Energy Policy 111 (2017) 85–94

Contents lists available at ScienceDirect

Energy Policy

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

Global primary energy use associated with production, consumption and international trade

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ARTICLE INFO

Keywords:
Energy
Input-output analysis
Production
Consumption
Trade imbalance

ABSTRACT

Presented in this study is a comprehensive analysis for energy use of different economic entities in global supply chains, including the exploiter, producer, consumer, intermediate trader and final trader. The systems input-output analysis method is adopted to trace the direct and indirect energy use associated with both intermediate production and final consumption activities in the economic system. In the world economy, 15% of the energy use embodied in trade turns out to be induced by final consumption, and 85% is attributed to intermediate production. Different trading patterns for different economies are identified with the separation between energy trade for intermediate production and that for final consumption. For Japan with a production-oriented trading pattern, intermediate trade should be a top priority in local trade structure adjustment, while final trade needs more attention for the government in the United States as the country is in a consumption-oriented trade pattern. This analysis aims to provide an in-depth insight into energy sustainability, as well as a sound scientific reference for policy making at the regional, national and global scale.

1. Introduction

Energy is fundamental to the economic progress and social development. Over the last 35 years, worldwide energy use has doubled, contributing significantly to the unprecedented economic growth and living standards improvement (BP, 2016). The global Gross Domestic Product (GDP) increased 6-fold and the average income per capita in the world quadrupled during that period (WB, 2015). In addition to the great benefits, the implications of such widespread energy consumption extend across a range of environmental problems. The majority of energy currently used globally is derived from fossil fuels, such as crude oil, natural gas and coal, which are also regarded as the dominant contributors to the air pollutants emissions and the greenhouse gases emissions (IEA, 2016a; IPCC, 2014). As the key link among the three pillars of economy, society and environment in sustainable development, energy use has become the most critical challenge of the world today (Jones and Warner, 2016).

In this context, extensive researches have been carried out to explore sustainable energy use. In these studies, indirect energy use has received great attention (Chen et al., 2017b; Liu et al., 2009). Different from direct energy use recording a region's energy consumption on its territory, indirect energy use measures the energy consumed in other regions to produce the goods and services that are demanded by this region (Arto et al., 2016). With economic globalization, countries in the world are closely connected by international trade, making indirect energy use an increasingly prominent phenomenon. In a recent evaluation on energy use of Macao, China, the indirect energy use of Macao is presented to be over 2 times as the direct use (Li et al., 2014). For Italy, about 70% of the total household final demand is met by the indirect energy use (Cellura et al., 2011). In comparison the share is 60% in South Korea (Park and Heo, 2007) and 47% in India (Pachauri and Spreng, 2002).

In order to combine the indirect energy use with the direct one, the embodied energy was conceptualized in the 1970s as a significant indicator for estimating the total energy requirements (Chapman, 1974). For a product or service, embodied energy is defined as the total (direct plus indirect) primary energy inputs to generate and sustain it (Costanza, 1980). So far, the embodied energy method has gained wide application in various economic systems at different scales (Chen and Chen, 2015; Limmeechokchai and Suksuntornsiri, 2007; Wu et al., 2016). Most of these previous researches applied the embodied energy concept to final consumption activities in economic systems, aiming at identifying the amount of energy embodied in the commodities and services that are used to meet the consumers' final demand (Chen and Chen, 2013). The consumers' demand is the driving force of economic production and energy consumption. A clear understanding of each

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http://dx.doi.org/10.1016/j.enpol.2017.09.024
Received 17 February 2017; Received in revised form 6 September 2017; Accepted 10 September 2017

consumer's contribution can help track the final destination of energy resources in global supply chains (David et al., 2011). What's more, numerous studies have pointed out that high-income countries tend to play the consumer role in global market, and other countries, especially emerging countries, become the producers and produce goods to serve the high-income countries through international trade (Rulli et al., 2013; Xia et al., 2016). As a result, the consumption-based energy accounting can greatly encourage the high-income countries to export the energy-saving and cleaner production technologies to emerging countries, which is conductive to achieving a reduction in global total energy use (Guan et al., 2014).

However, regarding the intermediate production, which holds an equally important position as the final consumption activity in the economic system, few investigations have been performed on the related embodied energy use (Johnson and Noguera, 2012; OECD, 2009; Zhang, 2015). In general, the conventional production-based energy accounting merely considers the energy resources that are directly used by local production processes, in line with the territorial-based principle under the Kyoto Protocol (Peters and Hertwich, 2007; Steininger et al., 2014). But presently, countries' economic development is with a high degree of specialization following the law of comparative advantage (Hummels et al., 2001). It becomes necessary for the producers to trade and cooperate with each other. For example, to sustain the manufacture of motor vehicles in Europe, local motor vehicles producers import steel as intermediate inputs from steel producers in China. To produce these steel products, substantial energy resources are consumed in China. In fact, such trade induced by intermediate production activities accounts for about two-thirds of global total trade volume, in magnitude twice the trade for final consumption (Chen and Han, 2015; Johnson and Noguera, 2012). It is therefore imperative to discuss the indirect energy use accompanied with the trade of intermediate products to probe into the producer's indirect effect on energy depletion.

Several organizations and scholars have tried to explore the producers' indirect responsibility for resource utilization and pollutant discharge. As early as 1994, the Organization for Economic Co-operation and Development (OECD) introduced the idea of extended producer responsibility for the purpose of waste minimization (Gallego and Lenzen, 2005). According to OECD, producers should bear the responsibility not only for the direct or on-site environmental impacts during the production process of their products, but also for the indirect or off-site impacts associated with upstream activities, such as materials selection and products design, and downstream activities of treatment or disposal of the products (OECD, 2001). Afterwards, Peters (2008) illustrated a detailed calculation for the production-based greenhouse gas emissions inventory, and the production-based emissions of a region were defined as the emissions embodied in its final production, i.e., the production of goods and services for both local and exported final consumption. On the basis of Peters' analysis, Kanemoto et al. (2012) clearly explained the term of production-based inventory, and redefined it as the total factor used to produce the products for final consumption. Recently, Liang et al. (2015) presented a downstream-production-based framework, to trace both direct and indirect mercury emissions caused by the production activities of a nation. In the work of Chen and Han (2015) regarding arable land use, the indirect land use associated with intermediate trade is integrated with local direct land use to compute the production-based land use for each producer. Yet the indirect energy use of the producers in global supply chains is still unclear.

Given the increasingly serious energy crisis worldwide (IEA, 2016b), the present paper places emphasis on primary energy resources, and aims to provide a systematic analysis of embodied energy use for the world economy. The direct and indirect energy use of various economic entities in global market, including the exploiter, producer, consumer, intermediate goods trader and final goods trader, are investigated from the embodiment perspective, in order to provide additional insights for energy conservation and carbon reduction.

2. Methodology and data

2.1. Input-output analysis

Originally proposed as an economic tool to represent the financial interactions between industries of a nation, the input-output analysis (IOA) has now developed into a main technique for embodiment accounting in the environmental field (Miller and Blair, 2009). As this technique gives a panorama of embodied physical flows for the entire system, it performs well in studies on the complicated economic system, especially global economic system (Huysman et al., 2014). Leontief (1970) firstly extended the economic IOA table to include the environmental data, which has been widely used and referred to as the environmentally extended IOA model. In this model, the direct energy consumption of each economic sector is assigned to be the virtual energy consumption of the goods and services delivered by the sector to meet final demand (Chen et al., 2017a; Hertwich and Peters, 2009; Wiedmann et al., 2013). In this way, one can predict the energy requirement when there is a change in the final demand for a certain goods or service. It is noted that the concept of virtual energy in environmentally extended IOA is only applied to the goods and services for final consumption, explicitly exclusive to those for intermediate production (Wu and Chen, 2017).

However, as discussed above, intermediate production and its associated trade occupy a considerable share in economic activities, and it is of great importance to uncover the related energy use to help shed light on how energy resources flow between both sectors and regions before being used for final consumption. Hence, based on the idea of "conservation of embodied energy", Bullard Iii and Herendeen (1975) proposed a modified IOA scheme and applied the concept of embodied energy to both intermediate production and final consumption as two basic components of total outputs. Then Chen and his co-workers generalized the modified IOA for embodiment analysis for various ecological endowments, like energy resources (Chen and Wu, 2017), water resources (Shao et al., 2017), land resources (Chen and Han, 2015), greenhouse gases (Chen et al., 2013), mercury (Chen et al., 2016) and so on, and termed it as the systems IOA model. In the systems IOA model, all goods and services, no matter if they are for intermediate or final use purposes, are considered with energy use hidden or embodied in them. Therefore, we adopt the systems IOA method in the present paper, for a systematic analysis of primary energy use by the globalized economy, with focus on production, consumption and international trade.

2.2. Algorithm

For the world economy as a m-region, n-sector coupled network, there are totally $m{\cdot}n$ entities in the table, as shown in Fig. 1. z_{ij}^{rs} ($r, s \in \{1, 2, \ldots, m\}$, $i, j \in \{1, 2, \ldots, n\}$) is the monetary value of goods and services sold by Sector i in Region r for intermediate production in Sector j of Region s, and f_i^{rs} is the monetary value of goods and services from Sector i, Region r to Region s for final consumption. The gray segment in Fig. 1 represents the trades of Region 1 with other foreign regions for both intermediate production and final consumption. The intermediate goods are defined as the goods that need further processing, including raw materials, while the final goods do not need further processing. The energy resources originally exist in the environmental system, and then are exploited and inputted into the economic system (Odum, 1996). Hence, e_i^r records the amount of primary energy resources directly exploited by Sector i in Region r from the natural environment as the exogenous supply to the economic system.

Embodied energy intensity (ε) is an important indicator. For a sector, it implies the average amount of direct plus indirect energy required in the supply chain to produce one unit of goods or service based on the current technology. In the systems IOA, the embodied intensity is calculated based on the biophysical input-output balance