Renewable and Sustainable Energy Reviews 69 (2017) 664–672

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Non-radial metafrontier approach to identify carbon emission performance and intensity

Qunwei Wang[a], Yung-Ho Chiu[b,*], Ching-Ren Chiu[c]

[a] College of Economics and Management & Research Center for Soft Energy Science, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

[b] Department of Economics, Soochow University, Taibei 1004 Taiwan, ROC

[c] Department of Business Administration, National Taichung University of Science and Technology, Taichung 404, Taiwan, ROC

ARTICLE INFO

JEL:
D24
O57
Q53

Keywords:
Carbon intensity
Performance decomposition
Metafrontier
DEA

ABSTRACT

Different carbon emitting nations and regions use different production technologies. To analyze potential sources of carbon intensity reduction, this study applied a metafrontier function and a non-radial data envelopment analysis (DEA) approach to propose a new carbon emission performance index. An empirical study of carbon emissions from 58 countries between 2001 and 2007 led to three key findings. First, different reference technologies lead to significant differences in carbon emission performance. Assessing carbon emission performance using the group frontier as the evaluation criterion consistently yields equal or greater performance than when using the metafrontier as the benchmark. Second, the carbon emission performance of Asia is lower than that of Europe and the Americas, but Asia has the greatest potential to reduce carbon intensity. Production technology levels in Asia have lagged behind levels in Europe and the Americas; these gaps, however, have gradually narrowed. Finally, ineffective management and gaps in production technologies are the two main contributors to carbon dioxide intensity. Management factors are more significant overall for Asia, Europe and America; However, different individual countries have different perspective on the sources of potential carbon intensity.

1. Introduction

Carbon dioxide emissions are a significant force behind global warming, sparking concern in the international community since the 1980s. A growing number of international organizations and countries are taking active measures to demonstrate this awareness and to cope with the challenges posed by climate change. The first inter-governmental climate agreement, the "United Nations Framework Convention on Climate Change (UNFCCC)," was signed in 1992. To clarify different countries' obligations to reduce emissions, 149 countries adopted the "Kyoto Protocol" in 1997. This agreement set quantified targets as constraints, and proposed principles for "common but differentiated responsibilities" to reduce carbon emissions.

The Copenhagen Climate Change Conference in 2009 failed to reach a consensus on emission reduction obligations and responsibilities in the post-Kyoto era, but did reaffirm the principle of "common but differentiated responsibilities." To implement this principle, more attention has been paid to methods for evaluating nation-level carbon dioxide emissions, because these methods form the basis for discussing and allocating national responsibilities. These methods also allow the measurement of carbon emission performance, and facilitate equitable development opportunities.

A number of indicators to evaluate carbon emissions have been developed, with different scopes, timeframes, and perspectives. In the 1990s, based on the emission reduction obligations under the "Kyoto Protocol," country-specific total carbon emissions emerged as an early indicator to apply [1,2]. Some industrialized and developed countries reduce total carbon emissions as a way to also mitigate greenhouse gas issues. However, while total carbon emission reduction indicators make it easy to identify sources of liability, these indicators do not adequately represent fairness in carbon emission rights. This is particularly true for developing countries that have not yet experienced industrialization and the face strong demand for carbon emissions due to economic development. Therefore, many developing countries advocate using carbon intensity, defined as the carbon dioxide emissions per unit of gross domestic product (GDP), to measure each country's carbon emissions.

The carbon intensity indicator has been adopted by an increasing number of international organizations and countries [3–5]. Many governments rely on carbon intensity as an indicator when developing

* Corresponding author.
E-mail address: echiu@scu.edu.tw (Y.-H. Chiu).

http://dx.doi.org/10.1016/j.rser.2016.11.199
Received 13 July 2014; Received in revised form 14 November 2016; Accepted 14 November 2016
1364-0321/

national carbon reduction targets. For example, the largest carbon dioxide emitter, China, promised to reduce its carbon dioxide emissions per unit of GDP in 2020 by 40–45% compared with the level of 2005. Indian, another major carbon dioxide emitter, has committed to lowering its 2020 carbon intensity by 20–25% compared to 2005 levels.

In addition to carbon dioxide intensity, scholars have proposed other indicators to evaluate carbon emission performance from other perspectives. Examples include carbon productivity [6], carbon emission per capita [7,8], total industrial carbon emission per capita [9], carbon emission per unit of energy [10], and carbon emission embodied in trade [11–13]. These indicators of carbon performance essentially measure total amounts, ratios of two relevant indicators, and focus on linear correlations between carbon emission performance and economic development. These indicators are referred to as single factor indicators.

Single factor indicators are simple to calculate and easy to understand; however, they do not reflect the true process of carbon dioxide production, and do not account for the roles of energy structure, economic development, and factor substitution [14–16]. This may lead to biased carbon emission performance scores. Given the problems associated with single-factor indicators, Zhou et al. [17] first proposed the “total factor carbon emission performance index” (TCPI). TCPI reflects the ratio of theoretical carbon emissions to actual carbon emissions. This index introduces a Malmquist CO_2 emission performance index (MCPI) for measuring changes in carbon emission performance over time.

Using the MCPI, Zhou et al. [17] applied the Shephard distance function and the data envelopment analysis (DEA) method to empirically study the world's 18 top CO_2 emitters from 1997 to 2004. Wang et al. [18] used the multi-directional efficiency (MEA) approach, rather than the Shephard distance function used in Zhou et al. [17], to evaluate China's energy and emission performance. Wang et al. [19] further noted that, in addition to the non-parametric DEA method, parametric stochastic frontier analysis (SFA) can also be used to measure and calculate the carbon emission performance.

Different from the TCPI, Zhou et al. [20] redefined the carbon emission performance index as the ratio of targeted carbon intensity to actual carbon intensity (ACI). The targeted carbon intensity was calculated by identifying the potential for increased GDP output and reduced carbon emission, driven by the non-radial directional distance function and DEA models. This approach reflects the fact that many countries adopted the carbon intensity indicator when setting emission reduction targets. Similar applications are found in Zhang et al. [21,22], and Yao et al. [23].

Conventional carbon emission performance measurements assume that decision-making units (DMUs) share common production technologies. However, production technologies differ based on differences in economic development and geographic environment. Therefore, scholars have started to estimate carbon emission performance using a metafrontier framework. For example, using a metafrontier non-radial Malmquist CO_2 emission performance index, Zhang and Choi [24] examined the dynamic changes in CO_2 emission performance at fossil fuel power plants in China. As another example, Du et al. [25] used a nonparametric metafrontier approach to estimate CO_2 emissions efficiency and potential emission reductions for 30 provinces in China. Yao et al. [23] provided a metafrontier non-radial directional distance function analysis that examined energy efficiency, carbon emission performance, and regionally-specific carbon emission reductions potential. Other scholars have also applied the metafrontier approach to study energy efficiency, including Chiu et al. [26], Wang et al. [16], Li and Lin [27], and Fei and Lin [28].

Previous studies have shared the following characteristics. First, theoretical research generally evaluates carbon emission performance using a total factor perspective based on production theory. In practice, however, individual countries generally rely on carbon intensity indicators with single factor characteristics to formulate emission reduction targets and policies. This has led to a disconnection between theory and practice. Second, while many have applied the single factor carbon emission performance index (i.e., the ratio of targeted carbon intensity to actual carbon intensity) proposed by Zhou et al. [20], few studies estimate carbon emissions performance from the perspective of the metafrontier. This may bias estimates. Third, existing studies focus on measuring and evaluating carbon emission performance, and do not discuss the causes of performance deficiencies.

The goal of this study is to propose a total factor measurement method for carbon emission performance that can also be associated with single factor indicators. To achieve this, this paper simultaneously considers non-radial slacks and production technology heterogeneity by integrating the TCPI redefined by Zhou et al. [20] with the metafrontier function. Compared with previous studies, this method allows a more accurate assessment of carbon emission performance potential, connecting theoretical indicators with actual applications. The study also decomposes the potential for carbon intensity reduction into technology potential and management potential, supporting policies that can target and optimize efficiency. The new index is then applied to empirically study the world's leading carbon emission countries.

2. Research methods

2.1. Metafrontier

The traditional DEA method used to measure operating efficiency and carbon emission performance assumes that all evaluated countries and regions (also known as decision-making units or DMUs) form one common production frontier. The performance of the DMU can then be judged by examining the distance from the production frontier. A prerequisite for this assumption is that all the countries are similar with respect to factors such as resource access, resource conversion capabilities, and the external environment. It also assumes that carbon dioxide emissions are produced under the same technological conditions.

In reality, it is inaccurate to assume that technological conditions are similar worldwide. Production technologies associated with carbon dioxide emissions tend to differ in different countries or regions [29]. These differences are driven by leading factors such as market conditions, legal constraints, resource endowments, and market openness [30]. Measurements of a country's or region's carbon emission performance are inadequate if those areas significantly differ in production technologies. Furthermore, these measurements do not support the principle of "differentiated responsibilities" in the international community.

To address the problems of a single production frontier, Hayami [31] and Hayami and Ruttan [32] proposed the concept of a metafrontier function. The concept accommodates differences in DMU production technologies, by assuming that the heterogeneity is reflected in other properties, such as region, type, and size. DMUs are placed indifferent groups based on the sources of technological heterogeneity. Each group serves as a production frontier, also known as a group frontier. A common production frontier or metafrontier is then obtained from the frontier envelopes generated by the different groups [33,34]. Battese and Rao [30], Battese et al. [35], O'Donnell et al. [36], Huang et al. [37], Assaf et al. [38], Lin et al. [39], Chiu et al. [40], Wang et al. [34] and others have applied the metafrontier function to study regional efficiency and productivity.

To construct a carbon emission performance measurement model that accounts for the heterogeneity of production technology, we assume there are N countries (i.e. N DMUs) being evaluated. Input factors include capital stock (K), labor (L) and energy (E); output factors include GDP (Y) and carbon dioxide emissions (C). Based on different production technologies, countries can be divided into H different groups. The number of DMUs in the h^{th} group is N^h, and