Resources, Conservation and Recycling xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

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

Full length article

The green efficiency of industrial sectors in China: A comparative analysis based on sectoral and supply-chain quantifications

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ARTICLE INFO

Article history:
Received 29 November 2016
Received in revised form 13 February 2017
Accepted 19 February 2017
Available online xxx

Keywords:
Industrial sectors
Green efficiency
Directional slacks-based inefficiency model
Input-output analysis
China

ABSTRACT

Industry is a main energy consumer and environmental polluter in modern society. The performance of China's industrial development should therefore be integratively measured in economic, environmental as well as energy and resource contexts. This study employs the directional slacks-based inefficiency model to calculate sectoral and supply-chain green efficiency (SGE and SCGE respectively) of 37 industry sectors in China. Energy and water consumption are selected as the model inputs. Output considerations include value-added (desirable output), and SO_2, NO_x and CO_2 emissions (undesirable outputs). Sectoral statistics data are used to calculate SGE while an input-output (I-O) analysis model, using China's 2012 economy benchmark data, is employed to quantify SCGE. Furthermore, the sectors that significantly contribute indirect energy consumption to China's industrial system are identified, and determinants of their SCGE are analyzed using the Tobit model. Results show that light industrial sectors present higher SGE but lower SCGE compared to that of heavy industrial sectors. Environmental regulation and independent innovation capacity promote industrial sectors' SCGE, while capital-labor ratio and foreign direct investment exert inhibiting effects. Based on model results, policy suggestions are presented to advance green industry transition in China.

1. Introduction

China's tremendous industrial development, over the last decade, is evidenced by the increase in its value-add from 4000 billion yuan in 2000 to 22,800 billion yuan in 2014, representing an annual growth rate of 10.5% (NBSC, 2015a). However, this progress was accompanied by significantly increasing energy and resource consumption and environmental pollution. China contributed 13.3% to global GDP in 2014, but the country was also responsible for overall consumption of the world's energy (22.4%), steel (47.2%), copper (36.9%), and aluminum (51%) (Du, 2015). Presently, approximately 70% of cities in China do not meet air quality standards issued by Chinese government (MEPC and GAQSIQ, 2012), and about 0.6 billion of the country's population is exposed to particle matter pollution (MIITC, 2016). To address the challenges to sustainable development of China's industries, the Chinese government initiated a new development pattern—a road to brand-new industrialization with Chinese characteristics—to enable rapid industrial growth while reducing energy and environmental impacts. As a result, the 12th Five-Year Development Plan (2011–2015) focuses on cultivating the awareness of a green pathway of industrial development, and in the 13th Five-Year Plan period (2016–2020) the government initiates stringent controls on industrial sectors' energy consumption, greenhouse gas (GHG) emissions, and ecological interruptions. But one of the initial steps toward the sustainable industry transition in China is to quantify and analyze the green efficiency of industrial sectors. By integrating the considerations of energy and resource consumption reduction, environmental pollution mitigation, and economic development, the green efficiency in this study is defined as the extent of energy and resource reliance and environmental pollution of industrial sectors' value-added creation.

Quantifying the industrial sectors' green efficiency primarily has two methodological options. One is to establish indicator systems, and then nondimensionalize and weight indicators (CIIGBC, 2012; Li and Pan, 2013). This approach has been widely adopted due to its streamline modeling procedures and public access to statistical data. However, subjective indicator selection and weighting cause

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http://dx.doi.org/10.1016/j.resconrec.2017.02.015
0921-3449/

Please cite this article in press as: Zhang, J., et al., The green efficiency of industrial sectors in China: A comparative analysis based on sectoral and supply-chain quantifications. Resour Conserv Recy (2017), http://dx.doi.org/10.1016/j.resconrec.2017.02.015

high uncertainty for study results. To enable complete and objective assessment, approaches such as stochastic frontier analysis (SFA) and data envelopment analysis (DEA) use all-factor considerations to evaluate industrial growth performance and productivity under energy and environmental constraints. The SFA was originally developed by Aigner et al. (1977) and Meeusen and Van Den Broeck (1977), and was thereafter further extended by Pitt and Lee (1981) and Barros and Antunes (2011). Existing studies have adopted SFA to calculate energy efficiency (Lin and Yang, 2013) and production factor allocation efficiency (Ouyang and Sun, 2015) for different industrial sectors in China, but the approach requires a specified production function, and is inapplicable to quantifications with multiple outputs (Lampe and Hilgers, 2015). The DEA is an assessment method based on relative efficiency. Charnes, Cooper and Rhodes developed the prototype DEA model—the CCR model in 1978 (Charnes et al., 1978) that was followed by the BCC model created by Banker, Charnes and Cooper (Banker et al., 1984). With the rising importance of sustainable development, energy and environmental considerations are gradually integrated into economic assessment, and DEA is used to calculate the all-factor green efficiency of industrial sectors. Since environmental pollutants fail to satisfy the "maximum outputs" hypothesis of the traditional DEA efficiency model, researchers regarded environmental pollutants as either input variables (Hailu and Veeman, 2001; Ramanathan, 2005), which fail to reflect the real production process (Seiford and Zhu, 2002), or applied a monotone decreasing transformation to the undesirable outputs (Hua et al., 2007), but this is valid only when variable returns to scale (Song et al., 2012) because of strong convexity constraints. Chung et al. (1997) developed the directional distance function (DDF) and treated environmental pollutions as undesirable outputs; this becomes the mainstream approach for green productivity analysis (Kaneko et al., 2010; Chang and Hu, 2010). However, DDF is a radial and input- or output-oriented approach. Radial measures overestimate the technical efficiency of decision making units (DMU) when inputs or outputs slack (Fukuyama and Weber, 2009), and oriented measures fail to simultaneously measure the efficiency from both input and output perspectives. As such, Tone (2001) developed the non-radial and non-oriented slacks-based measure (SBM). Existing studies have employed a non-radial directional distance function (NDDF) or SBM to calculate the resource and environmental efficiency for China's industrial sectors (Lin and Yang, 2014; Long et al., 2015). Combining the SBM and DDF, Fukuyama and Weber (2009) proposed a directional slacks-based measure of technical inefficiency and overcame the DMU's efficiency overestimation, enabling non-proportional adjustments of input and output efficiency. Fukuyama et al. (2011) further extended the directional slacks-based inefficiency (DSBI) model when undesirable outputs are considered, and measures of China's energy efficiency and productivity (Wang et al., 2013) and green growth index of industries (Zhang et al., 2015a) are available.

However, existing literature regarding the green efficiency of China's industrial sectors mainly focus on all-factor productivity analysis for certain regions and sectors, lacking nationwide cross-sector quantifications. Moreover, such studies primarily use data from individual sectors (e.g., sectoral energy consumption and emissions) and do not reflect economy-wide sectoral correlations and interactions. Egilmez et al. (2013) combines the input-output (I-O) model and DEA approach to analyze the eco-efficiency of manufacturing sectors in the U.S., but the model results fail to avoid the interruptions of radiality and orientation inherent in basic DEA model. To address the aforementioned knowledge gap, this study first calculates the sectoral green efficiency (SGE) for China's industrial sectors using sectoral data. The SGE is a production-based indicator that directly measures the efficiency of individual industry activities. We then use an input-output analysis model to quantify the total supply-chain energy and environmental footprints of each sector, and apply the results to the directional slacks-based inefficiency model to yield supply-chain green efficiency (SCGE). Next, we comparatively analyze the conventional sectoral and supply-chain green efficiency results to identify the fundamental sectors that are critical for improving the overall sustainability of China's industrial system. Finally, we use the Tobit model to analyze the determinants of the fundamental sector's SCGE to shed light on policy opportunities for enabling green industry advancement in China.

2. Study framework

Green efficiency, as defined in this study, consists of three dimensions: economy, resource and energy, and environment. The sectoral value-added is treated as a desirable output of China's industrial development, while undesirable outputs include SO_2, NO_X and CO_2 emissions due to their importance in the development of Chinese society (CCCP, 2011). Energy and water consumption are regarded as inputs of industrial production. For the above indicators, supply-chain footprints associated with per unit monetary output of each industrial sector are calculated by the I-O analysis model using statistics from the 2012 China input-output table, which is the most recent economic benchmark data available at the time of this writing. With these data, the DSBI model is employed to measure the green efficiency of 37 industrial sectors in China. Additionally, to better interpret the implications of supply-chain green efficiency, conventional sectoral green efficiency quantification is

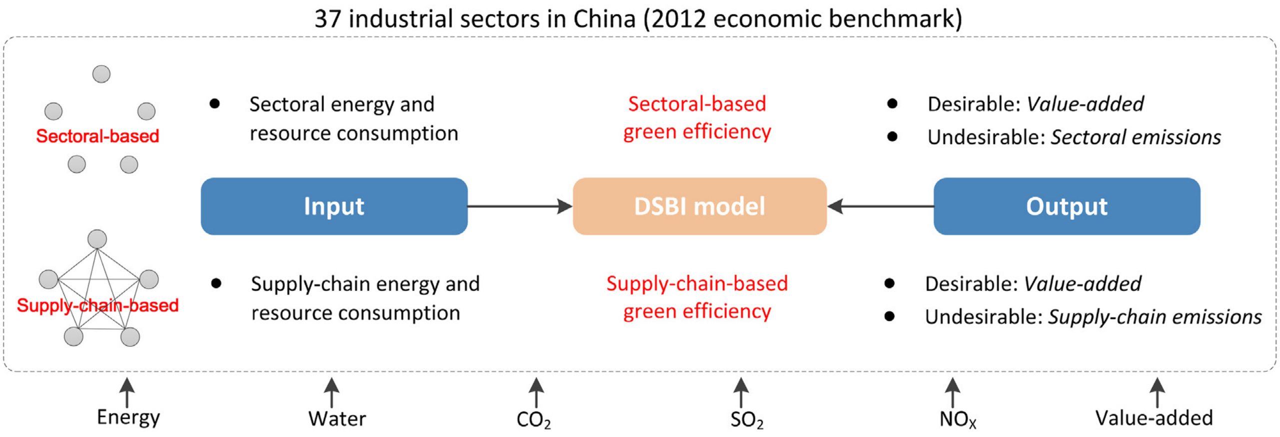

Fig. 1. Green efficiency quantifications for industrial sectors in China.

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