.g. Filippini and Hunt (2012), Zhou et al. (2012b) and Stern (2012).

[5] The definition of “non-radial”, employed in this study and Zhou et al. (2012a), is different from the conventional one specified in most of previous DEA studies such as Sueyoshi and Sekitani (2009a) and Sueyoshi and Goto (2012a,b,c,d,e). The conventional non-radial measurement measures the level of efficiency by slacks, not an efficiency score. However, in this study the amount of slack is replaced by an efficiency score related to each production factor (i.e., inputs, desirable and undesirable outputs). Thus, this research documents a new type of non-radial measure.

[6] In this study we choose CO_2 emissions as a representation of undesirable outputs since CO_2 emission reduction has received great attention in China. Nevertheless, other kinds of toxic by-products, e.g. NOx and SO_2, could also be investigated when studying a specific sector, e.g. Sueyoshi and Goto (2012c).