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Exploring energy flows embodied in China's economy from the regional and sectoral perspectives via combination of multi-regional inputeoutput analysis and a complex network approach

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Abstract

Rapid urbanization has produced considerable energy demands in China and increased pressure on sustainable development. Therefore, investigating the embodied energy flows induced by China's modern economy is important. By integrating the multi-regional inputeoutput (MRIO) model with the complex network approach, this study builds two embodied energy flow networks (EEFNs) from the regional and sectoral perspectives. The small-world nature is explored in the current EEFN by assessing the average clustering coefficient and average path length. Findings indicate that any disturbance occurring in key nodes or flows can generate substantial effects on the whole embodied energy system. From a regional perspective, Guangdong, Hebei, Jiangsu, Shanghai, and Zhejiang consistently rank highest in terms of centrality indices. From a sectoral perspective, the chemical industry, the smelting and pressing of metals, the transportation, storage, posts and telecommunications, and the manufacture of general and special purpose machinery are highly connected sectors in the EEFN. Community detection further reveals an apparent separation of amounts existing among communities. Heterogeneous effects within communities are also observed. Provinces located in the western and central areas of China act as energy suppliers to promote economic development in the eastern area. Economic cooperation organizations, when taken as a whole, exert more apparent influences on the embodied energy trade system. From a sectoral perspective, the embodied energy use of sectors in each community displays remarkable clustering features. The findings of this study can help formulate fair and reasonable energy-saving policies for suppliers and consumers from the regional and sectoral perspectives.

1. Introduction

Energy problems have attracted worldwide attention. In 2015, the world total primary energy supply reached 13.6 billion tons of coal equivalent and 32.3 billion tons of carbon dioxide were released to the environment [1]; such utilization has exacerbated a series of environmental issues, such as global warming and air pollution [2]. As one of the world's largest primary energy emitters, China is responsible for approximately 22% of the world total primary energy supply and nearly 30% of energy-related carbon dioxide emissions [1]. Given this background, China has pledged to reduce its carbon dioxide emissions by 60%e65% of gross domestic product by 2030 in comparison with the levels in 2005 [3]. Considering mandatory targets for energy conservation and the need for sustainable development in China, understanding the basic status, characteristics, and mechanism of the embodied energy (sum of direct and indirect energy) consumption of China's economy is imperative [4,5]. Single-region inputeoutput (SRIO) analysis is usually conducted to investigate the embodied energy use nationwide. However, this approach assumes no difference in production technology at home and abroad, which may lead to misinterpretation of actual environmental loads [6,7]. To develop fair and reasonable energy-saving policies, taking regional disparities and technological differences into account during environmental assessment is necessary [8,9].

A network model with region-specific characteristics is necessary to quantify interrelationships among different regions. Recent methodological improvements in multi-regional inputeoutput (MRIO) analysis allow quantification of cross-regional energy transmissions; here, details of environmental interactions can be captured by taking considering regional characteristics and sectoral differences [10]. Many studies have employed the MRIO model to quantify embodied energy consumption [11e13] and greenhouse gas (GHG) emissions in interregional trade [14e16], and investigate the forces driving embodied energy emissions over a specific period of time [17e19]. Most of these studies have concentrated on examining the volume of embodied energy use but lack investigations from a systematic and dynamic perspective. Some studies have combined MRIO method with other dynamic models to depict GHG emissions. Mi, Meng [20] discovered the mechanism of Chinese CO_2 emissions by integrating the MRIO model and structural decomposition analysis. Sodersten, Wood [€ 21] integrated the MRIO model with flow matrix method to allocate the GHG emissions among countries. Therefore, the flows of resource endowments interact and develop through the entire economy via the trade of commodities and services. Thus, a complex embodied energy system with numerous inflows and outflows is gradually developed, and analysis of this network provides a systematic perspective and theoretical tool for understanding the basic laws and features of the embodied energy system [22].

Complex network theory, as an effective analytical tool, can offer a novel method of evaluation that surpasses the benefits of specific node analysis methods used in traditional embodied energy studies to assess social networks [23,24], economic networks [25e27], transport networks [28] and other aspects [29,30]. Complex network theory has also been applied to gain insights into energy trade at the global level, such as the volume of energy use embodied between economic sectors in the international trade [31], the properties of global fossil energy trade [32,33] and the evolutionary trend of the global embodied energy in time-series [34]. Unfortunately, despite their merits, most studies are conducted at the international level and ignore regional disparities within a country, especially in the Chinese economic context. Gao, Su [35] quantified and tracked the coal, oil, natural gas, and non-fossil fuel flows of China's 30 provinces by applying complex network analysis. Sun, An [36] built three complex networks to explore the sectoral characteristics of the Chinese indirect energy flows based on timeseries data. These works use complex network theory to deduce the properties or rules of embodied energy flows at the sectoral and provincial levels, thereby providing references for further analysis.

With the aid of complex network theory, the present study analyzes the properties of embodied energy flows induced by the Chinese economy by dividing the whole energy flow system into two sub-networks from the regional and sectoral perspectives. The contributions of this study are as follows:

First, application of the MRIO model accounts for the divergence of the regional development of energy interactions occurring in China's economy; second, integration of the MRIO model and complex network theory provides insights into the embodied energy flow system via a systematic and dynamic manner; and third, recombination of two subnetworks affords in-depth analysis of the embodied energy flows from the regional and sectoral perspectives. The remainder of this paper is organized as follows: Section 2 introduces the methods and data sources used in this study, and Section 3 presents the results of the regional and sectoral features of the embodied energy flow system. Section 4 presents discussions and policy implications. Finally, Section 5 provides the conclusions.

2. Methods and data sources

2.1. Embodied energy flow quantification

The MRIO model is an effective technique with which to evaluate the environmental interactions caused by regional disparities from the topedown perspective; it is regarded as a theoretical foundation that can be used to quantify the volume of the embodied energy at the regional and sectoral levels. The coordination of the sectoral direct energy inputs based on inputeoutput analysis is presented in Table 1.

The basic monetary balance for sector i in the inputeoutput table can be formulated as

m n m

Ti^r ¼ Xs¼1 Xj¼1 ursij þXs¼1virs (1)

where u^{rs}_{ij} represents the intermediate input from sector i in region r to sector j in region s, v^{rs}_i represents the total final use in region s provided by sector i in region r, and T^r_i represents the total output of sector i in region r; here, m regions and n sectors exist in each region.

According to the energy flows, the energy equilibrium for sector i in region r can be formulated as

m n

eirTir ¼ Xs¼1 Xj¼1 ejsujisr þ zir (2)

where e^r_i represents the embodied energy intensity of sector i in region r, and z^r_i represents the direct energy consumption of sector i in region r.

Thus, the energy balance can be formulated in the following matrix equation.

ET ¼ EU þ Z (3)

² e1$_1$ z1$_1$ T 6@ 0

0 3 U ⁶ ¼66660 em1m 177777 ¼666660 zmm1
177777 ¼646 ::: ::: ::: :::m 757 ¼

e:::1n A7 T 6@ z::::::1n 1A37

::: ::: 0 0 ::: t_n

2 01

0 ::: 13 20 t1

0 :::

where E Z T t1$_2$ :::

4@ ^{en} A5 4@ ^{zn} A5

u11$_{11}$ :::u11$_{1n}$ u1$_{11}$m:::u1$_1$m$_n$

20 :::11 ::: :::111 ::: 0 :::1m ::: :::1 13

::: ::: ::: u ::: u

u ::: u^{mm} ::: :::

::: ::: ::: :::

::: u ::: u u

::: u$_{nn}$ which can be

further expressed as

64^{66666}6^0@@ unm11mn1111 :::

unn1nnmmn11^{A1}A^0@@ ummnmm11n11

:::u1mmnnnm ^{A1}A^{77777}775

E ¼ ZðT UÞ^1 (4)

Therefore, the embodied energy flows can be expressed as

Λ
F ¼ E U (5)

From a regional perspective, the embodied energy flows from region r to region s can be expressed as

n n
krs ¼ XXf ij^{rs} (6)

i¼1 j¼1

From a sectoral perspective, the embodied energy flow from sector i to sector j can be formulated as

m m kij ¼ Xr¼1 Xs¼1 f ij^{rs} (7)

2.2. Construction of the EEFN

The EEFN is a directed weighted network that can be expressed by the set

G ¼ ðA;XÞ (8)

where G represents the embodied energy network, A is the expression of the network nodes, the edges set X represents X^{rs} ¼fx^{rs}g or X_{ij} ¼fx_{ij}g, and x^{rs}, x_{ij} are the embodied energy flows from region r to region s and from sector i to sector j, respectively. If $k^{rs} > 0$, then x^{rs} ¼ 1 and its weight w^{rs} ¼ k^{rs}; otherwise, x^{rs} ¼ 0. If $k_{ij} > 0$, then x_{ij} ¼ 1 and its weight w_{ij} ¼ k_{ij}; otherwise, x_{ij} ¼ 0.

		S_1	...	S_n	...	S_1	...	S_n		
R_1	S_1									
	...									
	S_n									
...	...									
Rm	S_1	urs_{ij}							vrs_i	Tr_i
Direct energy input	...									
	S_n									

2.3. Complex network analysis

This study uses a series of parameters from complex network analysis to produce a detailed description of the characteristics and laws of the current embodied energy flow system. The detailed information, including the variables, definitions, and computational process, is provided in Table 2. In summary, the small-world nature, degree, strength, centrality, and community are explored to systematically and dynamically elaborate the energy connections in China's modern economy from the regional and sectoral perspectives.

2.4. Data sources and consolidation

The MRIO table used in this study was derived from the Chinese Academy of Science and published in 2010; this table describes the economic transaction data between 900 sectors of 30 regions in China (except Tibet and Taiwan), including 4 municipalities, 4 autonomous regions, and 22 provinces (Appendix A). Sectoral direct energy consumption data among the 30 regions were collected from provincial statistical yearbooks published in 2011 and the Chinese Energy Statistical Yearbook (2011). Given the conflicts of sector classifications between the statistical data and the MRIO table, this study employs the data treatment scheme [45] to disaggregate the collected direct energy data in compromise with the sector classifications of the MRIO table.

3. Analysis of results

3.1. Small-world nature

Table 1
Revised MRIO table published in 2010.

Input	Output					Total output
	Intermediate use			Final use		
	R_1	_	R_m	R_1	R_m	

In complex network theory, the small-world nature refers to a network in which more than half of the nodes are not neighbors and any pair of nodes selected randomly in the network can establish relationships by only taking a small number of steps [46]. This relationship can be mathematically identified by the average clustering coefficient and average path length from the micro and macro perspectives. According to the provincial results, the average clustering coefficient of the regional EEFN is 0.71 and the average path length is 1.329. By comparison, the average clustering coefficient is 0.814 for the sectoral EEFN and the average path length is 1.46. Both results imply that more than half of one node's partners are likely to be partners of other nodes. Meanwhile, the average energy transfer length from one node to another takes less than 1.5 steps. A small-world quotient substantially more than 1 is normally employed to confirm the existence of a small-word nature [47,48]. The small-world quotient is 6.89 and 8.51 in the regional and sectoral EEFNs, respectively, thereby confirming their small-world nature. Any disturbance that occurs in highly connected regions or sectors will spread quickly to adjacent nodes and may cause significant changes to the entire economy because of the sensitivity of the small-world network [49]. Therefore, adopting energy conservation strategies, such as implementing clean production and improving energy efficiency in key nodes with multiple connections within the network, can enhance the overall environmental performance of the Chinese economy.

3.2. Key flows

Weight edges in the EEFN refer to the volume of the embodied energy flow between nodes. Listed on the left side of Table 3 are the leading embodied energy flows from a regional perspective. The top 10 critical weight edges account for approximately 60% of the total embodied energy consumption, thus revealing that only a small number of flows determine the entire economic network. In fact, the top 10 critical energy flows form self-loop at the regional level, which indicates that most energy-intensive inflows and outflows take place within provinces. The embodied energy flows within developed regions, including Shandong (R15), Jiangsu (R10), and Guangdong (R19), are the leaders, accounting for more than 20% of the total energy consumption.

To shed light on the energy transfer between different regions, the spatial distribution pattern of the major embodied energy flows in interregional economic activities is presented in Table 3 (right) and Fig.1. The most prominent energy suppliers for China's modern economy mainly come from the central and western areas. Developed areas (e.g., Jiangsu (R10), Zhejiang (R11), and Beijing (R1)) mainly import energy from resource-abundant areas (e.g., Hebei (R3) and Shanxi (R4)) to power local economic activities. Shanxi (R4), as the largest energy supplier for Hebei (R3), contributes 30% of its total embodied energy in interregional trade to the latter. Yunnan (R25), the only province located in the western area in the

Table 2
Parameters for EEFN analysis.

Category	Variable	Characteristic	Calculation formula	Explanation
Small-world nature	Average clustering coefficient	The clustering coefficient reflects the possible connections between two nodes that are connected to the same node in the network. The average clustering coefficient is the average of all clustering coefficients and gauges the agglomeration degree of nodes in the network [37].	$C = \frac{1}{k} \times \frac{\sum_{h,a} w_{ph} w_{ha} w_{pa}}{\max(w_{ph}) \sum w_{hs} w_{sr}}$	a and h are the adjacent nodes of node p; k is the number of nodes
	Average path length	The average number of steps of the shortest paths for all possible pairs of nodes in the network [38].	$L = \frac{1}{k(k-1)} \sum_{p;q} d_{pq}$	d_{pq} is the shortest path between node p and q, which is defined as:
Degree analysis	In-degree	The in-degree of a specific node represents the number of total energy flows from other nodes connecting to this node [39].	$K_{in}(p) = \sum_q x_{qp}$	
	Out-degree	The out-degree of a specific node is the number of total energy outflows from the node to others.	$K_{out}(p) = \sum_q x_{pq}$	
Strength analysis	In-strength	In-strength describes the impact strength of a node [40] and represents the total energy consumption of a node in the network.	$Y_{in}(p) = \sum_q w_{qp}$	
Centrality analysis	Out-strength	Out-strength is the total energy production of a node in the network.	$Y_{out}(p) = \sum_q w_{pq}$	
	Betweenness centrality	Betweenness centrality represents the intermediary ability of a node and reflects the capability to determine the embodied energy flow from any other node [41].	$b_a = \sum_p \sum_q g_{paq}/g_{pq}$	b_a is the betweenness centrality of node a, g_{pq} is the number of shortest paths between node p and node q, and g_{paq} represents the number of these shortest paths passing through node a.
	Closeness centrality	The average weighted distance between a node and other nodes in the network indicates the extent of a node's centrality in the network [42].	$CC_p = \frac{k}{\sum_q w_{pq}^{1}}$	
	Eigenvector	Eigenvector centrality reflects a node's	$E = \frac{1}{\lambda} A e$	λ is the eigenvalue of A, e_q represents the

1 — 1 dpq ¼

minwpy þ :::þ

wyq

centralitysignificance via examining its connectionsP ¼ lXq pq q eigenvalue of its eigenvector.

to other key nodes [43].

Community Modularity The modularity measurement can explore 1kinq koutp Cp is the assigned community of node community agglomeration by quantifying Q ¼ 2w p;q "wpq 2w #dðCp;CqÞ p and dðCp; CqÞ is equal to 1 and 0;

the density of relationships within1 otherwise; w communities in wpq. comparison with the ¼ 2 relationships between communities [44]. p;q

Table 3

Results of the top 10 embodied energy flows from a regional perspective.

Source		Target	Source		Target
Shandong (R15)	/	Shandong (R15)	Hebei (R3)	/	Jiangsu (R10)
Jiangsu (R10)	/	Jiangsu (R10)	Hebei (R3)	/	Zhejiang (R11)
Guangdong (R19)	/	Guangdong (R19)	Shanxi (R4)	/	Hebei (R3)
Hebei (R3)	/	Hebei (R3)	Hebei (R3)	/	Beijing (R1)
Henan (R16)	/	Henan (R16)	Hebei (R3)	/	Shandong (R15)

Zhejiang (R11)	/	Zhejiang (R11)	Henan (R16)	/	Jiangsu (R10)
Liaoning (R6)	/	Liaoning (R6)	Yunnan (R25)	/	Guangdong (R19)
Sichuan (R23)	/	Sichuan (R23)	Henan (R16)	/	Zhejiang (R11)
Hunan (R18)	/	Hunan (R18)	Hebei (R3)	/	Liaoning (R6)
Hubei (R17)	/	Hubei (R17)	Liaoning (R6)	/	Jilin (R7)

list of provinces with the top 10 energy flows, provides more than 50% of its total energy in interregional export to Guangdong (R19). The energy flows show a geographic connection, i.e., energy transfer mainly occurs between a region and its surrounding regions, likely because regional economic integration can facilitate trade between the provinces and their surrounding partners owing to favorable policies and low traffic.

From a sectoral perspective, the top 10 embodied energy flows are presented in Table 4. These energy flows are responsible for nearly 40% of the total embodied energy consumption in China. The intra-sectoral energy transfers that occur in the smelting and pressing of metals (S14) is the leading embodied energy flow; this sector is also the leading supplier of energy flow, providing an extensive amount of embodied energy to the construction sector (S24), the manufacture of general, and special purpose machinery (S16), the manufacture of electrical machinery and equipment (S18), and the manufacture of metal products (S15). The energy flow from the manufacture of non-metallic mineral products (S13) to the construction sector (S24) is the largest inter-sectoral energy flow, accounting for nearly 15% of the total embodied energy imports in the latter. This characteristic of sectoral EEFN results from rapid urbanization, during which building materials (e.g., concrete, cement, glass, and brick) are extensively used through substantial expansion of infrastructure construction. Further study of these

Fig. 1. Major embodied energy flows of interregional economic activities in China.

energy-intensive flows may yield an efficient resolution for energy conservation and emission reduction.

3.3. Roles of regions and sectors

In this section, provinces with distinct roles in the Chinese economic system are discussed based on the centrality measurement (Fig. 2). Overall, Guangdong (R19), Hebei (R3), Jiangsu (R10), Shanghai (R9), and Zhejiang (R11) are at the forefront of the importance index. Guangdong (R19) ranks the first in terms of instrength, betweenness centrality, closeness centrality, and eigenvector centrality. This finding implies that Guangdong is the most important bridge and that it can transfer signal quickly by spreading it to its partners and then to all other provinces in the network via the shortest links. Hebei (R3) ranks the first in terms of out-degree and out-strength with the value much higher than those of others, thereby implying the important role of this province in the energy supply side of China's economy.

According to the in-degree results, Jiangsu (R10), Guangdong (R19), Beijing (R1), Shanghai (R9), and Zhejiang (R11) hold more inward energy links than other provinces (Fig. 2a). This ranking reflects the resource-dependent features of the local economy. For instance, as the capital and economic center of China, Beijing faces tremendous pressure to conserve local resources because of its rapid economic development. Given the increasing share of the tertiary industry and local resource restrictions, Beijing tends to depend on external sources for further development. In fact, the

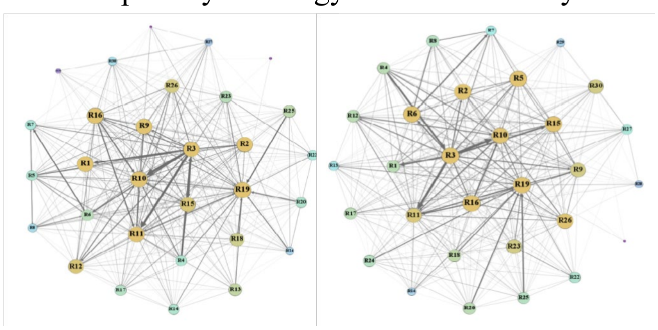
Table 4

Source		Target
Smelting and pressing of metals (S14)	/	Smelting and pressing of metals (S14)
Manufacture of non-metallic mineral products (S13)	/	Construction (S24)
Chemical industry (S12)	/	Chemical industry (S12)
Smelting and pressing of metals (S14)	/	Construction (S24)
Smelting and pressing of metals (S14)	/	Manufacture of general and special purpose machinery (S16)
Smelting and pressing of metals (S14)	/	Manufacture of electrical machinery and equipment (S18)
Manufacture of non-metallic mineral products (S13)	/	Manufacture of non-metallic mineral products (S13)
Production and distribution of electric power and heat power (S22)	/	Production and distribution of electric power and heat power (S22)
Smelting and pressing of metals (S14)	/	Manufacture of metal products (S15)
Manufacture of transport equipment (S17)	/	Manufacture of transport equipment (S17)

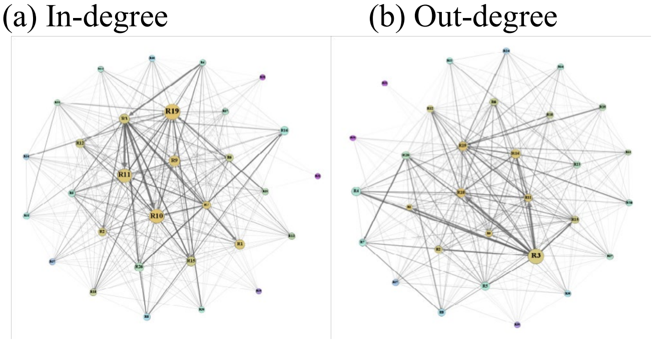
Results of the top 10 embodied energy flows from a sectoral perspective.

province was identified as a typical energy sink region in previous studies [50,51]. From an out-degree perspective, Hebei (R3), Henan (R16), Guangdong (R19), Tianjin (R2), and Inner Mongolia (R5) are the provinces with the largest out-degrees (Fig. 2b). Thus, these five provinces can be identified as critical driving regions with a largescale impact on the entire regional EEFN. Hebei (R3), Henan (R16), and Inner Mongolia (R5) are well-endowed with resources, generating positive spillover effects on other provinces on account of their natural resources. Guangdong (R19) and Tianjin (R2) mainly provide goods and services to interregional trade, which generate a large-scale impact on the embodied energy system. The distribution of node strength represents a distinct characteristic of spatial difference. In terms of demand, provinces with high energy imports are always located in the eastern area. For instance, the top three energy importers, namely, Guangdong (R19), Jiangsu (R10), and Zhejiang (R11), are located in the eastern coastal area and account for nearly 40% of the total energy imports among the provinces. Regional energy consumption in these provinces is dominated by the manufacturing industry, which requires extensive energy and resources from other provinces because of their resource-deficient features. In the energy supply side, provinces located in the central area, such as Hebei (R3), Henan (R16), Shanxi (R4), and Inner Mongolia (R5), provide massive energy by exporting typical energy-intensive products to support economic activities in China. In contrast to these provinces, Qinghai (R28), Ningxia (R29), and Hainan (R21) have relatively low inflows and outflows, all of which are located in the most under-developed areas with lower economic trade activities compared with others.

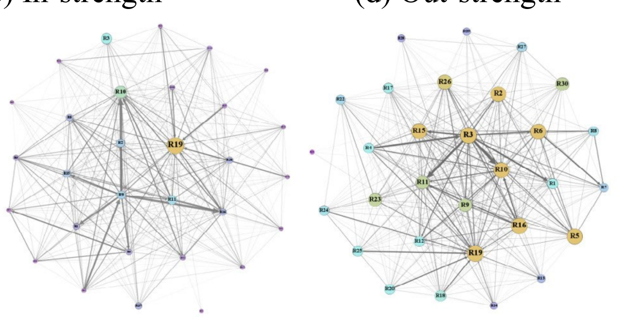
In network terminology, betweenness centrality is a parameter that explores the intermediality or bridge nature of nodes and can facilitate identification of bottlenecks in the whole network [52]. As shown in Fig. 2c, Guangdong (R19), Jiangsu (R10) and Hebei (R3) are critical bridges in China's economic system. Therefore, advancing clean production in these provinces can tighten their hold on the embodied energy running through them, which is conducive to upgrade the energy structure of economic activities and improve energy efficiency. Turmoil occurring in the energy supply system of these bridges may cause a series of shocks and breaks in the energy transfer process through the upstream and downstream supply chains. To make matters worse, the whole EEFN may be subdivided into several separate modules without interconnections. The eigenvector centrality reflects a node's significance on the basis of the importance of its connections. In comparison with betweenness centrality, Beijing (R1) holds the second position in terms of eigenvector centrality but a lower position in terms of betweenness centrality. This result indicates that Beijing is relatively weak in connecting multiple regions while occupying a central position in connecting to regions with the highest impact. In other words, Beijing has immense potential for determining national energy reduction given its structural priority in energy flow network. By



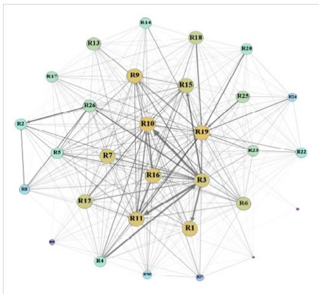
(a) In-degree (b) Out-degree



(c) In-strength (d) Out-strength

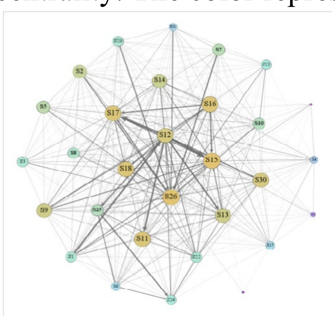
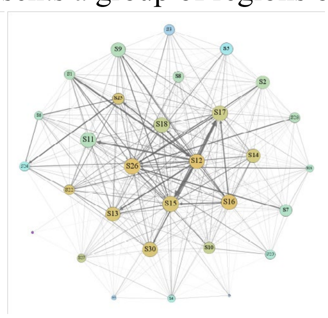


(e) Betweenness centrality (f) Closeness centrality

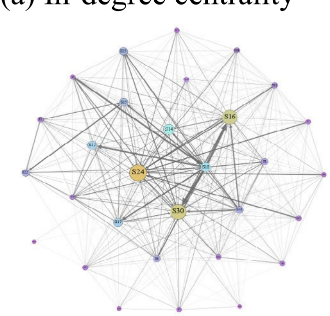
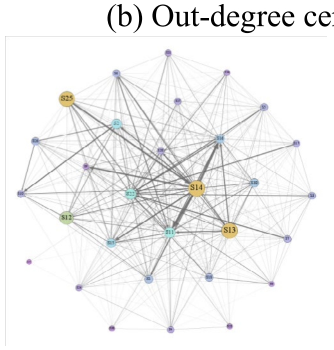


(g) Eigenvector centrality

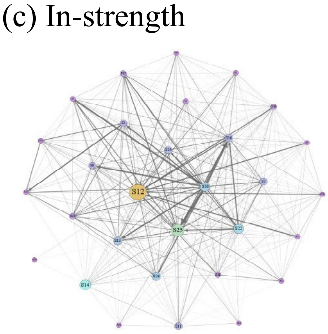
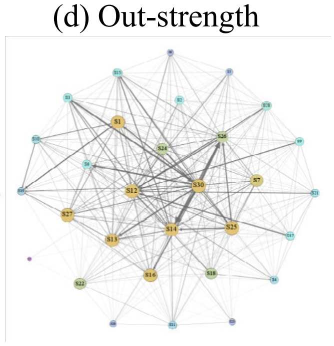
Fig. 2. Importance parameters for regional EEFN. Note: The thickness of a line denotes the volume of the embodied energy flow between regions. The size of the node represents the corresponding centrality. The color represents a group of regions based on their centrality values.

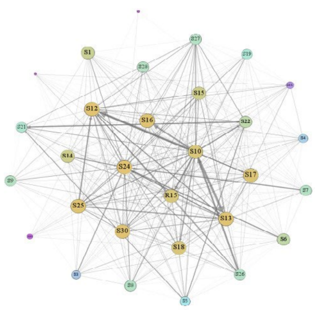
(a) In-degree centrality (b) Out-degree centrality

(c) In-strength (d) Out-strength

(e) Betweenness centrality (f) Closeness centrality

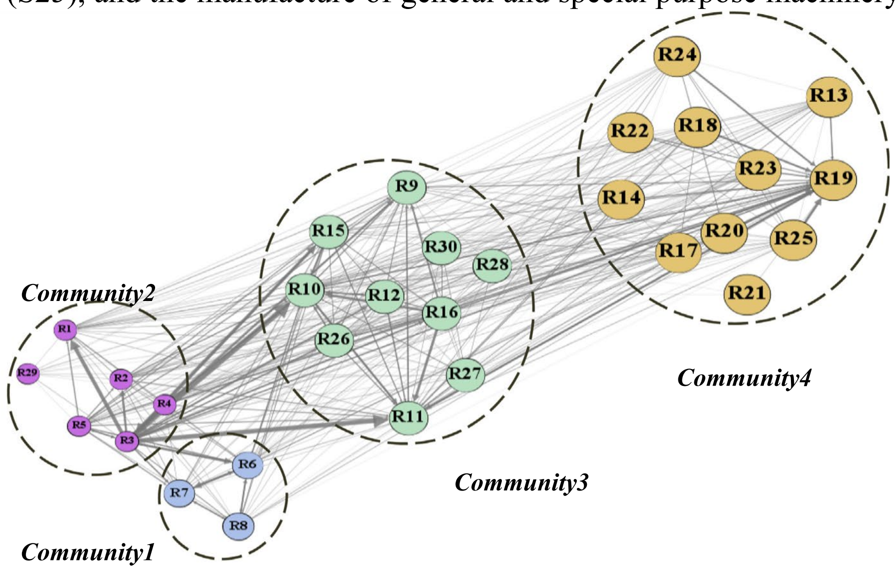


(g) Eigenvector centrality

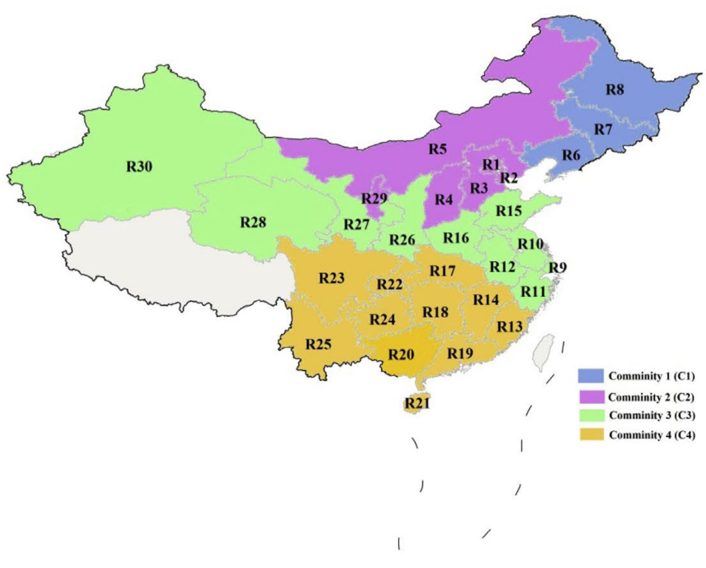
Fig. 3. Importance parameters for sectoral EEFN. Note: The thickness of a line denotes the volume of embodied energy flows between sectors. The size of the node represents the corresponding centrality. The color represents a group of sectors based on their centrality values.

contrast, Hebei (R3) takes the lead position in terms of betweenness centrality but a low value in terms of eigenvector centrality. This result is mainly caused by Hebei being the most critical supplier for sustaining the energy flow network in China, thereby exporting energy in multiple ways.

Besides analyzing critical provinces, this study also explores the key sectors of the EEFN by utilizing centrality theory. Fig. 3 shows rankings that are diverse in terms of the different indices, which means each sector plays a different role and exerts varying influences on the EEFN. The chemical industry (S12), the smelting and pressing of metals (S14), the transportation, storage, posts and telecommunications (S25), and the manufacture of general and special purpose machinery (S16) lead



(a) Community structure of the regional EEFN



(b) Regional distribution of communities

Fig. 4. Regional modular structure of the EEFN.

in terms of centrality and could be identified as critical sectors in the embodied energy system.

Particularly, the chemical industry (S12) leads in the value of in-degree, out-degree, and betweenness and eigenvector centralities in the EEFN. Thus, this sector is not only highly interrelated with but also mutually influenced by others, which is critical in connecting and transferring energy between receivers and suppliers. Therefore, enhancing the energy efficiency of the chemical industry (S12) can have a wide range of benefits on the energy saving of other sectors.

In terms of embodied energy volume, the energy inflows and outflows of the top five sectors respectively account for 46% and
54.3% of the total embodied energy consumption of the country. Moreover, the construction sector (S24) leads in-strength measurements in the embodied energy system, accounting for 20% of the total amount of imported embodied energy. Given that China is on the fast-track of urbanization through its large-scale construction activities, the embodied energy consumption of the construction sector (S24) has increased significantly as constructionrelated activities require numerous products, goods, and services from the material production and service sectors. Thus, this industry receives energy inputs from a broad range of economic sectors. In terms of out-strength, the smelting and pressing of metals (S14), the manufacture of non-metallic mineral products (S13), and the chemical industry (S12) consistently hold high values in the EEFN. The scale-free network preference reveals that highweighted flows prefer to link with nodes with high strength, which, to some extent, illustrates the preferential attachment mechanism of Chinese EEFN. In terms of closeness centrality, the value gaps among the sectors are small. Thus, various sectors play nearly equal roles in the economy.

3.4. Communities

This study uses community detection to explore regional agglomeration by quantifying the density of relationships within communities in comparison with the relationships between communities. As shown in Fig. 4a, the regional EEFN can be divided into four sub-communities, which implies an apparent separation of amounts existing among communities. Approximately threequarters of the provinces cluster into the two largest communities (C3 and C4), while C1 includes only three regions.

Close examination of the communities indicates that the distribution of communities is highly related to the presence of regional economic cooperation organizations. Fig. 4b depicts the distribution pattern of communities via a colored map of China; here, provinces in the same community are marked by the same color. C1 includes three provinces, all of which are located in the northeast and considered the Old Industrial Base of the country. C2 comprises six provinces located mainly in the northern regions of China. C3 has 10 provinces, some of which are located in the coastal area, including the Yangtze River Delta. C4 is located in the southern region, including the Pearl River Delta and the Chuan-Yu agglomeration economy.

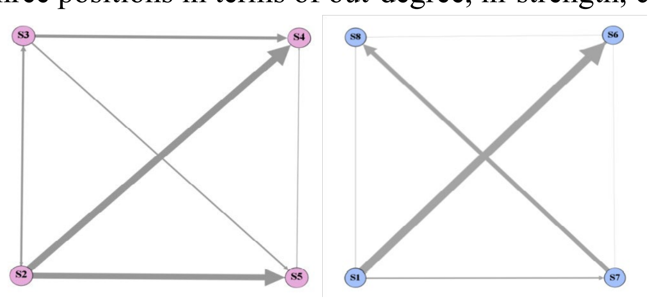
Heterogeneous effects are observed within communities. For example, C2 and C3 can be described as "one nucleus and multitude weak; " these communities include the most-developed economic rims (e.g., Jing-Jin-Ji and Yangtze River Delta) and under-developed western provinces (e.g., Xinjiang and Qinghai). This finding further highlights spatial spillover and leakage effects on the energy interaction system of China.

From a sectoral perspective, four sub-communities can be identified (Fig. 5). The results of sectoral embodied energy consumption display significant clustering features. C1 is comprised of four sectors, all of which are related to the mining industry (i.e., mining and washing of coal (S2), extraction of petroleum and natural gas (S3), mining and processing of metal ores (S4), and mining and processing of nonmetal ores (S5)). The four sectors in C2 include a number of less energy-intensive sectors, such as the agricultural and light industries. C3, which consists of 11 sectors, is dominated by the industrial sector. C4 includes the service sector and a number of other typical energy-intensive sectors that comprise the major energy consumers in China's economy. Centers also exist within the communities (here, centers are those sectors with inflows and outflows far greater than those of others). For instance, the sectors of smelting and pressing of metals (S14), construction (S24), and manufacture of non-metallic mineral products (S13) are centers within C4.

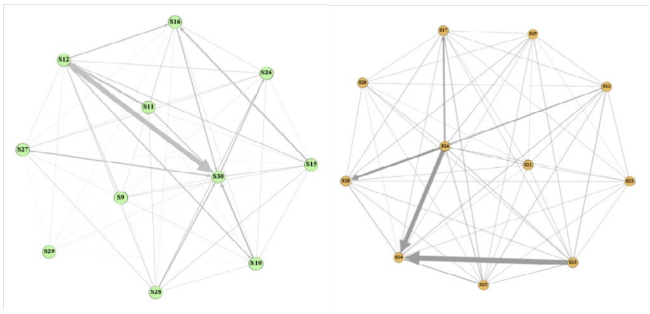
4. Discussions and policy implications

Given the national emphasis on agglomeration economy, economic cooperation organizations have considerable influences on China. Thus, in this section, this study treats the economic cooperation organizations, namely, Jing-Jin-Ji, Northeast Three Provinces, Yangtze River Delta, and Chuan-Yu agglomeration economy, as nodes to elaborate their importance in the embodied energy flow system.

The related results are presented in Table 5. Economic cooperation organizations apparently play important roles in the Chinese embodied energy flow system. Jing-Jin-Ji ranks the first among these organizations in terms of degree centrality and out-strength; by comparison, the Yangtze River Delta ranks the first in terms of in-strength, closeness, betweenness, and eigenvector centrality. Chuan-Yu agglomeration economy ranks lower than other economic organizations because of its economic level and geographical location. It's worth to notice that Guangdong (R19) firmly occupies the top three positions in terms of out-degree, in-strength, close-



(a) Community 1 (b) Community 2



(c) Community 3 (d) Community 4 Fig. 5. Sectoral modular structure of the EEFN.

ness, betweenness, and eigenvector centrality among other economic cooperation organizations. This is mainly because Guangdong is one of the most economically prosperous provinces in China and includes the Pearl River Delta, which is one of the most developed agglomeration economies in the country. Above all, the economic cooperation organizations are highly influential in the embodied energy flow system. Given the reinforcement of regional integration, the role of economic cooperation organizations in the energy trade network can be expected to become more crucial and transform the current pattern of China's economy toward diversity and multi-polarization.

The small-world nature of a network provides dynamic insights into economic relations from the aspects of regions and sectors. Any positive or negative effect on key nodes may spread quickly to other nodes in the network through the national supply chain, thereby causing significant changes to the system functions. This nature demonstrates that the current embodied energy system in China's modern economy is robust to random disturbances but vulnerable to conscious shocks. From a sectoral perspective, the chemical industry (S12), the smelting and pressing of metals (S14), the transportation, storage, posts and telecommunications (S25), and the manufacture of general and special purpose machinery (S16) are highly connected sectors of the EEFN. These sectors are typical energy-intensive consumers, which further emphasize the fact that the growth of China's economy is heavily dependent on massive energy consumption. The construction sector (S24) also leads energy consumption in the embodied energy system, which

Table 5
Importance of nodes in the centrality measurement based on economic cooperation organizations.

No	Degree analysis		Strength analysis		Closeness centrality	Betweenness centrality	Eigenvector centrality
	In-degree	Out-degree	In-strength	Out-strength			
1	Ra	Ra	Rc	Ra	Rc	Rc	Rc
2	Rb	Rc	R19	Rb	Ra	Ra	R19
3	Rc	R19	Ra	Rc	R19	R19	Ra
4	R16	Rb	Rb	R16	Rb	Rb	Rb
5	R19	R26	R15	R4	R26	R16	R18
6	R15	R15	R16	R19	Rd	R26	R13
7	Rd	R16	R26	R15	R16	Rd	R15
8	R26	Rd	Rd	R26	R15	R15	Rd
9	R18	R25	R18	Rd	R30	R18	R16
10	R20	R4	R13	R8	R27	R30	R20
11	R27	R18	R8	R18	R4	R20	R25
12	R30	R13	R25	R24	R18	R27	R17
13	R17	R17	R17	R25	R8	R4	R26
14	R4	R20	R20	R20	R25	R25	R14
15	R13	R8	R30	R17	R24	R17	R24
16	R24	R14	R4	R27	R20	R29	R4
17	R25	R30	R14	R14	R17	R13	R30
18	R14	R27	R27	R30	R13	R24	R27
19	R29	R24	R24	R13	R14	R8	R8
20	R28	R29	R29	R28	R29	R28	R29
21	R8	R28	R28	R29	R28	R21	R21
22	R21	R21	R21	R21	R21	R14	R28

Note: Ra represents the Jing-Jin-Ji, Rb refers to the Northeast Three Provinces, Rc refers to the Yangtze River and Rd refers to the Chuan-Yu agglomeration economy.

means infrastructure construction is a main power for economic growth in the country. From a regional perspective, Guangdong (R19), Hebei (R3), Jiangsu (R10), Shanghai (R9), and Zhejiang (R11) play prominent roles for energy savings in the EEFN. Therefore, energy-related policies should focus on these hubs to accelerate transitions in energy consumption behavior and improve energy efficiency.

In summary, findings from both the regional and sectoral perspectives reveal that strict regulation should be implemented for typical energy suppliers to adjust their energy consumption patterns and encourage them to provide more value-added and energy-efficient products. For energy consumers, concerted efforts from the consumption side are necessary to achieve clean production. Shouldering more responsibility in the bargaining process is encouraged to urge suppliers to implement low-carbon and cleaner production. The energy conservation target responsibility system of China, which was proposed by the Chinese government at the beginning of the 12th Five-Year Plan, sets mandatory energy reduction targets at the regional level. In contrast to the first version created in

2007, this target system is more informed as it takes regional disparities into consideration. However, although these targets are considered to be stratified, their application to the inner area context remains insignificant. For instance, according to the results of this study, Guangdong (R19), Jiangsu (R10), and Zhejiang (R11) are the largest energy-consuming provinces of China, while Hebei (R3) and Henan (R16) are their leading suppliers. However, despite the different roles of these regions, they face similar energy reduction targets ranging from 16% to 18% in the 12th Five-Year Plan. Therefore, clear separation of energy reduction targets should exist among regions in accordance with their diverse roles and statuses in energy consumption.

Nodes with a high betweenness centrality that act as bridges in the network also dominate the embodied energy system. Similar to control the spread of epidemics, controlling the sources and media at the same time is effective. Therefore, the government should implement firm restrictions on these bridges to control the spread of environmental pollution and accelerate the shift in production structure in these nodes.

The results of community analysis provide solid evidence for determining to what extent the effects of a group of nodes have within the community compared with that outside of it. Therefore, community divisions can help decision makers understand the potential influences of policy implementation given that the nodes in their communities enjoy close proximity in terms of spillover effects of the regional policy. Hence, promoting regional integration in the same community can maximize the benefits and effectiveness of policy intervention.

5. Conclusions

This study employed MRIO analysis and complex network theory to explore the features and laws of China's embodied energy system from the regional and sectoral perspectives. The findings can be regarded as a solid reference for formulating fair and reasonable energy-saving policies for energy suppliers and consumers. The results of this study are as follows:

(1) The regional and sectoral EEFNs present small-world nature, which means any disturbance occurring in highly connected regions or sectors will spread quickly to neighbors and may cause significant changes in the whole embodied energy system.
(2) The most energy-intensive inflows and outflows take place within provinces or sectors. From a regional perspective, the embodied energy flows from resource-abundant regions to developed areas with typical geographic connections. From a sectoral perspective, the embodied energy trade between energy-intensive sectors is relatively frequent.
(3) Guangdong (R19), Hebei (R3), Jiangsu (R10), Shanghai (R9), and Zhejiang (R11) are at the forefront of the most important centrality indices. Some sectors, namely, the chemical industry (S12), the smelting and pressing of metals (S14), the transportation, storage, posts and telecommunications (S25), and the manufacture of general and special purpose machinery (S16), are highly connected sectors in the entire network.

(4) Community detection implies an apparent separation of amounts existing between communities from both the regional and sectoral perspectives. Economic cooperation organizations are highly influential in the distribution of communities and the embodied energy flow system.

A three-step strategy must be implemented to achieve national energy conservation. First, the central government should release topedown mandatory energy reduction targets for key regions and sectors to control the volume of energy consumption. Second, restrictions should be implemented for media actors with a high value of centrality. This step can help control the spread of environmental pollution. Third, enhancing regional integration and coordination based on the results of community detection can develop a nationeregionelocal energy conservation framework, which can maximize the spillover effects of policies in the regional scale.

30 regions

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R1	Beijing	R16	Henan
R2	Tianjin	R17	Hubei
R3	Hebei	R18	Hunan
R4	Shanxi	R19	Guangdong
R5	Inner Mongolia	R20	Guangxi
R6	Liaoning	R21	Hainan
R7	Jilin	R22	Chongqing
R8	Heilongjiang	R23	Sichuan
R9	Shanghai	R24	Guizhou
R10	Jiangsu	R25	Yunnan
R11	Zhejiang	R26	Shaanxi
R12	Anhui	R27	Gansu
R13	Fujian	R28	Qinghai
R14	Jiangxi	R29	Ningxia
R15	Shandong	R30	Xinjiang

30 sectors

S1	Farming, forestry, animal husbandry and fishery	S16	Manufacture of general and special purpose machinery
S2	Mining and washing of coal	S17	Manufacture of transport equipment
S3	Extraction of petroleum and natural gas	S18	Manufacture of electrical machinery and equipment
S4	Mining and processing of metal ores	S19	Manufacture of communication equipment, computers and other electronic equipment
S5	Mining and processing of nonmetal ores	S20	Manufacture of measuring instruments and machinery for culture activity and office work
S6	Manufacture of foods and tobacco	S21	Other manufacturing
S7	Manufacture of textile	S22	Production and distribution of electric power and heat power
S8	Manufacture of textile wearing apparel, footwear, caps, leather, furs, feather(down), and related products	S23	Production and distribution of gas and water
S9	Processing of timber, manufacture of furniture	S24	Construction
S10	Manufacture of paper, printing, manufacture of articles for culture, education, and sports activity	S25	Transportation, storage, posts and telecommunications

S11	Processing of petroleum, coking, processing of nuclear fuel	S26	Wholesale trade and retail trade
S12	Chemical industry	S27	Hotel and restaurants
S13	Manufacture of non-metallic mineral products	S28	Tenancy and commercial services
S14	Smelting and pressing of metals	S29	Research and experimental development
S15	Manufacture of metal products	S30	Other services

Appendix A

References

[26]

[1] IEA. Key world energy statistic. Paris, France: International Energy Agency; 2017.

[27] [2] Shi J, Li H, Guan J, Sun X, Guan Q, Liu X. Evolutionary features of global embodied energy flow between sectors: a complex network approach. Energy 2017;140.

fill its commitment to reducing carbon [28]

[3] Guo D, Chen H, Long R. Can China ful dioxideemissionsinthe ParisAgreement?Analysis based on a back-

[29] propagation neural network. Environ Sci Pollut Control Ser 2018;25(27): 27451e62.

[30]

[4] Chen ZM, Chen GQ. Demand-driven energy requirement of world economy 2007: a multi-region inputeoutput network simulation. Commun Nonlinear

[31] Sci Numer Simulat 2013;18(7):1757e74.

[5] Hong J, Shen GQ, Guo S, Xue F, Zheng W. Energy use embodied in China's

[32] construction industry: a multi-regional inputeoutput analysis. Renew Sustain Energy Rev 2016;53:1303e12.

[6] Wiedmann T. A review of recent multi-region inputeoutput models used for

[33] consumption-based emission and resource accounting. Ecol Econ 2009;69(2): 211e22.

[7] Wiedmann T, Lenzen M, Turner K, Barrett J. Examining the global environ-mentalimpact of regional consumptionactivities d Part 2: review of

[34] inputeoutput models for the assessment of environmental impacts embodied in trade. Ecol Econ 2007;61(1):15e26.

[8] Lindner S, Liu Z, Guan D, Geng Y, Li X. CO 2 emissions from China's power

[35] sector at the provincial level: consumption versus production perspectives. Renew Sustain Energy Rev 2013;19:164e72.

[9] Zhang B, Chen ZM, Xia XH, Xu XY, Chen YB. The impact of domestic trade on

[36] China's regional energy uses: a multi-regional inputeoutput modeling. Energy Pol 2013;63(Complete):1169e81.

[37]

[10] Wiedmann T, Wilting HC, Lenzen M, Lutter S, Palm V. Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region inputeoutput analysis. Ecol Econ 2011;70(11):1937e45.

[38] [11] Chen GQ, Wu XF. Energy overview for globalized world economy: source, supply chain and sink. Renew Sustain Energy Rev 2017;69:735e49.

[39] [12] Chen W, Wu S, Lei Y, Li S. Interprovincial transfer of embodied energy between the Jing-Jin-Ji area and other provinces in China: a quantification using

interprovincial input-output model. Sci Total Environ 2017;584e585:990.
[40] [13] Chen ZM, Chen GQ. An overview of energy consumption of the globalized world economy. Energy Pol 2011;39(10):5920e8.
[41] [14] Su B, Ang BW. Inputeoutput analysis of CO2 emissions embodied in trade: a multi-region model for China. Appl Energy 2014;114:377e84.
[42]
[15] Mi Z, Zhang Y, Guan D, Shan Y, Liu Z, Cong R, et al. Consumption-based emission accounting for Chinese cities. Appl Energy 2016:184.
[43] [16] Qi T, Winchester N, Karplus VJ, Zhang X. Will economic restructuring in China reduce trade-embodied CO2 emissions? Energy Econ 2014;42:204e12.
[44]
[17] Su B, Ang BW, Li Y. Input-output and structural decomposition analysis of Singapore's carbon emissions. Energy Pol 2017;105:484e92.
[45] [18] Su B, Thomson E. China's carbon emissions embodied in (normal and processing) exports and their driving forces, 2006e2012. Energy Econ 2016;59: 414e22.
[46] [19] Wei J, Huang K, Yang S, Li Y, Hu T, Zhang Y. Driving forces analysis of energy-related carbon dioxide (CO2) emissions in Beijing: an inputeoutput structural
[47] decomposition analysis. J Clean Prod 2017;163:58e68.
[20] Mi Z, Meng J, Guan D, Shan Y, Song M, Wei Y-M, et al. Chinese CO2 emission flows have reversed since the global financial crisis. Nat Commun 2017;8(1): [48] 1712.
[21] So€dersten C-JH, Wood R, Hertwich EG. Endogenizing capital in MRIO models: [49] the implications for consumption-based accounting. Environ Sci Technol
[50] 2018;52(22):13250e9.
[22] Schweitzer F, Fagiolo G, Sornette D, Vegaredondo F, Vespignani A, White DR.
[51] Economic networks: the new challenges. Science 2009;325(5939):422e5.
[23] Zareie A, Sheikhahmadi A. A hierarchical approach for influential node
[52] ranking in complex social networks. Expert Syst Appl 2018;93:200e11.
[24] Raducha T, Gubiec T. Coevolving complex networks in the model of social interactions. Phys Stat Mech Appl 2017;471:427e35.
[25] Gao X, An H, Fang W, Li H, Sun X. The transmission of fluctuant patterns of the forex burden based on international crude oil prices. Energy 2014;73:380e6. Wang M, Zhao L, Du R, Wang C, Chen L, Tian L, et al. A novel hybrid method of forecasting crude oil prices using complex network science and artificial intelligence algorithms. Appl Energy 2018;220:480e95.
Wang M, Chen Y, Tian L, Jiang S, Tian Z, Du R. Fluctuation behavior analysis of international crude oil and gasoline price based on complex network perspective. Appl Energy 2016;175:109e27.
Shanmukhappa T, Ho IW-H, Tse CK. Spatial analysis of bus transport networks using network theory. Phys Stat Mech Appl 2018;502:295e314. Adamic LA, Huberman BA, Barabasi AL, Albert R, Jeong H, Bianconi G. Powerlaw distribution of the world wide web. Science 2000;287(5461):2115.
Duan C, Chen B. Energyewater nexus of international energy trade of China. Appl Energy 2017;194:725e34.

Nuss P, Chen WQ, Ohno H, Graedel TE. Structural investigation of aluminum in the US economy using network analysis. Environ Sci Technol 2016;50(7). Hao X, An H, Qi H, Gao X. Evolution of the exergy flow network embodied in the global fossil energy trade: based on complex network. Appl Energy 2016;162:1515e22.

Chen B, Li JS, Wu XF, Han MY, Zeng L, Li Z, et al. Global energy flows embodied in international trade: a combination of environmentally extended inputeoutput analysis and complex network analysis. Appl Energy 2018;210: 98e107.

Shi J, Li H, Guan J, Sun X, Guan Q, Liu X. Evolutionary features of global embodied energy flow between sectors: a complex network approach. Energy 2017;140:395e405.

Gao C, Su B, Sun M, Zhang X, Zhang Z. Interprovincial transfer of embodied primary energy in China: a complex network approach. Appl Energy 2018;215:792e807.

Sun X, An H, Gao X, Jia X, Liu X. Indirect energy flow between industrial sectors in China: a complex network approach. Energy 2016;94:195e205. Holme P, Min Park S, Kim BJ, Edling CR. Korean university life in a network perspective: dynamics of a large affiliation network. Phys Stat Mech Appl 2007;373:821e30.

Brandes U. A faster algorithm for betweenness centrality. J Math Sociol 2001;25(2):163e77.

Barrat A, Barthelemy M, Vespignani A. The architecture of complex weighted networks: measurements and models. Proc Natl Acad Sci U S A 2004;101(11): 3747e52.

Barrat A, Barthelemy M, Pastorsatorras R, Vespignani A. The architecture of complex weighted networks. Proc Natl Acad Sci U S A 2004;101(11):3747e52. Opsahl T, Agneessens F, Skvoretz J. Node centrality in weighted networks: generalizing degree and shortest paths. Soc Network 2010;32(3):245e51. Freeman LC. Centrality in social networks conceptual clarification. Soc Network 1978;1(3):215e39.

Bonacich P, Lloyd P. Eigenvector-like measures of centrality for asymmetric relations. Soc Network 2001;23(3):191e201.

Blondel VD, Guillaume JL, Lambiotte R, Lefebvre E. Fast unfolding of communities in large networks. J Stat Mech 2008;2008(10):155e68.

Su B, Huang HC, Ang BW, Zhou P. Inputeoutput analysis of CO2 emissions embodied in trade: the effects of sector aggregation. Energy Econ 2010;32(1): 166e75.

Carvalho VM. From micro to macro via production networks. J Econ Perspect 2014;28(28):23e47 (25).

Watts DJ. Networks, dynamics, and the small-world phenomenon. Am J Sociol 1999;105(2):1e10.

Watts DJ, Strogatz SH. Collective dynamics of 'small-world' networks. Nature 1998.

Davis GF, Yoo M, Baker WE. The small world of the American corporate elite, 1982e2001. Strat Organ 2003;1(3):301e26.

Liu Z, Geng Y, Lindner S, Guan D. Uncovering China's greenhouse gas emission from regional and sectoral perspectives. Energy 2012;45(1):1059e68. Hong J, Shen Q, Xue F. A multi-regional structural path analysis of the energy supply chain in China's construction industry. Energy Pol 2016;92:56e68. Blo€chl F, Theis FJ, Vega-Redondo F, Fisher EON. Vertex centralities in inputoutput networks reveal the structure of modern economies. Phys Rev E 2011;83(4):046127.