Applied Energy 211 (2018) 590–603

Contents lists available at ScienceDirect

Applied Energy

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

Understanding the energy metabolism of World economies through the joint use of Production- and Consumption-based energy accountings

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HIGHLIGHTS

- Production- and Consumption-based energy accounting methods (PBA and CBA) are reviewed.
- A methodological way for the joint use PBA and CBA methods is discussed and formalized.
- Both PBA and CBA are adopted to identify energy efficiency hotspots in South Africa region.
- The energy metabolism of national economies can be represented through a unique Sankey diagram.

ARTICLE INFO

Keywords:
Production-based accountings
Consumption-based accountings
Multi-Regional Input-Output analysis
Energy efficiency
EORA
South Africa

ABSTRACT

Understanding the energy metabolism of national economies is nowadays crucial for policymakers in order to define effective policies and to properly set energy efficiency targets. Energy accountings based on the traditional Production-based accounting method (PBA) allows to understand how primary energy is directly extracted, traded, transformed and used within each economy. On the other hand, Consumption-based accounting method (CBA) allows to understand the ultimate economic purposes of such energy flows. The information provided by the joint application of these approaches may provide useful and complementary insight on the national energy metabolism, allowing to identify hotspots for potential interventions from both the supply and demand side.

This paper reviews PBA and CBA energy accounting methods, presenting a possible way for the joint use of their results, consistently represented by means of one unique Sankey diagram. This will be useful to have a comprehensive insight on the energy metabolism of national economies, supporting analysts and policymakers in the identification of energy efficiency hotspots. The method is applied to South Africa and to the neighbor country of Botswana, based on data provided by IEA energy statistics and the EORA26 Multi-Regional Input-Output model, taking into account non-renewable fossil energy (raw coal, crude oil and natural gas) and considering the reference year 2013.

Results suggest that the joint use of PBA and CBA methods may provide useful information on the hidden energy links among national economies, helping analysts and policymakers in defining alternative energy efficiency policies. For this reason, the Authors argue that results of CBA should be provided alongside energy statistics based on the traditional PBA approach.

1. Introduction

Based on recent energy policy reviews and assessments provided by international authorities (IEA among others) energy efficiency is still a crucial issue in energy policy agenda both at national and international levels [1–4], and it has been identified as one of the key activities required to pursue the global climate change goals set in COP21 in Paris [5], to increase energy security of national economies, and to contribute in job creation [6,7]. Possible critical issues that may emerge from the allocation of energy efficiency policies have been pointed out in literature: for example, energy efficiency interventions may be followed by the so-called *rebound effect*, which ultimately cause a further increase in energy consumption [8–11]. On the other hand, other researchers agrees that while rebound effect is a fact, its overall effects would not overwhelm the energy savings due to the implementation of energy efficiency interventions [12–14]. Beside the debate concerning the rebound effect, reducing pressure in non-renewable energy resources, decreasing price of energy by avoiding wastefulness, and

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http://dx.doi.org/10.1016/j.apenergy.2017.10.090
Received 6 July 2017; Received in revised form 16 October 2017; Accepted 26 October 2017
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Nomenclature

Symbol	Quantity [Unit]
$\widetilde{\mathbf{E}}(1 \times N)$	Total Embodied Energy Supply vector [toe]
$\mathbf{A_i}(n \times n)$	Technical Coefficient matrix [M€/M€]
$\mathbf{B_i}(1 \times n)$	exogenous transactions coefficients vector [toe/M€]
$\mathbf{E_{DS}}(n \times n_t)$	supply side decomposition matrix [toe]
$\mathbf{E_{SS}}(n_t \times n_t)$	supply side decomposition matrix [toe]
$\mathbf{E_i}(n \times 1)$	embodied energy vector [toe]
$\mathbf{L_i}(n \times n)$	Leontief Coefficient matrix [M€/M€]
$\mathbf{R_i}(1 \times n)$	exogenous transactions vector [toe]
$\mathbf{Z_i}(n \times n)$	endogenous transaction matrix [M€]
$\mathbf{e_i}(n \times 1)$	unit embodied energy vector [toe/M€]
$\mathbf{f_i}(n \times n)$	Final Demand [M€]
$\mathbf{x_i}(n \times 1)$	total economic production [M€]
n_t	total number of sectors [–]
i,j	ith and jth economies [–]
N	number of economies [–]
n	number of sectors in each economy [–]
$\mathbf{I}$	Identity matrix [–]
$\mathbf{i}$	summation vector of appropriate dimensions [–]
TFC	Total Final Consumption [Mtoe]
TPES	Total Primary Energy Supply [Mtoe]

Acronyms

CBA	consumption-based accountings
DEA	Data Envelopment Analysis
GHG	Greenhouse Gases
IEA	International Energy Agency
IEA	International Energy Agency
IO	input-output
MRIO	Multi-Regional Input-Output
PBA	Production-based accountings
SDA	Structural Decomposition Analysis
TEES	Total Embodied Energy Supply
TFC	Total Final Consumption
toe	tons of oil equivalent
TPES	Total Primary Energy Supply
UNFCC	United Nations Climate Change Convention

reducing energy related harmful emissions should be sufficient reasons to fostering an efficient use of energy.

The concept of efficiency commonly refers to the ratio of benefits to expenses. Therefore, energy efficiency refers to the ratio between the benefits gained (not necessarily measured in terms of energy), and the energy used to provide such benefits. Energy efficiency interventions can be applied in different ways and to different contexts: (a) increasing the efficiency of energy conversion processes and devices; (b) increasing the efficiency related to the end-uses of energy on the demand side; (c) reducing the energy used by the supply chains of non-energy-related goods and services delivered for final use. Interventions b and c are achieved by means of technical, organizational, institutional, structural or behavioral changes [15]. A wide range of energy efficiency definitions can be retrieved in literature: among others, Patterson defines a series of indicators used to measure energy efficiency from the economic and the physic perspectives, focusing on the direct consumption of energy caused by economic segments at national level [16]. Oikonomou et al. distinguish among *energy efficiency* and *energy saving* interventions: the former is the result of a technical improvement, while the latter is related to the end-user's behavior and the reduction of final demand of energy products [17]. Among others, Honma and Zhou propose the *Data Envelopment Analysis* (DEA), which consist in a non-parametric method based on linear a programming model for the estimation of production frontiers used to empirically measure productive efficiency of decision making units, and it is being adopted with increasingly frequency in energy economics discipline [18,19]. Other methods have been reviewed by Tanaka et al., which recognize different indicators, such as the absolute energy consumption, the energy intensity, the diffusion of specific energy saving technology and the thermal efficiency [20].

A critical issue in quantifying the energy efficiency of production and consumption activities resides in the choice of the appropriate energy accounting method. In general, energy requirements of one generic system can be evaluated based on the *Production-based* (PBA) or the *Consumption-based* (CBA) paradigms. Beside the issue of scarcity of non-renewable energy stocks (namely raw coal, crude oil and natural gas), fostering an efficient and rational use of non-renewable energy resources is relevant, since they provide more than 80% of the whole global energy production, resulting as the major responsible for GHG and pollutants emissions [21,22]. Considering one generic national economy, PBA quantify the *Total Primary Energy Supply* (TPES) through the algebraic sum between the primary energy produced by the considered national economy and the energy imports/exports, which after discount losses on conversion processes and industry own uses, turns into the *Total Final Consumption* (TFC), defined as the energy directly consumed by industries and households [23]. PBA approach has been adopted to account for national energy consumption and GHG emissions by most statistics organizations, including International Energy Agency and British Petroleum, and it has assumed by the Kyoto Protocol as the standard method to account for and to determine the responsibility for CO2 emissions at national level [24]. On the other hand, CBA allows to account for the energy directly and indirectly consumed by industrial activities to support the production of goods and services ultimately consumed by households as final demand (i.e. the *energy embodied* in goods and services). CBA are usually based on macro-economic models, and Leontief's Input-Output models among others [25]. Recently, Afionis et al. reviewed advantages and drawbacks of the use of PBA and CBA, revealing that CBA is becoming increasingly relevant for policy-making, since it allows to understand the drivers for primary energy consumption, providing estimations of the energy effects due to structural changes within the economy [26]. PBA accountings are able to reflect the actual path of energy resources, including production, international trades, and losses taking place in conversion and transmission processes. However, PBA does not allow to understand the full scope of the energy production and conversion chain, since the link between energy production and the consumption of goods and services is missing. Due to this fact, PBA policies defined in the past years was responsible for environmental leakages, giving place to the displacement of pollutant activities from developed to developing countries [27,28]. Indeed, many production activities with small direct energy requirements could have large *indirect* energy requirements (e.g. the construction industry), and this fact could dupe policy-makers when designing energy strategies. Finally, energy embodied in international trades are not reflected neither, so it is not possible to analyze the energy links between countries beyond the energy trades that can be directly measured. On the other hand, CBA allows to quantify the primary energy embodied in final products (i.e. the driver of the energy consumption), taking also into account the full path of international trades, and thus helping analysts in clarifying responsibilities in terms of energy consumption embedded into final products traded among countries and economic sectors. Despite these advantages, CBA are characterized by several problems. First of all, quality of results of CBA strictly depends on the accuracy, availability and comprehensiveness of Input-Output models [27]: since the energy and environmental impact of goods and services is a global concern, the space boundary for the CBA analysis should include the whole World economy, and the

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