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# Global energy flows embodied in international trade: A combination of environmentally extended input–output analysis and complex network analysis

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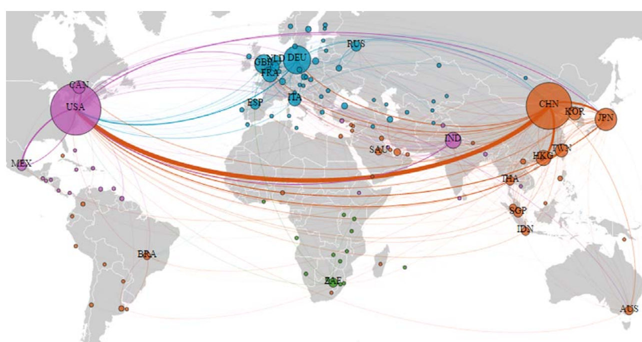
## HIGHLIGHTS

- The EEFN embodies the small-world nature and scale-free property at global level.
- 4 communities are detected to understand the regionalization of EEFN.
- Different role played by economies in EEFN are identified with centrality measures.
- A diversity index is developed to quantify the security of embodied energy supply.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Significant energy flows embodied in international trade have evolved into a complex interconnected flow network. Therefore, this study applies a variety of complex network analysis tools to uncover the structure of embodied energy flow network (EEFN) at global, regional and national level, based on environmentally extended input–output analysis (EEIOA). At global level, small-world nature has been found, implying the economies are highly connected through embodied energy transfer. EEFN is proved to be a heterogeneous network due to the scale-free power-law distribution of degree/strength. At regional level, 4 communities are detected and members in the same regional cooperative organizations, such as EU, ASEAN, NAFTA and AU, tend to be classified into the same community, indicating that EEFN embodies the characteristics of regionalization and multi-polarization. At national level, some key economies, such as USA, China and Germany, are always at the forefront of network-based centrality measures and EEIOA-based accountings. Furthermore, the security of embodied energy supply is evaluated for each economy. Consequently, policy implications of the results are discussed, which could provide additional insights for policy formulation to enhance energy security.

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## 1. Introduction

Economic growth and human welfare improvement are coupled with ever-increasing resources depletion, especially energy resource [1–3]. World total primary energy supply more than doubled from 6.10E + 03 Mtoe (million tonnes of oil equivalent) in 1973 to 1.37E + 04 Mtoe in 2014. The world total final consumption, meanwhile, increased from 4.66E + 03 Mtoe to 9.43E + 03 Mtoe [4]. It's projected that global proved oil, natural gas and coal reserve by the end of 2015 are only able to satisfy the current demand for 51, 53 and 114 more years, respectively, making energy security a critical issue for sustainable development [5].

Due to the uneven distribution of energy resources, international energy commodity trade, such as oil, natural gas and coal, has become a more important way to meet the energy demand of countries where energy resources are in deficiency. With the intensifying globalization, global supply chains are further sliced up and usually span multiple economies, leading to the transfer of direct and indirect energy resource use via international trade. For example, an economy relying on energy imports to support domestic production can cut off energy imports by outsourcing its energy-intensive industries. Therefore, direct energy trade network is insufficient to capture the full spectrum of energy transfer among economies, as it neglects the leakage effects associated with indirect energy use to produce the traded goods and services [6]. To tackle with the indirect effect, one can resort to the concept of embodied energy originated in system ecology, which is termed as total (direct and indirect) energy required to produce economic or environmental goods and services as if this amount of energy is incorporated or embodied in the product itself [7,8]. In contrast to the direct energy consumption analysis which only considers on-site immediate energy consumption, embodied energy analysis integrates historical and off-site formation and thus provides a more systematic perspective of energy use [9,10]. With the aid of input–output analysis, it has been extensively employed to quantify energy embodied in trade at different scales, such as international trade [11,12], national external trade [13,14], interprovincial trade [15,16] and urban external trade [17,18]. The interrelation between energy use and international trade makes energy security and sustainable energy management a more complex issue [19].

Previous IOA-based studies have verified that there is a significant amount of embodied energy flows through international trade, which has evolved into a complex network. Although the intricate international embodied energy flow has been depicted by many studies, the structure of the interwoven embodied energy flows lacks in-depth analysis from a network perspective. The structure of the flow system is closely related to functions [20,21], through which the global embodied energy flow system could be understood from a new angle. In addition, previous EEIOA-related studies only characterize the importance of an economy based on its income-induced downstream energy use, production-induced onsite technical energy use and consumption-induced upstream energy use. However, these economies with large energy inflows and outflows (i.e., hubs) are also important, as they act as the collectors and distributors in global energy flow system [22]. Moreover, identifying these economies as bottleneck of the whole system by controlling the in-between energy flows (i.e., bridges) is critical to reduce the energy supply risks [23]. By identifying different roles played by an economy in the complex flow system, more targeted policies could be implemented accordingly. Besides, conventional energy security framework is usually confined in the context of direct energy commodity trade [24]. A network-based energy security analysis by taking indirect energy flow into consideration could provide additional insights for energy security strategy. The development of complex network theory has offered an effective tool to modelling the complex embodied energy flow system, in which the economies are treated as the nodes and embodied energy flow as the edges. Currently, complex network theory has been applied to analyze various direct energy commodity trade network, including oil [25–28], natural gas [29,30] and fossil fuels [31–34]. Yet a comprehensive analysis of global embodied energy flow network within the framework of complex network is still lacking.

In this paper, the complex network method is applied to quantitatively analyze global characteristics, regional structures and national importance and energy security in the embodied energy flow network (EEFN). By taking the indirect energy use into account, EEIOA is used to construct the global directed and weighted EEFN with insignificant flow relationships filtered out. To our knowledge, this study is considered to be the first attempt to identify the global embodied energy flow patterns from a complex network perspective. It is also expected that the current study will be instructive for comprehensive strategies formulation to construct trans-regional collaboration mechanism for sustainable energy use to ensure energy security.

The remainder of the paper is organized as follows: the methodology and data sources are explained in Section 2; Section 3 presents the empirical results. Discussions and implications are listed in Section 4 and concluding remarks are illustrated in Section 5.

## 2. Methodology and data

### 2.1. Environmentally extended input–output analysis

Originally developed by Leontief in 1930s, input–output analysis was only used to explore the interdependencies among industries in an economy [35]. Later, the input–output model was further extended to to evaluate the environmental and social impacts caused by the economic activities, which has been widely used to analyze resources use (energy [36], land [37], water [38] and material [39]), pollutant emissions ($CO_2$ [40], mercury [41,42], black carbon [43] and $PM_{2.5}$ [44]) and employment [45]. As one of the mostly used methods, EEIOA is taken to map the international embodied energy flows. Under the framework of EEIOA, energy flows embodied in trade only include goods and services trade for final use, as on-site technical energy consumption of all investigated sectors is assigned to the final use by means of Leontief inverse matrix. The EEIOA-based energy input–output model for world economy is presented in Table 1. The global embodied energy flow can be calculated by:

$$q^{st} = \sum_{irj} c_i^r l_{ij}^{rs} f_j^{st} \tag{1}$$

where $q^{st}$ is the embodied energy flow from Economy $s$ to Economy $t$ ($s \neq t$); $c_i^r$ represents technical energy consumption by Sector $i$ in Economy $r$; $f_j^{st}$ stands for goods or services trade by Sector $j$ from Economy $s$ to Economy $t$ as final demand; $l_{ij}^{rs}$ is the element of Leontief inverse matrix $L$, which can be achieved by:

$$L = (I-A)^{-1} \tag{2}$$

where $I$ is the identity matrix; $A$ is the direct requirement coefficient, whose element can be calculated as:

$$a_{ij}^{rs} = z_{ij}^{rs}/x_j^s \tag{3}$$

where $z_{ij}^{rs}$ is the intermediate use of Sector $j$ in Economy $s$ provided by Sector $i$ in Economy $r$; $x_j^s$ is the total output of Sector $j$ in Economy $s$.

### 2.2. Global embodied energy flow network

Based on the EEIOA, the global embodied energy flow network is represented by a set $N = (E,F)$, where the economies $E = (e_1,e_2\cdots e_n)$ are taken as the network nodes and the embodied energy flows set $F$ as the network edges:

$$F = \{f_{st}\} = \{q_{st} \times a_{st}\} \text{ where } a_{st} = \begin{cases} 1 \text{ if } q_{st} > 0 \\ 0 \text{ otherwise} \end{cases} \tag{4}$$

Therefore, a directed weighted network is constructed to model the