Energy Economics 61 (2017) 261–269

Contents lists available at ScienceDirect

Energy Economics

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

The multi-factor energy input–output model

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ARTICLE INFO

Article history:
Received 22 April 2016
Received in revised form 7 November 2016
Accepted 25 November 2016
Available online 9 December 2016

JEL classifications:
Q43
C67
O13
Q01
Q40
Q49

Keywords:
Energy input–output analysis
Embodied energy
Energy efficiency
Primary energy
Final energy

ABSTRACT

Energy input–output analysis (EIO analysis) is a noteworthy tool for the analysis of the role of energy in the economy. However, it has relied on models that provide a limited description of energy flows in the economic system and do not allow an adequate analysis of energy efficiency. This paper introduces a novel energy input–output model, the multi-factor energy input–output model (MF-EIO model), which is obtained from a partitioning of a hybrid-unit input–output system of the economy. This model improves on current models by describing the energy flows according to the processes of energy conversion and the levels of energy use in the economy. It characterizes the vector of total energy output as a function of seven factors: two energy efficiency indicators; two characteristics of end-use energy consumption; and three economic features of the rest of the economy. Moreover, it is consistent with the standard model for EIO analysis, i.e., the hybrid-unit model. This paper also introduces an approximate version of the MF-EIO model, which is equivalent to the former under equal energy prices for industries and final consumers, but requires less data processing. The latter is composed by two linked models: a model of the energy sector in physical units, and a model of the rest of the economy in monetary units. In conclusion, the proposed modelling framework improves EIO analysis and extends EIO applications to the accounting for energy efficiency of the economy.

1. Introduction

Energy input–output analysis (EIO analysis) has been widely used to understand the role of energy in the economy since the 1960s (Miller and Blair, 2009; Park, 1982). This method consists in the accounting for energy flows in the economy, and it has mainly relied on two conventional models: the hybrid-unit and the direct impact coefficient models. However, these and other current EIO models – including the models by Alcántara and Roca (1995), and Kagawa and Inamura (2001) – offer a limited representation of energy flows. I.e., these models do not describe the energy flows according to the conversion and use processes that these flows experience throughout the economy. In order to improve EIO analysis, better EIO models must be developed.

The present paper introduces a novel EIO model that improves the analysis of energy flows in the economy: the multi-factor energy input–output model (MF-EIO model). This model is based on current models and on Guevara and Rodrigues (2016), who built a model of primary energy use for structural decomposition analysis. This paper also introduces an approximate version of the MF-EIO model, which is equivalent to the former under equal energy prices for industries and final consumers, but requires less data processing.

The MF-EIO model, compared to current models, has a detailed representation of energy flows according to the processes of energy conversion and to the levels of energy use in the economy. It characterizes the vector of total energy output as a function of seven factors: two energy efficiency indicators (direct energy intensity, and primary-to-secondary energy conversion efficiency); two characteristics of end-use energy consumption (direct energy demand composition and final energy demand); and three economic features of the rest of the economy (structure of the rest of the economy, non-energy input structure of the energy sector, and final non-energy demand).

The proposed model can improve the conclusions obtained through current EIO analysis. Moreover, it extends EIO applications to the accounting of energy efficiency of the economic system.

The paper is structured as follows: Section 2 presents a description and discussion of current EIO analysis and models; Section 3 introduces the MF-EIO model and its approximate version; Section 4 discusses the factors, advantages and issues of the proposed model are discussed; and Section 5 presents the general conclusions. Appendix A provides the complete notation used in this paper.

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http://dx.doi.org/10.1016/j.eneco.2016.11.020

2. Energy input–output analysis

Energy input–output analysis (EIO), developed in the late 1960s and the 1970s, accounts for the energy flows in the economy and organizes them into an input–output system (Bullard and Herendeen, 1975a; Casler and Wilbur, 1984; Miller and Blair, 2009). The objective of EIO analysis is to determine the total energy requirements of the economic system to meet final demand. This method has a simple representation of the economic structure; and, therefore, it provides a propitious framework to model the relationships between energy use and economic activities (Dietzenbacher et al., 2013; Duchin and Steenge, 1999; Suh, 2009). In this section, current models and applications of EIO analysis are described.

2.1. Energy input–output models

There are two conventional models in EIO analysis: the hybrid-unit EIO model (H-EIO model, Section 2.1.1) and the direct impact coefficient EIO model (DIC-EIO model, Section 2.1.2). The former is considered the standard in EIO analysis because of its solid theoretical foundations (Casler and Wilbur, 1984; Griffin, 1976; Hawdon and Pearson, 1995; Miller and Blair, 2009). Nevertheless, the DIC-EIO model is the most used, because it is easy to construct and is not data-intensive. As an example, two thirds of published structural decomposition studies applied to energy in the period 1995–2014 used the DIC-EIO model (Guevara, 2014; Su and Ang, 2012). There are few other models that have been developed to improve EIO analysis, which have hardly been used.

2.1.1. The hybrid-unit energy input–output model

The H-EIO model was originally developed by Bullard and Herendeen (1975a) and Bullard and Herendeen (1975b)[1] based on the conservation of embodied energy, which establishes that the energy embodied in the output of an industry is equal to the energy embodied in its intermediate inputs plus its direct energy inputs.

The H-EIO model starts from the basic input–output identity for a closed economy, i.e.,

$$\boldsymbol{x} = \boldsymbol{Zi} + \boldsymbol{f} \tag{2.1}$$

where matrix $\boldsymbol{Z}$ of size $n \times n$ represents the total interindustry transactions, vector $\boldsymbol{x}$ of length n is the total output and vector $\boldsymbol{f}$ of length n corresponds to final demand. The n industries, represented in $\boldsymbol{Z}$, consist of r energy industries and $n-r$ non-energy industries (for convenience, energy industries are placed first in the index of industries).

It is possible to determine a similar identity for energy flows in physical units as

$$\boldsymbol{g} = \boldsymbol{Ei} + \boldsymbol{h} \tag{2.2}$$

where vector $\boldsymbol{g}$ of length r is total energy use (or total output of energy industries), matrix $\boldsymbol{E}$ of size $r \times n$ represents energy flows from energy industries to all industries (energy and non-energy), and vector $\boldsymbol{h}$ of length r represents energy deliveries to final demand.

The monetary-unit rows of energy industries in $\boldsymbol{Z}$, $\boldsymbol{f}$ and $\boldsymbol{x}$ from Eq. (2.1) are substituted by the corresponding physical-unit rows of $\boldsymbol{E}$, $\boldsymbol{h}$ and $\boldsymbol{g}$, respectively, in order to construct a hybrid-unit system (graphically shown in Fig. 2-1):

$$\boldsymbol{x}^* = \boldsymbol{Z}^*\boldsymbol{i} + \boldsymbol{f}^* \tag{2.3}$$

where $\boldsymbol{x}^*$ is the hybrid-unit vector of total industrial output, $\boldsymbol{Z}^*$ is the hybrid-unit matrix of interindustry flows; and $\boldsymbol{f}^*$ is the hybrid-unit vector of final demand.

Fig. 2-1 shows that the matrix $\boldsymbol{Z}^*$ can be partitioned in four sub-matrices, i.e.,

$$\boldsymbol{Z}^* = \begin{bmatrix} \boldsymbol{Z}^*_\theta & \boldsymbol{Z}^*_\tau \\ \boldsymbol{Z}^*_\pi & \boldsymbol{Z}^*_\psi \end{bmatrix} \text{ or } \begin{bmatrix} \boldsymbol{E}_\theta & \boldsymbol{E}_\tau \\ \boldsymbol{Z}^*_\pi & \boldsymbol{Z}^*_\psi \end{bmatrix} \tag{2.4}$$

where $\boldsymbol{E}_\theta$ and $\boldsymbol{E}_\tau$ are the sub-matrices of energy flows between energy industries, and of direct energy demand (i.e., energy flows to non-energy industries or the intermediate demand for energy by non-energy industries) in physical units, and $\boldsymbol{Z}^*_\pi$ and $\boldsymbol{Z}^*_\psi$ are the sub-matrices of intermediate demand for non-energy products by energy industries and non-energy industries, respectively. Note that the first two sub-matrices define the matrix of interindustry energy flows in Eq. (2.2) ($\boldsymbol{E} = [\boldsymbol{E}_\theta \ \boldsymbol{E}_\tau]$).

The model in Eq. (2.3) is then solved for $\boldsymbol{x}^*$, as in the basic input–output model, through the use of the hybrid-unit technical coefficient matrix, $\boldsymbol{A}^* = \boldsymbol{Z}^*\widehat{\boldsymbol{x}^*}^{-1}$, as:

$$\boldsymbol{x}^* = (\boldsymbol{I} - \boldsymbol{A}^*)^{-1}\boldsymbol{f}^* = \boldsymbol{L}^*\boldsymbol{f}^* \tag{2.5}$$

where $\boldsymbol{L}^*$ is the hybrid-unit inverse Leontief matrix or total requirements matrix, which can be partitioned in four sub-matrices, see also Casler and Wilbur (1984), as:

$$\boldsymbol{L}^* = \begin{bmatrix} \boldsymbol{L}^*_\theta & \boldsymbol{L}^*_\tau \\ \boldsymbol{L}^*_\pi & \boldsymbol{L}^*_\psi \end{bmatrix} \tag{2.6}$$

where

- $\boldsymbol{L}^*_\theta$ is the sub-matrix of total energy requirements (including primary and secondary energy) of energy industries per unit of final energy demand;
- $\boldsymbol{L}^*_\tau$ is the sub-matrix of total direct energy requirements of non-energy industries per unit of final non-energy demand;
- $\boldsymbol{L}^*_\pi$ is the sub-matrix of total non-energy requirements of energy industries per unit of final energy demand; and
- $\boldsymbol{L}^*_\psi$ is the sub-matrix of total non-energy requirements of non-energy industries per unit of final non-energy demand.

Eq. (2.5) is further modified to determine a matrix $\boldsymbol{\alpha}$ that enables the calculation of the total energy requirements of the economy to meet final demand, i.e., the matrix that solves the equation:

$$\boldsymbol{g} = \boldsymbol{\alpha}\boldsymbol{f}^*$$

As seen in Fig. 2-1, $x^*_i = g_i$ for $1 \le i \le r$, so it is possible to establish a simple relationship $\boldsymbol{g} = \boldsymbol{Kx}^*$, where $\boldsymbol{K}$ is a bridge matrix of size $r \times n$, with entries $K_{ij} = 1$ for $i = j$ (indexes of energy industries) and $K_{ij} = 0$ for $i \neq j$. This bridge matrix extracts the elements of $\boldsymbol{x}^*$ that correspond to the output of energy industries.

Consequently, matrix $\boldsymbol{\alpha}$, known as the total energy requirements matrix, is calculated as.

$$\boldsymbol{\alpha} = \boldsymbol{K}(\boldsymbol{I} - \boldsymbol{A}^*)^{-1} = \boldsymbol{KL}^*$$

By partitioning $\boldsymbol{\alpha}$, it is possible to separate total energy output in two components: one caused by final demand for energy products ($\boldsymbol{h}$) and the other by final demand for non-energy products ($\boldsymbol{f}_{ne}$), so

$$\boldsymbol{g} = \boldsymbol{\alpha}_\theta\boldsymbol{h} + \boldsymbol{\alpha}_\tau\boldsymbol{f}_{ne} \tag{2.7}$$

[1] The work of Bullard and Herendeen (1975a) was contemporary to other attempts to build a consistent energy input–output model by, e.g., Krenz (1974), Wright (1974) and Wright (1975).