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Embodied rare earths flow between industrial sectors in China: A complex network approach

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ABSTRACT

Both the direct and indirect need of rare earths (RE) as an important raw material has driven the transfer of RE between different sectors, forming a complex network of RE flows in the economy. However, previous studies have focused primarily on the direct use of RE and neglected the indirect effect and the network characteristics that greatly hinders the sustainable use of RE. To solve this problem, this paper builds an embodied RE network by combining both input-output analysis and complex network theory. By analyzing the clustering coefficient and the average path length of the network, we find that the embodied RE flow network can reveal the small world nature characteristics. Moreover, chemicals and the scrap sector are the strongest sectors of the direct effect, indirect effect and intermediate effect based on the comprehensive analysis of the network's degree centrality, eigenvector centrality, and betweenness centrality, respectively. Furthermore, the establishment of embodied RE flow relations is focused on the related sectors of infrastructure construction and the petrochemical industry based on the analysis of each sector's weighted edges that carry embodied RE flow. Furthermore, the 41 sectors of an embodied RE flow network can be divided into four industrial clusters that are related closely to each other. Among the clusters, the E & C cluster is the core of the entire network. Finally, we provide policy implications on the sustainable use of RE through industrial restructuring.

1. Introduction

Due to their distinctive and unique physical and chemical properties, rare earths (RE) are widely used in various fields of the national economy. The consumption of RE in China was over 65,000 tons in 2013, thus accounting for 65% of the world's total consumption for that year (USGS, 2015). With the constant economic restructuring in China, the direct consumption of RE in all industries has drawn the attention of researchers with respect to the stability of industries related to RE. In recent years, experts have not only focused on the direct consumption of RE in all industries, but they have also considered the flow of embodied RE resources among economic sectors as a new research topic. The concept of embodied RE originates from previous research on ecological elements and thus represents the total amount of RE resources consumed during whole processes, including machining, manufacturing, transporting, etc., i.e., the sum of direct consumption and indirect consumption in the production chain.

According to the studies on the flow of RE resources among sectors of all industries, the identification of the cluster of RE industries, the key industries in the flow of embodied RE resources, and the key paths of their flow among sectors has significance with respect to the establishment of policies for sectors of all industries in China, the reduction of RE consumption and the loss of RE resources in the context of economic restructuring.

Currently, the studies on RE resources focus primarily on the trade of rare earths (He et al., 2014; Wang et al., 2016; Ge et al., 2016), on the markets and terminal industries (Chen, 2011; Morrison and Tang, 2012; Wang et al., 2017a), on policy adjustment (Wübbeke, 2013; Han et al., 2015), and on supply and demand (Castor and Hedrick, 2006; Gschneidner, 2011; Mclellan et al., 2013; Wang et al., 2015; Wang

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et al., 2017b). However, there remains a shortage of studies on the flow of embodied RE resources between sectors. The identification of the cluster of RE industries, the key industries in the flow of embodied RE resources, and the key paths of their flow among sectors in the studies on the flow of RE resources among sectors of all industries has significance for the establishment of policies for sectors of all industries in China, for the reduction of RE consumption and for the reduction in the loss of RE resources in the context of economic restructuring.

Fortunately, there is substantial research on embodied resources in other fields that may provide solid empirical investigations and represent a good reference for understanding the studies on RE resources among sectors. The concept of an embodied resource was first proposed as embodied energy (Bullard and Herendeen, 1975; Costanza, 1980; Huettner and Costanza, 1982), which is the amount of energy used in the production, manufacture, use and disposal of a good or service (An et al., 2015). The concept of embodied energy has attracted the attention of many scholars and experts from other fields and has been applied to embodied water (Chiu et al., 2009; Treloar et al., 2004; Chen et al., 2012; Liang and Zhang, 2012), embodied materials (Liang et al.,2017), embodied pollutant emissions (Liang et al., 2015; Chen et al., 2016; Liang et al., 2016; Li and Chen, 2013; Li et al., 2016, 2017), embodied exergy, etc. (Bruckner et al., 2012; Ju and Chen, 2011; Duchin and Levine, 2013; Chen and Chen, 2010; Chen et al., 2009; Chen et al., 2010; Zhou et al., 2010). As a consequence, some researchers have focused on the calculations of inter-sector natural resource flows. By applying an ecological network analysis, the number of resource flows among sectors and the structure of systems are revealed (Fath et al., 2007; Huang and Ulanowicz, 2014; Dai et al., 2012). In recent years, some researchers have applied complex network theory in the analysis of embodied resource flows among industries, thus analyzing the relationship structure of the network and the role of each sector within the system (An et al., 2015; Sun et al., 2015). Accordingly, the extant studies provide plenty of meaningful references for this paper.

Based on the calculated resource flows among industries in 2010 using input-output theory, we built a network of the flow of those resources in China with industries as nodes and flows as edges. We then put forward policies and suggestions for the industries related to RE resources in China based on our findings from the analysis of the resource flows among sectors, the identification of the key paths of their flow among sectors and the cluster of RE industries.

2. Methodology and data

2.1. Input-output method

Rare earths consumption in industry supply chains includes the consumption due to the final demand of one single industrial sector and the use in intermediate production processes by other industrial sectors. An embodied analysis of rare earths can capture the above direct and indirect consumption flows in the economy based on the input-output table.

The basic monetary balance in the input-output table is expressed as

$$X= Z+ y= AX + y \tag{1}$$

where X represents the total output, which can be expressed as a vector; Z denotes the intermediate demand matrix; y is the final demand vector composed of household consumption, government consumption, gross capital formation, and export; and A represents the direct demand matrix and indicates the relationships between sectors of the economy. The total output vector X is expressed by Eq. (2) based on the assumption of a nonsingular $(I - A)$.

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

where I is the identity matrix, and $(I - A)^{-1}$ is the Leontief inverse matrix. Eq. (2) explains that the gross output is consumed by the final consumption y and the corresponding intermediate use $(I - A)^{-1}$ from each sector.

The total (both direct and indirect) rare earths consumption is expressed by multiplying the total output by each sector's rare earths intensity, i.e., rare earths consumption per unit output from each sector i, as determined by Eq. (3):

$$E= F(I - A)^{-1}y \tag{3}$$

where E represents the matrix of the total embodied rare earths consumption, and F denotes the vector of the rare earths intensity for each sector.

2.2. Complex network techniques

A complex network consists of nodes and edges that link the nodes, as in Eq. (4)

$$G= (N, E) \tag{4}$$

where G represents a complex network; N denotes the set of nodes in the network; and E represents the set of edges in the network.

If i is a network node, we define $i \in N$. If there is a link between i and j, the direction of mercury flow in the network, the edges are also weighted. If $(i, j) \in E$ we write $e_{i,j} > 0$; otherwise, $e_{i,j} = 0$. The matrix of the mercury flow between industrial sectors is expressed in Eq. (5);

$$E= \begin{bmatrix} e_{11} & \cdots & e_{1n} \\ \vdots & \ddots & \vdots \\ e_{n1} & \cdots & e_{nn} \end{bmatrix} (i, j= 1,2,\dots,n), \text{ where } e_{ij} = \varepsilon_i \times x_{ij} \tag{5}$$

For this study, the other two useful concepts from complex network theory are in-degree and out-degree. The in-degree of i is the number of starting nodes that go to node I, and the out-degree of j is the number of destination nodes that node j can reach.

Sectors are represented as nodes here. Embodied rare earths flow relations between sectors are represented as edges whose directions denote the embodied rare earths flows and whose weights denote the value of rare earths flows. Based on these notations and equations, the weighted mercury flow network can then be established.

2.2.1. The small world nature

The small world nature refers to the network in which most nodes are not neighbors of one another, but where most nodes can be reached from every other node via a small number of steps (Carvalho, 2014). When analyzing a small world nature, the measurement is generally a clustering coefficient and the average path length (Sun et al., 2016).

The clustering coefficient is defined as the ratio N/M averaged over all nodes, where N is the number of edges between the neighbors of node i, and M is the maximum number of edges that can exist between the neighbors of node i. The average path length is defined as the number of edges in the shortest path between two nodes averaged over all pairs of nodes (Watts and Strogatz, 1998).

2.2.2. The theory of centrality

2.2.2.1. Degree centrality. We write the weighted in-degree of node i, I_i as the sum of the amount of embodied rare earths from sector j to sector i, as expressed in Eq. (6):

$$I_i = \sum_{j=1} e_{ji} \tag{6}$$

where e_{ji} denotes the amount of rare earths embodied from sector j to sector i. The larger one sector's weighted in-degree is, the more embodied the consumption of rare earths.

Similarly, we use the weighted out-degree O_i, which is the sum of the amount of embodied RE flow from sector i to sector j, as expressed in Eq. (7)