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Multiplicative structural decomposition analysis of aggregate embodied energy and emission intensities

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ABSTRACT

Aggregate intensity indicators, such as the ratio of a country's energy and emissions to its GDP, are often used by researchers and policymakers to study energy and environmental performance. This paper analyzes the relationship between energy (or emissions) and value added (or GDP) from a different viewpoint, namely from the demand rather than the production perspective, using the input–output (I–O) framework. The aggregate embodied intensity (AEI), defined as the ratio of embodied energy (or emissions) to embodied value added, can be defined at the aggregate, final demand category and sectoral levels. The total aggregate intensity can be presented as a weighted sum of the AEIs at the final demand category or sectoral level. Changes of the AEI at different levels can be decomposed to identify the driving forces using multiplicative SDA. A study using the latest 2007 and 2012 datasets of China indicates that (a) its aggregate intensity of CO_2 emissions was mainly determined by the AEI in investment and (b) the emission intensity effect generally contributed the most to the AEI ratio changes at different levels. The proposed framework can be applied to other aggregate intensity indicators and extended to multi-country/region analysis.

1. Introduction

Sustainable development requires balancing economic growth, energy consumption and the resulting environmental impacts. Aggregate intensity of energy consumption, defined as the energy consumed per unit of gross domestic product (GDP), and aggregate intensity of carbon dioxide (CO_2) emissions, defined as CO_2 emissions per unit of GDP, have been recommended for evaluating the overall performance of energy utilization and climate change mitigation (IAEA, 2005). Many countries have set performance targets using these aggregate intensity indicators. For example, the 13th Five-Year Plan (2016–2020) of China includes a reduction of its aggregate energy intensity and aggregate carbon intensity by 15% and 18% respectively (State Council, 2016). As stated in their Intended Nationally Determined Contribution (INDC) submissions, China and India are committed to reduce their aggregate CO_2 emission intensities by 60–65% and 33–35% of the levels in 2005 by 2030 respectively (UNFCCC, 2015).

Decomposition analysis has been widely used to quantify the driving forces of changes of an aggregate indicator over time. When dealing with aggregate indicators for energy consumption and CO_2 emissions, index decomposition analysis (IDA) and structure decomposition analysis (SDA) have been the most popular approaches among researchers and practitioners.[1] In general, IDA is less data-intensive and easier to apply. In contrast, SDA relies on the input–output (I–O) data and is more complex. IDA has been widely used in studies that deal with either aggregate quantity or intensity indicators (Ang and Zhang, 2000; Xu and Ang, 2013), while SDA has traditionally been used in studies involving aggregate quantity indicators (Su and Ang, 2012a). More recently, the application of SDA to aggregate intensity indicators has gained in popularity. Examples of recent studies are Fan and Xia (2012), Michel (2013), Zeng et al. (2014), Zhang and Lahr (2014), Xia et al. (2015), and Su and Ang (2015, 2016).

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[1] Comparisons of the two approaches with specific reference to energy and emission are reported in Hoekstra and van den Bergh (2003), Su and Ang (2012a) and Wang et al. (2017).

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In decomposition analysis, both the additive and multiplicative forms of decomposition can be formulated. Usually, the additive form is applied to an absolute change of an aggregate quantity indicator, while the multiplicative form is applied to a relative change of an aggregate intensity indicator (Ang et al., 2010; Su and Ang, 2012a, 2015). With recent methodological developments in multiplicative SDA, decomposition analysis can be conducted at both the aggregate and sectoral levels. The decomposition technique used in the multiplicative SDA is mainly the multiplicative D&L method (Dietzenbacher et al., 2000), which is analogous to the generalized Fisher index method in IDA (Ang et al., 2004). Originally the decomposition results obtained using the D&L method can only be given at the aggregate level. Su and Ang (2014b) subsequently introduce the attribution analysis to give the contribution of the individual components at the sectoral level.[2] Due to the complexity in model development, Su and Ang (2015) introduce four models for calculating the aggregate carbon intensity of a country using the I–O framework, taking into account I–O model and decomposition method selection, imports assumption, and GDP calculation approach. Recently, the multiplicative SDA framework has been further extended to spatial SDA analysis in Su and Ang (2016).[3]

In the last few years, many studies have been reported on how various final demand categories affect countries' energy consumption and the resulting carbon emissions using the Leontief I–O framework (Leontief, 1970). They include studies on the embodiments in household consumption (e.g. Kok et al., 2006; Liu et al., 2011; Zhu et al., 2012; Zhang, 2013; Das and Paul, 2014; Su and Thomson, 2016; Su et al., 2017), investment (e.g. Guan et al., 2008; Chen and Chen, 2010; Fu et al., 2013; Markaki et al., 2013; Su and Thomson, 2016; Su et al., 2017) and international trade (e.g. Weber et al., 2008; Su and Ang, 2010, 2014a; Su et al., 2013; Peters et al., 2011; Feng et al., 2013; Sato, 2014; Su and Thomson, 2016; Su et al., 2017). Some other studies further analyze the value added embodied in international trade, such as Chen et al. (2012), Dietzenbacher et al. (2012), Koopman et al. (2014), Los et al. (2015) and Liu et al. (2016). Particularly, Dietzenbacher et al. (2012) and Liu et al. (2016) calculate the carbon intensity of embodied emissions in exports, dividing embodied emissions in exports by embodied value added in exports. The concept is the same as that of aggregate embodied intensity of exports proposed in this paper. Compared with the traditional definition of aggregate intensity from the production perspective, the measurement of aggregate embodied intensity can explain the relative contributions of different demand categories to emissions and value added from the demand perspective.

This paper proposes a framework of aggregate embodied intensity using the Leontief I–O framework and further applies the SDA to study the driving factors of aggregate embodied intensity changes over time. Its contributions are: (a) defining the aggregate embodied intensity at aggregate, final demand category and sectoral levels; (b) obtaining the relationship among the aggregate embodied intensity at different levels; (c) applying the SDA analysis to decompose the aggregate embodied intensity changes at different levels; and (d) deriving alternative decomposition equalities using the decomposition results obtained at the detailed sectoral levels. The remaining sections of the paper are organized as follows: Section 2 gives the general definitions of aggregate embodied intensity at different levels. Section 3 applies the multiplicative SDA to study the driving factors of aggregate embodied intensity changes over time. Numerical results of an empirical study using China's 2007 and 2012 datasets are presented in Section 4. Section 5 summarizes the findings and conclusions.

2. Definitions of aggregate embodied intensity

For environmentally extended I–O modeling, the imports assumption and I–O model selection are important components in an empirical analysis. Since most of the embodiment studies in the literature use the Leontief I–O model (Wiedmann et al., 2007; Sato, 2014; Zhang et al., 2017) and non-competitive imports assumption is more suitable for embodiment studies (Su and Ang, 2013), we consider only the Leontief I–O model with non-competitive imports assumption.

2.1. Aggregate embodied (energy/emission) intensity

For the I–O table using the non-competitive imports assumption, the standard Leontief I–O model can be formulated as

$$x = Z_d \cdot 1 + y = A_d x + y \tag{1}$$

where x is the vector of total output, Z_d is the matrix of domestic intermediate consumption, $A_d = Z_d \cdot (\hat{x})^{-1}$ is the matrix of domestic production coefficients, and y is the vector of domestic final demand. Rearranging Eq. (1) leads to the following Leontief I–O model with non-competitive imports as

$$x = (I - A_d)^{-1} y = L_d y = L_d \left(y_{df} + y_{ex} \right) \tag{2}$$

where $L_d = (I - A_d)^{-1}$ is the domestic Leontief inverse matrix, y_{df} is the vector of domestic final consumption,[4] y_e is the vector of domestic exports, and $y = y_{df} + y_{ex}$.

With the energy (or emission) intensity vector f_v representing the energy (or emissions) per unit of value added, the total energy (or emissions) from production can be formulated as

$$\begin{aligned} E &= f_v{}' v = f_v{}' \left(\hat{k} \cdot x \right) = f_v{}' \hat{k} \cdot L_d y = f_v{}' H_d y \\ &= f_v{}' H_d \left(y_{df} + y_{ex} \right) = f_v{}' H_d y_{df} + f_v{}' H_d y_{ex} = E_{df} + E_{ex} \end{aligned} \tag{3}$$

where v is the vector of value added, $k = (\hat{x})^{-1} v$ is the vector of primary input coefficient, $H_d = \hat{k} \cdot L_d$ is the matrix of domestic value added requirement coefficients, $E_{df} = f_v{}' H_d y_{df}$ is the energy (or emissions) embodied in domestic final consumption and $E_{ex} = f_v{}' H_d y_{ex}$ is those embodied in domestic exports.

For the I–O table using the non-competitive imports assumption, the GDP value can be calculated using the production approach as[5]

$$\begin{aligned} GDP &= 1' v = 1' \left(\hat{k} \cdot x \right) = 1' \hat{k} \cdot L_d y = 1' H_d y \\ &= 1' H_d \left(y_{df} + y_{ex} \right) = 1' H_d y_{df} + 1' H_d y_{ex} = GDP_{df} + GDP_{ex} \end{aligned} \tag{4}$$

where $GDP_{df} = 1' H_d y_{df}$ is the value added embodied in domestic final consumption, and $GDP_{ex} = 1' H_d y_{ex}$ is the value added embodied in domestic exports.

The aggregate embodied intensity (AEI) is defined as the ratio of embodied energy (or emissions) to embodied value added. In I–O analysis of energy (or emissions), the AEI in aggregate is the same as the total aggregate intensity (AI) of energy (or emissions) as

$$AI = \frac{E}{GDP} = \frac{f_v{}' H_d y}{1' H_d y} = AEI \tag{5}$$

[2] The attribution analysis is firstly introduced in Choi and Ang (2012) as an extension of traditional IDA.

[3] Decomposition analysis conducted over time is called temporal decomposition. The analysis can also be conducted to study variations of an aggregate indicator between regions at a certain point in time, which is called spatial decomposition analysis. Spatial decomposition analysis frameworks can also be found in Ang et al. (2015, 2016).

[4] In I–O tables, domestic final consumption includes five sub-categories, i.e. rural consumption (RC), urban consumption (UC), government consumption (GC), gross fixed capital formation (GFCF) and inventory change (IC). For ease of explanation in Sections 2 and 3, we only differentiate domestic final consumption y_{df} and domestic exports y_{ex} in the formulation.

[5] There are three approaches to calculating the GDP, i.e. production, income and expenditure approaches (United Nations, 1993). In I–O analysis, both the production and expenditure approaches are commonly used.