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Carbon productivity growth, technological innovation, and technology gap change of coal-fired power plants in China☆

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ABSTRACT

This paper proposes a sequential meta-frontier Luenberger productivity index (SMLPI) that incorporates undesirable outputs to measure carbon productivity growth over time. This new index combines the concepts of sequential production technology, meta-frontier directional distance function, and the Luenberger productivity Index to produce a composite indicator, so that it can take group heterogeneities and the progressive nature of technology into consideration for productivity measurement. The SMLPI is then applied to a unique dataset of China's coal-fired power plants, including 5048 observations covering the period 1999–2008. The results show an increasing trend of carbon productivity growth during the sample period for both state- and non-state-owned power plants. Further decomposition analyses show that the production technology also exhibits an increasing trend for both groups, but the efficiency change exhibits a decreasing trend. For the state-owned group, the technology gap decreased before 2003, but increased thereafter. On the contrary, for the non-state-owned power plants, the technology gap increased before 2003, but decreased thereafter.

1. Introduction

As one of the biggest carbon dioxide (CO_2) emitters in the world, China has made great effort to reduce carbon emissions. China's 11th Five-Year Plan required a mandatory goal of 20% reduction in energy intensity (energy consumption per unit of GDP) for the period of 2006–2010. The 12th Five-Year Plan further set a carbon intensity (CO_2 emissions per unit of GDP) reduction target of 17% for the period of 2011–2015. In 2015, the Chinese government declared its new reduction target, i.e., to achieve a 60–65% reduction in carbon intensity, compared to the 2005 level, by 2030.

China's power sector is one of the major contributors to CO_2 emissions. According to statistics from the International Energy Agency (IEA), fossil fuel electricity generation accounted for approximately 50% of coal consumption and 48% of CO_2 emissions in China (IEA, 2013). The power sector is under considerable pressure to reduce its energy use and carbon emissions. For the past decade, many industrial policies have been implemented to improve the energy efficiency and carbon productivity of the power sector, such as the "replacing small units with large ones" policy.[1] According to the statistics, during the 11th Five-Year Plan period, the fossil fuel power sector had reduced its CO_2 emissions by 1.74 billion tons with 2005 as the base year (Xinhuanet, 2011). However, an empirical question to measure the productivity change of the power plants in China still remains.

The development of directional distance function and frontier analysis makes it possible to measure the environmental efficiency and productivity of the power sector (Färe et al., 2005; Lee, 2005; Murty et al., 2007; Zhang and Choi, 2013a; Zhang et al., 2013; Zhou et al., 2012). However, from the view of methodology, there are some caveats worth emphasizing.

First, two types of indices can be used for environmental productivity measurement: the Malmquist–Luenberger index and the Luenberger index. The Malmquist–Luenberger index, proposed by Chung et al. (1997), measures productivity growth using a ratio and is based on the geometric mean of the directional distance functions. Contrarily, the Luenberger index measures productivity growth in an additive way by using the arithmetic mean of the distances between two periods (Zhang and Wang, 2015).

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[1] The "replacing small unit with large ones" policy encourages power-generating plants to build large-scale units and close its small ones.

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Most of the previous studies are based on the Malmquist–Luenberger index.[2] However, just as Boussemart et al. (2003) pointed out, the Malmquist index overestimates productivity changes because it provides productivity measures nearly twice those given by the Luenberger productivity index. Later literature also shows that the Luenberger index is more robust than the Malmquist index, since the arithmetic index can also allow extreme values, such as zero, while a geometric index cannot (Fujii et al., 2014).

Second, many previous studies neglected incorporating group heterogeneities for environmental productivity measurement of the power sector. The production sets of different groups may greatly differ because of differences in capital stocks, economic infrastructure, resource endowments, and any other characteristics of the physical, social, and economic environments (Battese et al., 2004; O'Donnell et al., 2008; Oh and Lee, 2010). For this consideration, Oh (2010) proposed a meta-frontier Malmquist–Luenberger index to incorporate group heterogeneities in environmental productivity growth measurement.

Third, the conventional productivity indices (the Malmquist–Luenberger index and the Luenberger index) do not take the nature of technology into consideration appropriately. In general, from the macroeconomic perspective, technology is always progressing or, at least, remains unchanged. However, the conventional productivity indices cannot exclude the case of long-run technical deterioration when measuring environmental productivity change. To overcome this weakness, Oh and Heshmati (2010) proposed the sequential Malmquist–Luenberger index as a new approach to taking the progressive nature of technology into account.

In this paper, we attempt to investigate the carbon productivity growth of China's coal-fired power plants. To avoid the drawbacks of previous studies, we propose the Sequential Meta-frontier Luenberger Productivity Indicator (SMLPI) as a new environmental productivity index for measuring the carbon productivity growth of China's power plants. This new index combines the concepts of meta-frontier, sequential production sets, and the Luenberger productivity index, so it can handle the group heterogeneities and reflect the progressive nature of technology in productivity measurement at the same time. This is the first possible contribution of this paper.

The second possible contribution of this paper is that our analysis is based on a unique, large, unbalanced panel dataset of China's coal-fired power plants that includes 5606 observations covering the period 1999–2008. Although some previous studies have explored the environmental efficiency of power plants in China, their samples were relatively small.[3] For example, Wei et al. (2013)'s analysis was based on a cross-sectional dataset that only included 124 power plants located in China's Zhejiang province; Zhang and Choi (2013b) used only a limited sample of 259 large state-owned plants in China; Du and Mao (2015)'s analysis was based on pooled cross-sectional data from 2004 to 2008; and Du et al. (2016)'s analysis was focused on 648 power plants in 2008. Our empirical research could be considered as the first paper to use a large dataset to investigate the carbon productivity change for China's power industry at the plant level.

The rest of the paper is organized as follows: Section 2 introduces the methodology, i.e., the sequential meta-frontier Luenberger productivity index; Section 3 describes the data; Section 4 reports the empirical results; and Section 5 concludes the paper.

2. Methodology

Assume there are k=1,...,K power plants and t=1,...,T time periods. Each power plant uses inputs $x = (x_1,...,x_N) \in \Re_+^N$ to produce good outputs $y = (y_1,...,y_M) \in \Re_+^M$ and bad outputs $b = (b_1,...,b_J) \in \Re_+^J$. The production possibility set can be defined as follows

$$P(x) = \{(y, b): x \text{ can produce } (y, b)\} \tag{1}$$

A number of assumptions are required to specify and model production technology when the good outputs and bad outputs are jointly produced (Färe et al., 2005).

The first assumption is that inputs are strongly disposable, so that

$$\text{if} x' \geq x, \ \text{ then } P(x') \supseteq P(x) \tag{2}$$

This assumption suggests that the output set will not shrink if the inputs used in production activity are increased.

The second assumption assumes that the good outputs and bad outputs are jointly produced, that is to say

$$\text{if } (y, b) \in P(x) \text{ and } b = 0, \ \text{ then } y = 0 \tag{3}$$

This null-jointness assumption implies that if no bad output is produced, then it is impossible to produce any good output.

The third assumption imposes weak disposability of good outputs and bad outputs on the production possibility set

$$\text{if } (y, b) \in P(x) \text{ and } 0 \leq \theta \leq 1, \ \text{ then } (\theta y, \theta b) \in P(x) \tag{4}$$

This assumption implies that proportional contraction of good outputs and bad outputs is feasible, as long as the original combination of good outputs and bad outputs is technically feasible.

Finally, we assume that the good outputs are strongly disposable, which can be stated as

$$\text{if } (y, b) \in P(x) \text{ and } y \geq y', \ \text{ then } (y', b) \in P(x) \tag{5}$$

This assumption means that if an observed combination of good outputs and bad outputs are feasible, then any combination with less good outputs is also feasible.

To measure the environmental efficiency of a power plant, we resort to the directional output distance function (DDF) which is defined on the production possibility set. Formally, the DDF can be defined as follows

$$D(x, y, b; g_y, -g_b) = \max\{\beta: (y + \beta g_y, b - \beta g_b) \in P(x)\} \tag{6}$$

where $g = (g_y, g_b) \in \Re_+^H \times \Re_+^J$ is the direction vector which specifies the movement directions of outputs. The DDF seeks the maximum expansion of good outputs and contraction of bad outputs, simultaneously. Following the pioneering work of Chung et al. (1997), we choose the direction vector to be g=(y, b).

In order to consider group heterogeneities in production activities and technical progress effect, we need to define three types of production possibility sets: contemporaneous group production possibility set, sequential group production possibility set, and sequential meta-production possibility set (Oh, 2010; Oh and Heshmati, 2010).

The contemporaneous production technology for group s at time period t is defined as follows

$$P_s^t(x) = \{(y^t, b^t): x^t \text{ can produce } (y^t, b^t) \text{ using technology s atperiod t}\} \tag{7}$$

where the subscript s indicates group s and the superscript t indicates time period t. The contemporaneous production technology for group s at time period t is constructed from the observations in group s at time period t only.

The sequential group production technology for group s at time period t can be defined as

$$\overline{P}_s^t(x^t) = P_s^1(x^1) \cup P_s^2(x^2) \cup \ldots \cup P_s^t(x^t) \tag{8}$$

The sequential group production technology for group s at time

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[2] For applications of Malmquist–Luenberger index at industry level, one can refer to Weber and Domazlicky (2001) and Färe et al. (2001) for the manufacturing sector, and Nakano and Managi (2008) for the power-generation sector. Studies at economy-wide level have been conducted by many research groups. For example, Jeon and Sickles (2004), Yörük and Zaim (2005), and Kumar (2006) analyzed the environmental productivity growth of different countries.

[3] Some previous studies investigated the environmental efficiency of power sector in China based on provincial data, please see Wang et al. (2013), Bi et al. (2014), Duan et al. (2016) and Wang et al. (2017).