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Changing energy intensity of economies in the world and its decomposition☆

Chunhua Wang *

School of International Trade and Economics, University of International Business and Economics, 10 Huixin Dong Jie, Chaoyang District, Beijing 100029, China

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ABSTRACT

This paper decomposes energy intensity change across countries into five components attributable to technological catch-up, technological progress and changes in capital–energy ratio, labor–energy ratio and output structure. It is found that (1) technological progress, capital accumulation and output structure change contributed to the decline of energy intensity from 1980 to 2010, (2) changes in labor–energy ratio drove up energy intensity, and (3) spatial and temporal heterogeneity existed regarding relative importance of the five components.

1. Introduction

Driven by the prospect of maintaining energy supply security, improving air quality, and controlling greenhouse gas emissions, while simultaneously promoting economic growth, many countries throughout the world are undertaking significant efforts to reduce their economic energy intensities (i.e., energy consumption per unit of output). Currently, world-wide changes in energy intensity are hugely disparate, for example, energy intensity in Luxembourg declined at a rate of 3.2% annually from 1980 to 2010, while it increased at an annual rate of approximately 6.6% in Paraguay during the same time period.

The roles of energy in the process of economic growth and its contributions to productivity are controversial topics in the literature. Many previous studies suggested that energy input contributes to total factor productivity growth (Jorgenson, 1986; Murillo-Zamorano, 2005; Schurr, 1982), while some others did not find supporting evidence (Denison, 1985; Gullickson and Harper, 1987). In a recent review, Stern (2011) concluded that energy is an important factor because production is a function of capital, labor, and energy, not just the former two or just the latter. A related line of research examines the dynamics of energy intensity over time (see, e.g., Duro et al., 2010; Jakob et al., 2012; Le Pen and Sévi, 2010; Liddle, 2009, 2010; Miketa and Mulder, 2005; Mulder and de Groot, 2012). Authors found mixed results regarding whether energy intensity converges across countries (or regions or between countries sector by sector). The present paper mainly focuses on the forces that drive the changes over time which have not been well understood (Metcalf, 2008).

Decomposition analyses provide important insights regarding trends in both energy consumption and energy intensity changes. Changes in aggregate energy intensity are usually decomposed into a structural effect (i.e., the impact associated with the output structure of an economy) and an intensity effect (i.e., the impact associated with changes in sectoral energy intensity). In a comprehensive review, Ang and Zhang (2000) summarized that the main contributor to decreases in the aggregate energy intensity in industrialized countries and in most developing countries was declining sectoral energy intensity, while the impact of structural change was smaller in comparison. However, the decomposition analyses did not uncover the sources of the declines of sectoral energy intensity. Some case studies (Ma and Stern, 2008; Sue Wing, 2008; Welsch and Ochsen, 2005) also found evidence supporting the conclusion that intensity effect was a more important contributor and provided further investigations on the causes of such effects. On the contrary, structural change was found to be a major one by several recent studies (Huntington, 2010; Mulder and de Groot, 2012). A possible explanation for the inconclusive results is that different time periods and/or regions were covered in the studies. As economy evolves, the major driver for the declines of energy intensity may change over time.

The existing energy decomposition literature did not pay much attention to production technology of the economy, although energy

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* Tel.: +86 10 6449 3581; fax: +86 10 6449 3042.
E-mail address: Chunhua.Wang@rocketmail.com.

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consumption is a relevant productive input (Murillo-Zamorano, 2005). Thus, the effects of two important drivers of economic growth—technological catch-up and technological progress on energy intensity change were largely neglected. Furthermore, most studies in this line of literature ignored the contributions from other types of inputs such as labor and capital which are used to produce output with energy input. The present paper aims to contribute to these and single out the effects of technological catch-up, technological progress and changes in relative levels of the three types of inputs over time.

Using methods based on production theory, we decompose energy intensity change within a production system which allows one to relate the change to total factor productivity and effects from other inputs. We try to identify the sources of changes in energy intensity of a sample of countries from 1980 to 2010 and to examine the relative contributions of the sources behind the changes.

This paper has two major contributions to the literature on energy decomposition. First, output distance functions and data envelopment analysis are used to model energy as an input factor in the process of producing outputs along with other input factors such as capital and labor. Then energy intensity change between two time periods is decomposed into five components: technological catch-up, technological progress, and changes in capital–energy ratio, labor–energy ratio and output structure. The results not only link energy intensity change to total factor productivity change, but also provide insights about the results from the existing decomposition analysis. Second, we use recent cross-region data observed at the country level,[1] which complements most of the previous studies in the decomposition literature which mainly relied upon sector data. To account for structural effect, some sectoral information across countries are also gathered for the present paper. The decomposition framework proposed in this paper has a further advantage in that it does not assume any functional form of the production function. However, it should be noted that our analysis can be viewed as an accounting exercise which generates new results regarding the sources of energy intensity changes; it does not provide fundamental reasons for the changes.

We collect and analyze data for about 100 countries on gross domestic product, physical capital stock, employment, and energy consumption from 1980 to 2010. Major findings of the paper can be summarized as follows: (1) technological progress, capital accumulation and output structure change contributed to the declines of energy intensity from 1980 to 2010, (2) changes in labor–energy ratio drove up energy intensity, and (3) spatial and temporal heterogeneity existed regarding the relative contributions of the sources.

The remainder of the paper is organized as follows. Section 2 briefly develops the framework for decomposing energy intensity change into five components. Section 3 describes data and its sources. Section 4 reports and discusses decomposition results. The final section concludes.

2. A decomposition framework

The decomposition framework used here is a modification and extension of the one on labor productivity change proposed by Kumar and Russell (2002) who considered a production system with two inputs—capital and labor. This approach of decomposing productivity growth was initiated by Färe et al. (1994), and it has been used by Kumar and Russell (2002), Henderson and Russell (2005), and other authors to examine labor productivity growth. Following Wang (2007, 2011), we consider a production system with three inputs—capital, labor, and energy. Using Shephard output distance functions (Shephard, 1970) and the "ideal" index-number formula proposed by Seigel (1945), energy intensity change is decomposed into components. We describe main procedures in this section. More details can be found in Appendix A.

[1] Duro and Padilla (2011) also emphasized the relevance of regions as unit of analysis in studying cross-country energy intensity inequality.

For each time period $t = 1, 2, \ldots, T$, the production technology is given by the set

$$S^t = \{(K_t, L_t, E_t, Y_t) : (K_t, L_t, E_t) \text{ can produce } Y_t\}, \tag{1}$$

where the variables are capital K_t, labor L_t, energy E_t, and outputs (from three sectors of the economy: agriculture, industries, and services) $Y_t = \left(Y_{1,t}, Y_{2,t}, Y_{3,t}\right) \in \Re^3_+$. Standard conditions which suffice to define output distance functions are imposed on the production set S^t, e.g. S^t is a closed set and inputs and outputs are freely disposable.[2] The output distance function at time period t is defined as

$$D_o^t(K_t, L_t, E_t, Y_t) = inf\left\{\theta : (K_t, L_t, E_t, Y_t/\theta) \in S^t\right\}, \tag{2}$$

which measures the maximum feasible expansion of the observed output, Y_t, given the input vector, (K_t, L_t, E_t), and technology, S^t. In other words, it calculates how far observed production is from maximum potential production. The value of the distance function is defined as "technical efficiency" of the production unit or country. Given production technology and input bundle, higher output will indicate a higher value of the function which means that the production unit is more technically efficient. We note that it is always true that $D_o^t(K_t, L_t, E_t, Y_t) \le 1$. It is equal to one if and only if the observation (K_t, L_t, E_t, Y_t) is on the boundary or frontier of the technology, S^t. It is the case when production is technically efficient (Färe et al., 1994; Farrell, 1957).

We further assume that the production technology is constant-returns-to-scale (CRS).[3] For notational convenience, we let $k_t \equiv \frac{K_t}{E_t}$ and $l_t \equiv \frac{L_t}{E_t}$, respectively, denote capital–energy ratio and labor–energy ratio in time period t. Using output distance functions and production technology at time period t as a reference, we can decompose changes in energy intensity between time periods t and τ in the following way:

$$\begin{aligned}
\frac{E_\tau/\overline{Y}_\tau}{E_t/\overline{Y}_t} &= \frac{D_o^t(K_t, L_t, E_t, Y_t)}{D_o^\tau(K_\tau, L_\tau, E_\tau, Y_\tau)} \times \frac{D_o^\tau(K_\tau, L_\tau, E_\tau, Y_\tau)}{D_o^t(K_\tau, L_\tau, E_\tau, Y_\tau)} \\
&\times \left\{\left[\frac{D_o^t(k_\tau, l_t, 1, y_t)}{D_o^t(k_t, l_t, 1, y_t)}\right]^2 \cdot \left[\frac{D_o^t(k_\tau, l_\tau, 1, y_\tau)}{D_o^t(k_t, l_\tau, 1, y_\tau)}\right]^2 \cdot \frac{D_o^t(k_\tau, l_t, 1, y_\tau)}{D_o^t(k_t, l_t, 1, y_\tau)} \cdot \frac{D_o^t(k_\tau, l_\tau, 1, y_t)}{D_o^t(k_t, l_\tau, 1, y_t)}\right\}^{\frac{1}{6}} \\
&\times \left\{\left[\frac{D_o^t(k_t, l_\tau, 1, y_t)}{D_o^t(k_t, l_t, 1, y_t)}\right]^2 \cdot \left[\frac{\left(D_o^t k_\tau, l_\tau, 1, y_\tau\right)}{D_o^t(k_\tau, l_t, 1, y_\tau)}\right]^2 \cdot \frac{D_o^t(k_t, l_\tau, 1, y_\tau)}{D_o^t(k_t, l_t, 1, y_\tau)} \cdot \frac{D_o^t(k_\tau, l_\tau, 1, y_t)}{D_o^t(k_\tau, l_t, 1, y_t)}\right\}^{\frac{1}{6}} \\
&\times \left\{\left[\frac{D_o^t(k_t, l_t, 1, y_\tau)}{D_o^t(k_t, l_t, 1, y_t)}\right]^2 \cdot \left[\frac{D_o^t(k_\tau, l_\tau, 1, y_\tau)}{D_o^t(k_\tau, l_\tau, 1, y_t)}\right]^2 \cdot \frac{D_o^t(k_\tau, l_t, 1, y_\tau)}{D_o^t(k_\tau, l_t, 1, y_t)} \cdot \frac{D_o^t(k_t, l_\tau, 1, y_\tau)}{D_o^t(k_t, l_\tau, 1, y_t)}\right\}^{\frac{1}{6}} \\
&\equiv EFF \times TECH(\tau) \times KE^t \times LE^t \times OS^t
\end{aligned} \tag{3}$$

where $\overline{Y}_t \equiv Y_{1,t} + Y_{2,t} + Y_{3,t}$ is total amount of output, and $y_t = \left(\frac{Y_{1,t}}{\overline{Y}_t}, \frac{Y_{2,t}}{\overline{Y}_t}, \frac{Y_{3,t}}{\overline{Y}_t}\right)$ denotes output structure in time period t. Appendix A provides more details on how the decomposition components are obtained. As discussed earlier in this section, $D_o^t(K_\tau, L_\tau, E_\tau, Y_\tau)$ in the second term of the right hand side of Eq. (3) measures the maximal change in output required to make $(K_\tau, L_\tau, E_\tau, Y_\tau)$ feasible in relation to production technology S^t. Thus, the second term in the decomposition measures technological progress (i.e. the shift of the production frontier) between the two time

[2] For more details on those conditions and properties of the distance functions, see Färe (1988).

[3] While many empirical works rejected the hypothesis that the technology is CRS, it could be used as a benchmark in Data Envelopment Analysis. CRS technology "provides bounds on the underlying true-but unknown-technology", and it captures a "long run" (Färe et al. (1997) provides additional arguments). CRS technology was also assumed in several recent studies in various areas, including Kumar and Russell (2002) and Henderson and Russell (2005) on labor productivity growth and Murillo-Zamorano (2005) on the role of energy on productivity growth. These papers selected two years for empirical analyses on productivity change.