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Decomposing energy intensity change: A combination of index decomposition analysis and production-theoretical decomposition analysis

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HIGHLIGHTS

- This paper presents a comprehensive framework for decomposing changes of energy intensity.
- The proposed framework combines IDA and PDA.
- IDA is extended to investigate the mechanism of sectoral energy intensity change.
- The proposed approach overcomes the limitation of PDA.

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ABSTRACT

What drives energy intensity change has been a hot topic in energy economics. This paper presents a comprehensive framework combining index decomposition analysis (IDA) and production-theoretical decomposition analysis (PDA) for investigating the mechanisms of change of energy intensity. The proposed approach extends IDA to account for sectoral energy intensity change and overcomes the weaknesses of PDA in terms of quantifying effects of changes in industrial structure and energy composition. The combination of IDA and PDA also possesses all the three properties such as factor-reversal, time-reversal and zero value robust. More importantly, the decomposed effects are mutually exclusive as well. We apply the proposed approach to identify and quantify the driving forces of changes of energy intensity across China's provinces between 2005 and 2010. Results show that technological change and capital-energy substitution are the major drivers of the declining energy intensity.

1. Introduction

What drives energy intensity change has been a hot topic in energy economics since the world oil crisis in 1970s. Technically, it can be analyzed by attributing change of energy intensity to several pre-defined effects using decomposition analysis. In this context, structural decomposition analysis (SDA) and index decomposition analysis (IDA) are two commonly used techniques.

SDA is built on input–output (IO) model and uses information such as final demand and input–output coefficients from IO table. Clearly, SDA requires more data which consequently enables it to single out the indirect effects such as technical effect and final demand effect. A review on the theoretical foundation and major features of SDA can be found in Rose and Casler [1]. Su and Ang [2] provided a review of some recent development on SDA.

Compared to SDA, IDA is a low data requirement which only uses data on sectoral output and energy consumption. Methodologically, IDA is built on the index number theory. It is flexible in problem formulation. As a result, there are a variety of different index methods that can be used in IDA. Thanks to the contribution of pioneer studies such as Reitler et al. [3], Boyd et al. [4], Liu et al. [5], Ang [6], Ang and Lee [7], Ang and Choi [8], Ang and Liu [9], Ang et al. [10], etc., the IDA framework has been well established. Currently, IDA has become a popular analytical tool for energy modeling. Many empirical studies covering a large body of countries have been reported. Representative examples include Choi et al. [11], Greening et al. [12], Zhang [13], Aguayo and Gallagher [14], Ma and Stern [15], etc. The IDA methodology and application

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issues were discussed in detail by Ang and Zhang [16] and Ang [17]. Additionally, Hoekstra and Van den Bergh [18] provided a comparison between SDA and IDA.

In the line of IDA, the change of energy intensity is generally decomposed into sectoral energy intensity change and industrial structure change. Sectoral intensity change is often used as a proxy for energy efficiency change which is of great interest not only for researchers but also for policy makers. However, under the IDA framework there are few attempts to provide economic interpretation on what drives the change of sectoral energy intensity[1]. Moreover, some fundamental factors (e.g., the substitution between energy and other production inputs, technical efficiency change, technological change) which greatly influence energy intensity change cannot be investigated under the existing IDA framework. It is therefore our purpose to extend IDA to account for the mechanisms of sectoral energy intensity change and incorporate some important factors in terms of production technology.

In this paper, we propose a comprehensive framework that combines IDA and PDA (production-theoretical decomposition analysis). The term PDA was first coined by Zhou and Ang [22] which proposed a framework for decomposing CO2 emissions based on production theory. The idea of PDA can date back to Färe et al. [23] which first proposed Malmquist productivity index and its decomposition. Kumar and Russell [24] proposed a modification of the model of Färe et al. [23] for studying changes in labor productivity. Pasurka Jr. [25] developed another PDA model to analyze changes of air pollution emissions. Zhou et al. [26] also adapted the Malmquist productivity index to measure total-factor carbon emission performance. In the field of energy research, Wang [27] first employed this approach to investigate changes in energy productivity (i.e., the reciprocal of energy intensity). Based on the Shephard output distance function in production theory, Wang [27] developed a novel decomposition that decomposes the change of energy productivity into several components such as effects of changes in technology, technical efficiency, energy composition, and industrial structure. A brief comparison among SDA, IDA and PDA can be found in Zhou and Ang [22].

There is one common place between IDA and PDA that they both attempt to quantify the impacts of changes in industrial structure and energy composition. However, they have considerable discrepancies in terms of formulation and quantification. On this point, PDA is not as intuitive and straightforward as IDA. Additionally, in PDA, changes in industrial structure and energy composition may give ambiguous conclusions[2]. Specially, when output shifts from high-energy consuming sectors to low-energy consuming sectors, it is reasonable to expect that such change in industrial structure will lower the overall energy intensity. Similarly, when the share of high quality energy in total energy consumption is increasing, it is expected to benefit the declining energy intensity. However, PDA may show contrary results. Examples can be found in Wang [28] and Wang [27]. The results of empirical study reported in Wang [28] revealed that for Beijing and Shanghai, the changes in industrial structure between 1990 and 2005 contributed negatively to the declining of energy intensity[3]. However, in both Beijing and Shanghai, the output shares of industrial sector in national economy were decreasing substantially while the shares of service sector were increasing largely[4]. With this fact, it is hard to imagine that the changes would increase energy intensity. In terms of quantifying the impact of change in energy composition, similar case can be found in Wang [27]. In fact, both cases we mentioned above happen in our application study. It seems that PDA may lead to misleading conclusions in quantifying the effects of changes in industrial structure and energy composition. In this sense, it is also our purpose to overcome the weakness of PDA.

The approach developed in this paper contains two stages. In the first stage of the decomposition, we use IDA to quantify the impacts of changes in sectoral energy intensity, industrial structure and energy consumption composition. In the second stage, the change of sectoral energy intensity is further decomposed into technological change, technical efficiency change, and effects of capital-energy substitution and labor-energy substitution. Combining the results of the two stage decomposition gives the whole mechanism behind the change of energy intensity. This combination extends IDA and overcomes the weakness of PDA as well. The idea can be depicted in Fig. 1.

The organization of the rest paper is as follows. Section 2 describes the methodology in detail. Section 3 is an application to analyze the China's provincial data between the years of 2005 and 2010. Section 4 concludes the paper.

2. Methodology

In literature, several different index methods for IDA have been proposed and used in empirical studies. Although different methods have different strengths and weaknesses, the choice of IDA methods seems a little arbitrary. Comparing various IDA methods, Ang [17] concluded that Log-mean Divisia index (LMDI) method is preferred to others, due to its possession of all the three desirable properties (namely, factor-reversal, time-reversal and zero-value robust). Currently, LMDI method has been widely used not only in academic studies but also in national statistical agencies and international organizations (Liu and Ang [30]).

Considering its strengths, LDMI method is employed in this study for the first stage of decomposition to quantify the effects originated from changes in sectoral energy intensity, industrial structure and energy composition.

Assume that the whole economy consists of N regions; each region has M different sectors; there are J different types of energy in use. Define the following variables for region n at time t.

Y_t^n = Gross product
$Y_{i,t}^n$ = Product of sector i
$E_{i,t}^n$ = Total energy consumption of sector i
$E_{ij,t}^n$ = The consumption of energy j in sector i
I_t^n = Overall energy intensity
$I_{i,t}^n$ = Energy intensity of sector i

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[1] Ma and Stern [15] label the sectoral intensity change as technological change effect to get more well economic explanation. However, as shown in the next section, the sectoral intensity change is not exactly equal to technological change effect since substitution between energy and other inputs, technical efficiency also influence sectoral energy intensity change. We also notice that some recent studies had attempted to investigate the sources of sectoral energy intensity change. For example, Choi and Ang [19] extend the methodology of IDA for attributing sectoral energy intensity change effect (labeled as real energy efficiency in their paper) to the contributions of different sectors. Such extended IDA approach has been empirically applied in [20,21]. But to our best knowledge, there are very few studies providing explainations on the mechanism of sectoral energy intensity change in economic theory.

[2] Theoretical proof is provided in Appendix A.

[3] Note that in Wang [28] and Wang [27] the decomposition is conducted to energy productivity change, the reciprocal of energy intensity change. Thus their decomposition results should be taken reciprocal for analyzing the effects on energy intensity. For instance, in Wang [28] the output structure effect on change in energy productivity of Beijing was calculated as 0.7028 which means such effect on change energy intensity can be calculated as 1.4429. In other words, the industrial structure change increased energy intensity by 44.29% in Beijing.

[4] According to NBSC [29], the share of secondary industry in GDP of Beijing decreased from 52.4% in 1990 to 29.1% in 2005, while the share of tertiary industry increased from 38.8% to 69.6%. Similar structural changes also happened in Shanghai during the same period. The share of secondary industry in GDP of Shanghai decreased from 64.7% in 1990 to 47.4% in 2005, while the share of tertiary industry increased from 30.9% to 51.6% accordingly.