https://doi.org/10.1016/j.scs.2019.101500

The evolution of patterns within embodied energy flows in the Chinese economy: A multi-regional-based complex network approach

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Abstract

China currently suffers from severe environmental issues, particularly with regard to its primary energy consumption. To address the complexity of energy flows, this study integrated a multi-regional input–output method and complex network theory to conduct an in-depth investigation of the functional and structural evolution of energy interaction patterns in the Chinese economy for 2007, 2010, and 2012. Results show that economic scale and trading frequency increased in the regional energy network, while sectoral energy connections remained stable from 2007 to 2012. A time-series analysis demonstrates that Guangdong (R19) was the most vital region for bridging the entire regional energy network and that it was located at the center of energy flow transfers. Sectoral investigation indicates that infrastructure construction remained dominant in the current Chinese economy. Any disruption that occurred in the construction sector may exceed supply capacity, and this would lead to energy crises in the embodied energy flow network. Regions were disaggregated and aggregated during the investigated period because of changes in spatial heterogeneity. Sectoral community analysis explores an evident process for industrial differentiation. The findings of this study provide a new angle through which to understand spatial heterogeneity and industrial structure in a time series manner.

1. Introduction

China is currently on a path of rapid urbanization and industrialization. This has, inevitably, generated severe environmental issues, particularly with regard to primary energy consumption (Liu et al., 2013). The BP statistical review of world energy 2018 indicates that China's primary energy consumption in 2013 accounted for 23.2% of global energy use.

The development of a range of methodological techniques has enabled the research community to gradually realize that energy interactions constitute a complex interconnected flow network (Chen et al., 2018). It follows, that, the complexity of energy flows can be addressed using a complex network method. This method depicts an intricate energy flow system by adopting several parameters from degree, strength, and centrality perspectives (Chen et al., 2018). For example, centrality analysis highlights the importance of a specific economy through its contribution to network connections, and in so doing provides a new angle by which to understand the vulnerability and robustness of energy flow systems. To date, numerous studies have investigated direct energy networks from different scales using complex network theory. Global-level investigations have dominated previous studies with a wide range of topics being addressed with regard to fossil energy (Hao, An, Qi, & Gao, 2016; Zhong et al., 2017), oil (Wang, Tian, & Du, 2016; Yang, Poon, Liu, & Bagchi-Sen, 2015), and natural gas (Geng, Ji, & Fan, 2014). At the national level, several studies have focused on infrastructual systems and industrial energy linkages in the Chinese context (Dunn, Wilkinson, & Ford, 2016; Yang, Ng, Xu, & Skitmore, 2018). However, investigating the direct energy network only measures the effects of onsite manufacturing process while failing to determine byproduct effects induced by “upstream and downstream” consumption processes. In the Chinese context, indirect energy accounts for a majority of total energy consumption (Liu et al., 2012). For example, the energy use embodied in the upstream supply chain accounted for over 90% of the total energy consumption of the construction sector (Hong, Shen, Guo, Xue, & Zheng, 2016). Therefore, direct energy accounting fails to provide a holistic map for understanding sectoral transfers and spatial distributions.

To address this issue, embodied energy, which is the sum of direct and indirect energies used during the entire production process, is used to illustrate overall energy utilization. Input–

output (IO) methods, such as the single region input–output (SRIO) and multi-regional input–output (MRIO) models, are commonly used to trace embodied energy flows. Theoretically, the SRIO model quantifies embodied energy use based on inter-sectoral relationships by taking the nation's whole economy as a single entity while failing to depict the spatial heterogeneity of energy connections (Hong, Gu, Liang, Liu, & Qiping Shen, 2019; Su & Ang, 2010). This method takes advantage of lower data requirements but suffers from methodological weaknesses as a consequence of assuming that the same production technology exists between foreign and domestic regions (Su, Huang, Ang, & Zhou, 2010). In contrast, the MRIO model allows for an examination of technological differences and regional disparities by placing all regions into a unified framework. This is an approach that is beneficial for exploring the interregional connections that exist between production and consumption sides (Su & Ang, 2011; Zhang, Chen, Xia, Xu, & Chen, 2013; Zhang, Qiao, Chen, & Chen, 2016). The treatment of interregional feedback effects is the major methodological difference that distinguishes the SRIO and MRIO models (Su & Ang, 2011). Practically, the MRIO model has been widely applied at global (Chen & Wu, 2017), national (Cui, Peng, & Zhu, 2015), regional (Hong et al., 2018; Zhang, Zheng et al., 2015), and urban levels (Zhang, Qiao, & Chen, 2015). In summary, the traditional IO method is a quantity-oriented approach, which quantifies total energy consumption by considering direct and indirect effects. The quantitative result of IO analysis is determined by the performance of direct energy consumption, production structures, and final demand volume; however, this method only minimally illustrates the functional and structural characteristics of energy interactions (Gao, Su, Sun, Zhang, & Zhang, 2018). Moreover, the intensity and direction of energy flows, and entities with large energy inflows and outflows are important actors that generate direct impacts on the patterns that emerge within energy flow systems.

However, systematic and scientific methods are lacking for the identification of the critical and influential actors that substantially affect the operation of an entire energy flow system; the diverse roles and interaction mechanisms of which remain ambiguous (Chen et al., 2018). Previous studies have attempted to address this issue using the structural path analysis (SPA) method. The SPA method is used to investigate energy interactions through the upstream supply chain by defining energy paths which regard upstream energy transmissions as an infinite path tree (Hong, Shen, & Xue, 2016; Lenzen, 2007; Zhang, Qu, Meng, & Sun, 2017). This method draws upon the focus of quantitative measurements of energy use embodied in each individual path. However, the method fails to determine the inherent patterns and characteristics of path connections from a network perspective. Therefore, adopting an approach that combines the IO model with complex network analysis provides additional insights into energy interaction patterns from systematic and dynamic perspectives.

From a network perspective, the understanding of an economy can be unscrambled through the aspects of the industrial structure, spatial characteristics, and temporal effect. Table 1 summarizes the perceptions of previous studies on energy network analysis with or without IO models. Databases from the United Nations, the International Energy Agency, and the national statistical authority have commonly been used as foundations for investigating direction energy interactions with complex network analysis. However, there is also an increasing trend which favors combining complex network analysis with the IO model to explore the mechanisms of embodied energy consumption. That said, a majority of current studies have only focused on one or two angles. Thus, although the trend towards undertaking multi-dimensional investigations is increasing (Hong et al., 2019), a temporal analysis of the spatial and industrial linkages in energy networks remains rare. This is particularly true of an economic network that sustain the operation of an economy predominantly through the use of two sub-networks. One sub-network is the sectoral network that describes the interconnections that exist among economic sectors, and indicates industrial structure. The other sub-network is the regional network that presents the crossregional energy flows induced by trading processes and this, therefore, indicates the spatial heterogeneity of energy distribution. A separate investigation of these two subnetworks can enable decision makers to enhance their understanding of energy flows from industrial and spatial perspectives.

The present study systematically analyzes the Chinese embodied energy flow network (CEEFN) from a temporal perspective by dividing the entire network into regional and sectoral sub-networks. In particular, this research uses the MRIO model and complex system theory as its underlying methods. The findings of this study can facilitate the exploration of the patterns and function changes in the embodied energy flow system from a network perspective. Thus, the current findings provide a new angle through which to understand spatial heterogeneity and industrial structure in a time series manner. This integrated investigation can facilitate better policy implementation by identifying the diverse roles and status of key sectors and regions in China's modern economy.

The reminder of this paper is organized as follows. Section 2 develops the methodology, including the MRIO model and complex network theory. Section 3 presents the results from the aspects of small world nature, key regions and sectors, and community detection. Section 4 is the discussion section whilst Section 5 concludes this study.

2. Methodology

2.1. MRIO method

The MRIO model enables a systematic quantification of embodied energy by considering regional disparities and technological differences. Zhang et al. (2013) and Hong, Shen, Guo et al. (2016) provided a detailed derivation process of the related formulas. The basic monetary balance in the IO table can be formulated as

$$X = (I - A)^{-1} Y \quad (1)$$

where X represents the sectoral total economic output with $(m \times n) \times 1$ dimensions; m and n represent the number of regions and sectors, respectively; $(I - A)^{-1}$ is the Leontief inverse matrix; Y is the final demand vector.

Subsequently, the vector of the embodied energy intensity E can be calculated as follows:

$$E = C(I - A)^{-1} Y \quad (2)$$

where C is the vector of the sectoral direct energy intensity obtained from statistic yearbook.

Therefore, the embodied energy flows can be expressed as follows:

$$F = \hat{E} U \quad (3)$$

The total embodied energy flow set Z represents $Z^{rs} = \{z^{rs}\}$ or $Z_{ij} = \{z_{ij}\}$. From a regional perspective, the total embodied energy flows from regions r to s can be expressed as follows:

$$z^{rs} = \sum_{i=1}^{n} \sum_{j=1}^{n} f_{ij}^{rs} \quad (4)$$

From the sectoral perspective, the embodied energy flow from sectors *i* to *j* can be formulated as follows:

$$z_{ij} = \sum_{r=1}^{m} \sum_{s=1}^{m} f_{ij}^{rs} \qquad (5)$$

Table1

Overviewoftheresearchangleofenergynetworkanalysisinpreviousstudies.

Reference	Spatial	Industrial	Temporal	Datasource	Method	Scale	Energyform	Studyperiod
Fanetal.(2014)	√			DirectionofTradeStatistics	CNT	Global	Direct	2010
Ji,Zhang,andFan,(2014)	√			GlobalTradeInformation	CNT	Global	Direct	2010
Shi,Zhou,Liu,Ye,andZhang,(2014)	√		√	UNComtrade	CNT	Global	Direct	2002-2010
Gengetal.(2014)	√		√	Statisticalreviewofworldenergy2001-2012	CNT	Global	Direct	2000-2011
Zhang,Ji,andFan,(2014)	√		√	GlobalTradeInformation	CNT	Global	Direct	2004,2008,2011
An,Zhong,Chen,Li,andGao,(2014)	√		√	UNComtrade	CNT	Global	Direct	1993-2012
Yangetal.(2015)	√		√	UnitedNationsdatabaseCOMTRADE	CNT	Global	Direct	1988-2013
Duetal.(2016)	√		√	UNComtrade,U.S.EnergyInformationAdministration,InternationalMonetaryFund	CNT	Global	Direct	2005-2014
Zhou,Wu,andXu,(2016)	√		√	ITCdatabase	CNT	Global	Direct	2001-2010
Wangetal.(2016)	√		√	USEnergyInformationAdministration	CNT	Global	Direct	2005-2014
Gaoetal.(2018)	√		√	UNComtrade	CNT	Global	Direct	2002-2013
KitamuraandManagi(2017)	√			InternationalTradeStatistics,WorldEconomicOutlookDatabase,BPstatisticalreviewofworldenergy	CNT	Global	Direct	2014
Sunetal.(2016)		√	√	ChinaEnergyStatisticalYearbook,ChinaStatisticalYearbook	SRIO,CNT	National	Direct	1997,2002,2007
Duetal.(2017)	√		√	UNComtrade	ModifiedIO,CNT	Global	Embodied	2002-2013
Shietal.(2017)		√	√	WorldInput-OutputDatabase	MRIO,CNT	Global	Embodied	1995-2009
Zhongetal.(2017)	√		√	UNComtrade	CNT	Global	Embodied	2000-2013
Haoetal.(2016)	√		√	UnitedNationsStatisticsDivision	CNT	Global	Embodied	1996-2012
Chenetal.(2018)	√	√		Eoradatabase	MRIO,CNT	Global	Embodied	2012
An,An,Wang,Gao,andLv,(2015)		√		ChinaEnergyStatisticalYearbook,ChinaStatisticalYearbook,andChinaIndustryEconomyStatisticalYearbook	SRIO,CNT	National	Embodied	2007
SunandAn(2018)		√		NationalBureauofStatisticsofChina,NationalEnvironmentalAccountingDatabase	SRIO,CNT	National	Embodied	2012
Tang,Hong,Liu,andShen,(2019)	√	√		MRIOtable,provincialstatisticalyearbooks,ChinaEnergyStatisticalYearbook	MRIO,CNT	Regional	Embodied	2010
Zhangetal.(2013)	√		√	MRIOtable,ChinaEnergyStatisticalYearbook	MRIO,ENA	Regional	Embodied	2002,2007

Note:CNTistheabbreviationofcomplexnetworktheory;UNComtradeistheabbreviationofUnitedNationsCommodityTradeDatabase.

2.2. Network construction and key parameters

In this study, the nodes in the network are the regions or sectors that generate or receive energy, while the trade relationships that exist among nodes are defined as edges. The weight of a given edge is equal to the amount of energy embodied in the flows. Therefore, the regional embodied energy flow network (REEFN) and sectoral embodied energy flow network (SEEFN) are directed weighted networks that can be expressed by the following general format:

$G N Y= (,),$ (6) where G and N represent the set of nodes and edges in the network and embodied energy network, respectively; and Y represents the adjacent matrix. If z >0, then y =1 and its weight $w = z$. Otherwise, y =0.

2.2.1. Small world nature

Small world nature is an important indicator that describes the possible path lengths that connect any two nodes in a specific network. This indicator refers to a network in which the majority of the nodes are indirectly connected but can be reached with only a few steps (Chen et al., 2018). This definition indicates that small world nature can be mathematically measured by two parameters, namely, *average clustering coefficient*, which reflects the probability that exists between any two nodes that are connected to the same node in the network; and *average path length*, which is the average of all clustering coefficients and gauges the tightness of the nodes in the network (Holme, Park, Kim, & Edling, 2007). Small world nature can be expressed as follows:

$\underline{1\quad}_{h\ v,}$ $w\ w\ wuh\ hv\ vu$

$C=,$

$$\sum \frac{\sum}{k \max(wuh) \sum h\ v,\ w\ whv\ vu}$$ (7) where k represents the number of nodes and u and v are the adjacent nodes of node h.

The average path length shows the average number of steps of the shortest paths for all possible pairs of nodes in the network (Brandes, 2001).

$$\frac{1}{k(\ -1)} \sum_{u\ v,} L = d_{uv} \qquad (8)$$

2.2.2. Importance index

Fan, Ren, Cai, and Cui, (2014) and Sun, An, Gao, Jia, and Liu, (2016) determined that the importance index that is used to identify the key nodes in a network are mainly comprised of three parameters; degree, strength, and centrality. The degree of a node equals the number of embodied energy flows that are connected to this node. In a directed network, the degree can be further divided into in- and outdegrees (Barrat, Barthélemy, Pastorsatorras, & Vespignani, 2004; Barrat, Barthélemy, & Vespignani, 2004). Node strength, which includes both in- and out-strengths, represents the total energy consumption or generation of a node in the embodied energy flow system. Betweenness centrality reveals the intermediary ability of a sector or region, and is normally used as a variable for identifying critical bridges. The eigenvector centrality explores the importance of a node by verifying its connections to other key nodes (Table 2).

2.2.3. Community analysis

Modularity measurements can explore community agglomerations by quantifying the density of relationships within communities compared with the relationships between communities (Blondel, Guillaume, Lambiotte, & Lefebvre, 2008). This measure can be expressed as follows:

$$\sum_{u,v}\left[w_{uv}-\frac{k_v^{in}\ {}_u^{out}}{2w}\right]\delta\ \ \underline{1}$$

Q=(C C_u, ${}_v$),

2w(9) where C_u is the assigned community of node u and(C C_u, ${}_v$) is equal to

Table 2

Formula of the importance indexes.

	Parameters	Formula
Degree analysis	In-degree	$K_u^{in} = {}_v\, y_{vu}$
	Out-degree	$Kuout = v\ yuv$
Strength analysis	In-strength	$T_u^{in} = {}_v\, w_{vu} = {}_v\, z_{vu}$
	Out-strength	$Tuout = v\ wuv = v\ zuv$
Centrality analysis	Betweenness centrality	$b_d = {}_u\ {}_v\ g_{udv}\ {}_{uv}/g$
	Eigenvector centrality	$E_u = \frac{1}{\lambda} v\ Y\ e_{uv\ v}$

Note: g_{uv} represents the number of shortest paths between nodes u and v, g_{udv} represents the number of the shortest paths that pass through node b, represents the eigenvalue of Y, and e_v is the eigenvalue of its eigenvector.

1 and 0. Otherwise, $w=\frac{1}{2}\sum_{u\ v,} w_{uv}$.

δ

2.3. Data collection and consolidation

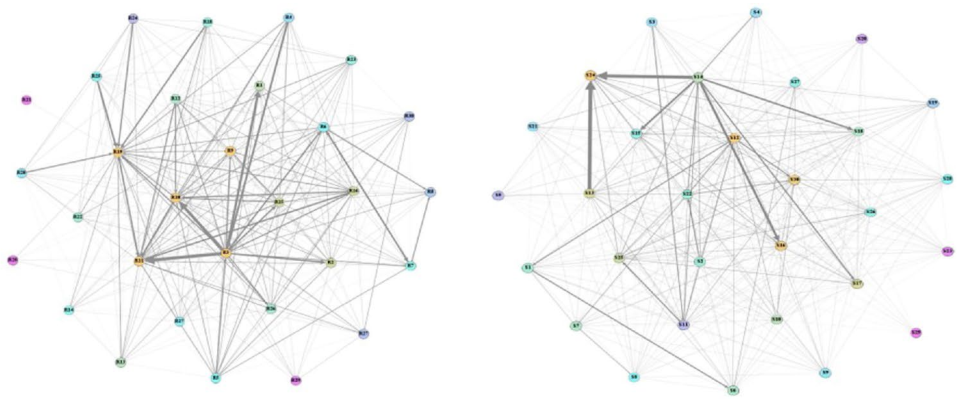
This study utilized time-series MRIO tables to account for the embodied energy flows of the Chinese economy. The MRIO tables compiled in 2007, 2010, and 2012 were collected; the first two tables were compiled by the Chinese Academy of Sciences (Zhang & Qi, 2012), whereas the third table was obtained from the findings of Mi et al. (2017). The basic units in the MRIO table comprise 30 regions which include 22 provinces, 4 municipalities, and 4 autonomous regions (see Appendix A, Table A1). In each region, 30 sectors cover all economic activities (see Appendix A, Table A2). Direct energy consumption data were collected from the provincial statistical yearbooks and energy balance tables in the *Chinese Energy Statistical Yearbook*. To exclude the effects of price fluctuations in the embodied energy assessment, the monetary flows in the MRIO tables were all converted into 2007 constant prices via a GDP deflator. Given the conflict of sectoral divisions between the MRIO table and the provincial statistical yearbooks, the compatibility of the two data sources had to be ensured by conducting sectoral disaggregation and aggregation. The assumption that sub-sectoral energy consumption data were proportional to economic output was used in the subsequent computational process.

3. Results

3.1. Network pattern changes

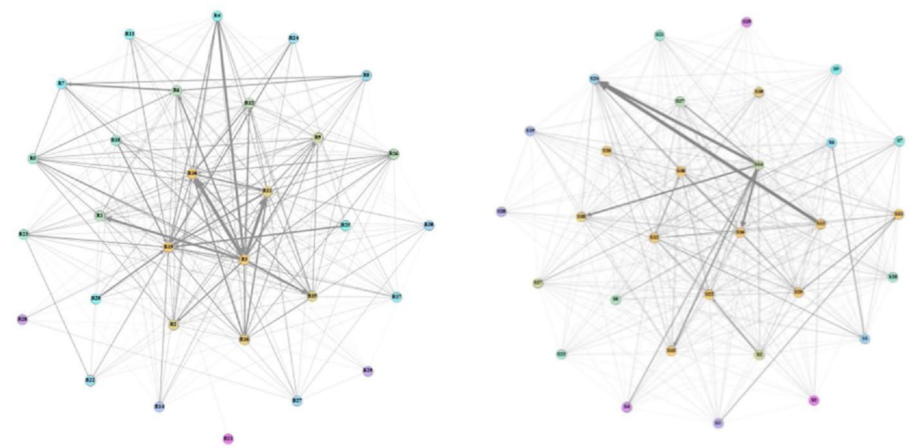
Fig. 1 provides an overview of the network pattern changes in the Chinese economy in a time series manner. From a regional perspective, an increasing number of embodied energy flows was noted among the regions as time progressed. Moreover, the strength of the embodied energy flows in 2012 was greater than those in 2007. These scale changes in the embodied energy flows demonstrate the increasing volume of the economy during the investigated period.

Furthermore, the dense spatial connections also imply that there was an enhancement of trade frequency during the trading process; indicating the importance of tracing cross-regional energy interactions on achieving energy reductions. From a sectoral perspective, the sectoral energy connections remained stable from 2007 to 2012. This indicates that comparatively small changes occurred to the industrial structure and sectoral interrelationships nationwide. In summary, the pattern of embodied energy networks do, to a degree, reflect the upward trajectory of China's economy, the driver of which was growing interregional trading processes. Meanwhile, the production structure and technological improvements played limited roles in the overall performance of embodied energy.



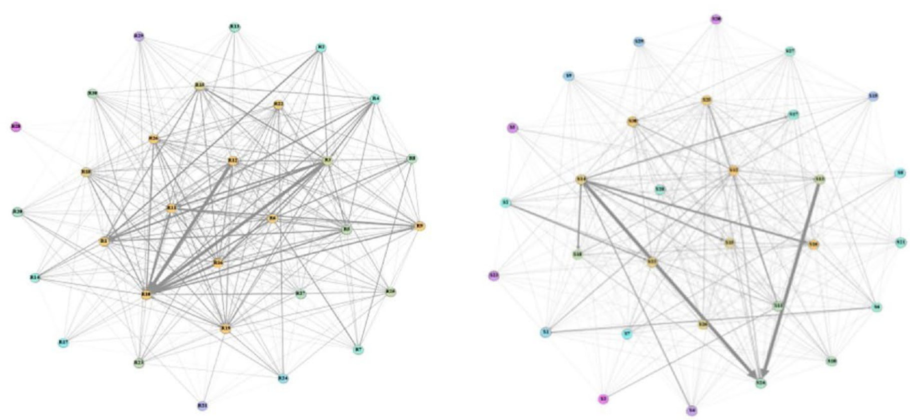
REEFN SEEFN

2007



REEFN SEEFN

2010



REEFN SEEFN

2012

Fig. 1. Changes of REEFN and SEEFN from 2007 to 2012.

3.2. Small world nature changes for random disturbances but sensitive and fragile to deliberate attacks on key nodes. That is, energy crises or disturbances that occur in the key The temporal results of the small world nature provide implications nodes will spread rapidly to others through direct and indirect flows. on the trajectory of transfer processes among the embodied energy This study used the average clustering coefficient and average path flows. The small world nature illustrates that the entire system is robust lengths to mathematically describe the small world nature. The results

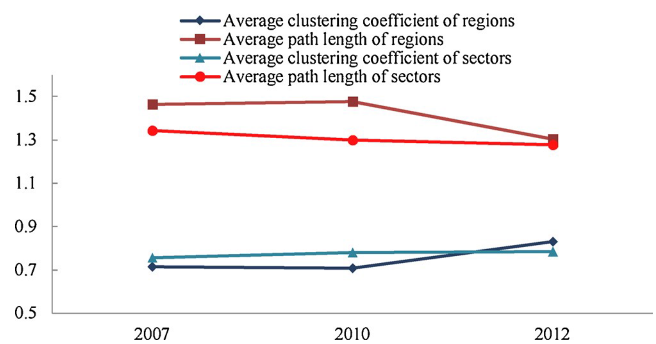


Fig. 2. Results of the small world nature.

in Fig. 2 show that the average clustering coefficients in REEFN and SEEFN were above 0.7 with the average path length being below 1.5 steps from 2007 and 2012. This result indicates that over half of a specific region's or sector's partners were likely to be the partners of other regions or sectors. SEEFN represented a highly-clustered network structure with the average clustering coefficient higher than that of REEFN in 2007 and 2010. However, the average coefficient of REEFN increased sharply in 2012 due to the continuous reinforcement of regional integration in China. Similarly, the average path lengths of REEFN and SEEFN both decreased between 2007 and 2012, which indicates that there were more tied connections between regions and sectors. Such strengthened relationships explored that the existence of key regions and sectors substantially impacted the energy security, which played vital roles in sustaining the operation of the entire embodied energy network. The enhancement of anti-risk capabilities and the implementation of advanced clean technologies in these key regions and sectors were effective in achieving sustainable development in China.

3.3. Key regions and sectors

To comprehensively evaluate the key regions and sectors in the Chinese economy, this study summarizes the importance indexes from regional and sectoral perspectives, including node degrees, node strengths, and network centrality. Table 3 shows the regional performances of these network indexes. The degree and strength of a node illustrates the sphere and intensity of influence generated from a specific node. The findings of this study indicate that Jiangsu (R10), Zhejiang (R11), and Guangdong (R19) were the leading regions with the highest number and volume of inflows. These regions are located in the most developed agglomeration economies (e.g., the Yangtze River Delta and the Pearl River Delta), and were (and remain) the drivers and engines of the Chinese economy. An overview of the top 10 regions in the in-degree and in-strength indicated that over 80% of these regions were located in three agglomeration economies, namely, Jing-Jin-Ji, the Yangtze River Delta, and the Pearl River Delta. In contrast, Hebei (R3), Henan (R16), and Inner Mongolia (R5) were the leaders in the out-degree and out-strength of energy flows. These regions are traditional resource-abundant areas that commonly act as resource suppliers in the interregional exploitative relationship. To verify the validity of the results, Table 4 compared the leading regions identified in this study with previous research with regard to in-strength and outstrength. It was found that the results were highly consistent. Moreover, although Guangdong (R19) has a wide range of connections for energy exports, its volume was comparatively small. This result may be a consequence of the fact that Guangdong mainly exports services or minimally energy-intensive products to other regions. The results relating to the issue of centrality indicated that Guangdong (R19) was undoubtedly the most vital region for bridging the entire regional energy network and that it was located at the center of energy flow transfers. This finding revealed the fact that Guangdong was a bottleneck that influences energy transmissions between receivers and suppliers. Given the characteristics of energy consumption, Jiangsu (R10) was found to be vital in connecting and transferring energy flows for the demand side, while Hebei (R3) was the key region that sustained the operation of the supply side of the network.

Table 5 shows the importance indexes of SEEFN. The chemical industry (S12), the manufacture of general and special purpose machinery sector (S16), and the construction industry (S24) occupied the top positions in degree analysis. The S24, the other services sector (S30), and S16 were the three leading sectors in terms of energy instrength. This distribution reflects the two driven model of China. The first model comprises the infrastructure construction driven economy, in which the construction sector has wide and strengthened connections with other economic sectors. The other model relates to the serviceoriented economy, and its performance is consistent with ongoing structural upgrading in China. The results of the in-strength analysis indicate that although service-driven development was present, the volume of this development remained negligibly low compared with that which exists in construction activities. The construction sector received the largest energy flows from 2007 to 2012, with total volume received being more than double that of the next highest economic sector. For example, the chemical industry (S12), the manufacture of non-metallic mineral products sector (S13), and the smelting and pressing of metals sector (S14) are three energy-intensive sectors that are highly related to the production of building materials. Therefore, the construction-driven consumption pattern made these sectors the leaders in the production side. Meanwhile, the sequence of sectors in the different importance indexes was stable which suggested that changes to the economy's structure were negligible during the investigated period.

Betweenness centrality explores the linkage characteristics of a specific node in a network. Nodes with a high value of betweenness centrality can be regarded as a bottleneck that determines energy flow transfers among the nodes. The eigenvector centrality calculates the importance of a node by referring to the importance of the nodes that connect to it. In centrality analysis, the service sector (S30) notably occupied a leading position in the betweenness centrality compared with eigenvector centrality. The reason for this is that the service sector provides a basis for the economy's operation by providing finance, information, labor, and technology services, and thereby has multiple connections with other sectors. In contrast, the construction sector (S24) obtained a high value of eigenvector centrality, but a low value in betweenness centrality. This result demonstrates that although the construction sector was weak in the breadth of its connections with the whole economy, it nevertheless continued to play a critical and central role in connecting with sectors that possessed the highest impacts on the network. This result implies that there is immense potential for the construction sector to achieve energy savings nationwide.

Table 6 summaries the results of the comparative analysis undertaken for this research with regard to important indexes from a sectoral perspective. The results obtained in this study were in-line with those from previous studies where the chemical industry was recognized as one of most important sectors due to its high value of in-degree, outdegree, and betweenness centrality from 2007 to 2012. Given the ongoing economic transition process in China, the service sector played a more critical role in receiving and connecting energy from the entire economy; indeed, it occupied a top position with respect to both instrength and centrality. *3.4. Community analysis*

The spatial distribution of REEFN was explored using community detection, which is an approach that divides the nodes based on the density of their links. Fig. 3 presents the results of the community analysis. In general, the division of provinces, which comprised four groups of regions, possessed a stable pattern from 2007 to 2012.

Table 3

Importance indexes for REEFN.

Degree											
In-degree						Out-degree					
2007		2010		2012		2007		2010		2012	
R10	28	R19	29	R11	29	R3	27	R3	27	R3	28
R19	28	R10	28	R10	28	R10	25	R16	26	R16	28
R3	27	R1	27	R12	28	R19	25	R19	24	R5	27
R9	27	R3	27	R19	28	R11	24	R10	23	R10	27
R11	25	R9	27	R26	28	R16	24	R6	22	R19	27
R16	25	R11	27	R9	27	R6	24	R15	22	R26	27
R15	24	R12	25	R16	27	R15	22	R26	22	R6	26
R26	24	R2	24	R1	26	R9	21	R2	21	R18	26
R2	23	R15	24	R6	26	R2	20	R5	20	R11	25
R1	21	R16	23	R22	26	R5	20	R11	20	R12	25

Node strength

In-strength						Out-strength					
2007		2010		2012		2007		2010		2012	
R19	18346	R19	18330	R10	25600	R3	24716	R3	24194	R3	19089
R11	17999	R10	16142	R11	14270	R16	9422	R16	8998	R16	12227
R10	14845	R11	15668	R19	11747	R10	8420	R5	8235	R5	11851
R3	10971	R9	9262	R1	11103	R6	8417	R4	8219	R10	10446
R9	7984	R3	8497	R9	9777	R19	7948	R19	8058	R6	9773
R1	6366	R1	7604	R12	9711	R5	7594	R10	7937	R4	9311
R15	6280	R15	7358	R16	8951	R15	7197	R6	6784	R12	8545
R6	5933	R6	6558	R15	7544	R4	6600	R15	6276	R26	8328
R2	5728	R12	6077	R6	7208	R11	5326	R11	5295	R1	6769
R16	5399	R7	5274	R3	6628	R26	5129	R26	5237	R11	6148

Centrality

Betweenness centrality						Eigenvector centrality					
2007		2010		2012		2007		2010		2012	
R19	85.52	R19	92.43	R19	83.05	R19	1.00	R19	1.00	R11	1.00
R3	57.03	R3	59.89	R10	81.68	R10	1.00	R10	1.00	R12	1.00
R10	44.19	R10	41.94	R16	52.09	R3	0.96	R1	1.00	R19	1.00

R16 33.74 R16 38.62 R26 45.09 R9 0.96 R9 0.99 R10 0.99 R27 29.27 R27 29.32 R27 28.60 R11 0.96 R11 0.98 R26 0.99 R11 24.17 R2 24.49 R6 20.84 R15 0.86 R3 0.97 R16 0.98 R9 21.67 R11 21.24 R3 20.68 R16 0.85 R12 0.95 R9 0.97 R2 17.39 R15 19.47 R1 17.94 R2 0.84 R15 0.90 R1 0.96 R15 15.05 R9 13.78 R5 15.98 R13 0.83 R13 0.88 R6 0.96 R26 12.98 R26 11.24 R11 15.19 R1 0.80 R16 0.86 R22 0.93

Table 4

Results of comparative analysis of important indexes from a regional perspective.

Index	2007		2010	
	Zhang et al. (2013)	This study	Gao et al. (2018)	This study
In-strength	R3, R19, R10	R19, R11, R10	R19, R10, R3	R10, R11, R19
Out-strength	R4, R3	R3	R3	R3, R16, R5

However, the group numbers varied with the passage of time. In 2007, an explicit geographic insulation was observed, in which four groups were located in Eastern, Western, Southern, and Northern China, respectively. However, aggregation and disaggregation occurred from 2007 to 2010. First, the northern group was divided into the Northeast Three Provinces (NTP) and part of the northern area. Secondly, the eastern and western areas were connected and integrated into the central group. In 2012, slight changes occurred based on the levels recorded in 2010; Hubei (R17) was moved from the central to the northern group whilst Jiangxi (R14) and Hunan (R18) were transferred from the southern to the central group. Two dominant trends were observed during the investigated period. First, a division occurred in the northern regions; NTP and Jing-Jin-Ji took different responsibilities and tended to adopt diverse strategies for economic development. Secondly, trading strength and frequency was enhanced in the central area. This therefore enabled this region to act as a bridge between Eastern and Western China and also meant that the area absorbed additional regions from the southern group. In particular, Hubei (R17) changed its membership from southern, to central, and thence to the northern group in 2007, 2010, and 2012, respectively. This implies that the province was seeking the most coherent strategic position and economic environment for its further development. In summary, the results of community analysis were consistent with the physical geographic connections and virtual administration divisions that exist within agglomeration economies. Such geography–administration nexus illustrated the power of government-led administrative regulation in economic operation and energy distribution in China.

Fig. 4 shows the result of the community analysis in SEEFN . The findings show that the changes in sectoral membership within various communities were consistent with the processes of industrial

Table 5

Importance indexes for SEEFN.

Degree											
In-degree						Out-degree					
2007		2010		2012		2007		2010		2012	
S12	28	S12	29	S12	28	S12	29	S12	29	S12	29
S24	27	S16	27	S24	27	S22	29	S22	29	S22	29
S16	26	S24	27	S16	26	S25	29	S25	29	S25	29
S30	26	S30	26	S30	26	S30	29	S26	29	S30	29
S13	24	S13	25	S13	24	S11	27	S30	29	S11	27
S17	24	S17	24	S17	24	S15	27	S11	28	S15	27
S25	23	S18	24	S25	23	S26	27	S15	28	S26	27
S10	22	S25	24	S10	22	S13	26	S16	28	S13	26

S14	22	S10	23	S14	22	S16	25	S13	27	S16	25
S6	21	S14	23	S6	21	S2	24	S10	26	S2	24

Node strength

In-strength						Out-strength					
2007		2010		2012		2007		2010		2012	
S24	77181	S24	96662	S24	118665	S14	89637	S14	107529	S14	128510
S30	34267	S30	40205	S14	42038	S12	45226	S12	48574	S12	65141
S16	29371	S16	39339	S16	41856	S13	37051	S13	47928	S13	51890
S14	28720	S14	28726	S30	37842	S22	31390	S22	36185	S22	46493
S18	21234	S18	28722	S18	30829	S11	28569	S25	36031	S25	41858
S12	19968	S12	25656	S12	28611	S25	27601	S11	27934	S11	37223
S15	19529	S17	24166	S17	27112	S2	18258	S2	23825	S2	27518
S17	18293	S15	21475	S15	23917	S15	17554	S15	18931	S15	18481
S25	16751	S25	20432	S22	23261	S1	13954	S16	16824	S1	16459

S6	16075	S22	19950	S13	22474	S16	12256	S30	14963	S30	14059

Centrality

Betweenness centrality						Eigenvector centrality					
2007		2010		2012		2007		2010		2012	
S12	40.7	S12	33.8	S12	28.8	S12	1.00	S12	1.00	S12	1.00
S30	39.4	S16	24.8	S14	21.4	S24	0.96	S24	0.95	S24	0.94
S13	24.3	S30	21.1	S16	18.5	S16	0.94	S16	0.94	S14	0.94
S16	23.8	S13	20.7	S22	16.5	S30	0.94	S30	0.92	S16	0.92
S14	19.0	S15	18.6	S13	16.1	S13	0.87	S13	0.89	S30	0.91
S25	18.4	S25	15.6	S30	15.3	S25	0.87	S25	0.87	S13	0.91
S22	16.1	S26	15.5	S15	13.9	S17	0.86	S17	0.85	S25	0.89

S17 14.8 S14 14.1 S25 13.3 S10 0.82 S18 0.85 S22 0.85 S26 13.0 S18 13.7 S26 13.0 S14 0.81 S10 0.83 S6 0.83

S15	12.5	S22	11.9	S11	10.9	S6	0.80	S15	0.83
	S18	0.83							

differentiation and economic agglomeration. Accordingly, the entire economy gradually formed four categories based on different energy consumption behaviors, namely, light industries (C1), energy-intensive heavy industries (C2), machinery manufacturing industries (C3), and high value added service sectors (C4) in 2012. Furthermore, the group sectors showed a tight interrelationship and formed a complete supply chain, which was beneficial in improving production efficiency and

Table 6

reducing energy loss in secondary transmissions. For example, C2 comprised six sectors, where

	Sun et al. (2016)	This study	Tang et al. (2019)	This study	Sun and An (2018)	This study
In-degree	S12, S24	S12, S24	S12, S30, S16	S12, S16, S24	S24, S12	S12, S24
Out-degree	S12, S22	S12, S22	S12, S24, S30	S12, S26, S30	S22, S12, S25	S12, S22, S25
In-strength	S14, S24, S12	S24, S30, S16	S24	S24	S14, S24, S12	S24, S14, S16
Out-strength	S14, S12, S22	S14, S12, S13	S14, S13, S12	S14, S12, S13	S12, S20, S14	S14, S12, S13
Betweenness centrality	S12, S16, S22	S12, S30, S13	S12	S12	S12	S12
Eigenvector centrality	S30, S12, S24	S12, S24, S16	S12, S16, S24	S12, S24, S16		

Results of comparative analysis of important indexes from a sectoral perspective.

Index	2007	2010	2012

mining and processing of nonmetal ores (S5) was the mining industry located upstream of the manufacture of non-metallic mineral products sector (S13) and the smelting and pressing of metals sector (S14). Subsequently, S13 and S14 were the major energy suppliers for the manufacture of communication equipment, computers, and other electronic equipment (S19), other

2007

2010

2012

Fig. 3. Community division in REEFN.

manufacturing (S21), and the construction industry (S24). Hong et al. (2018) also explored similarly intense industrial connections among S13, S14, and S24.

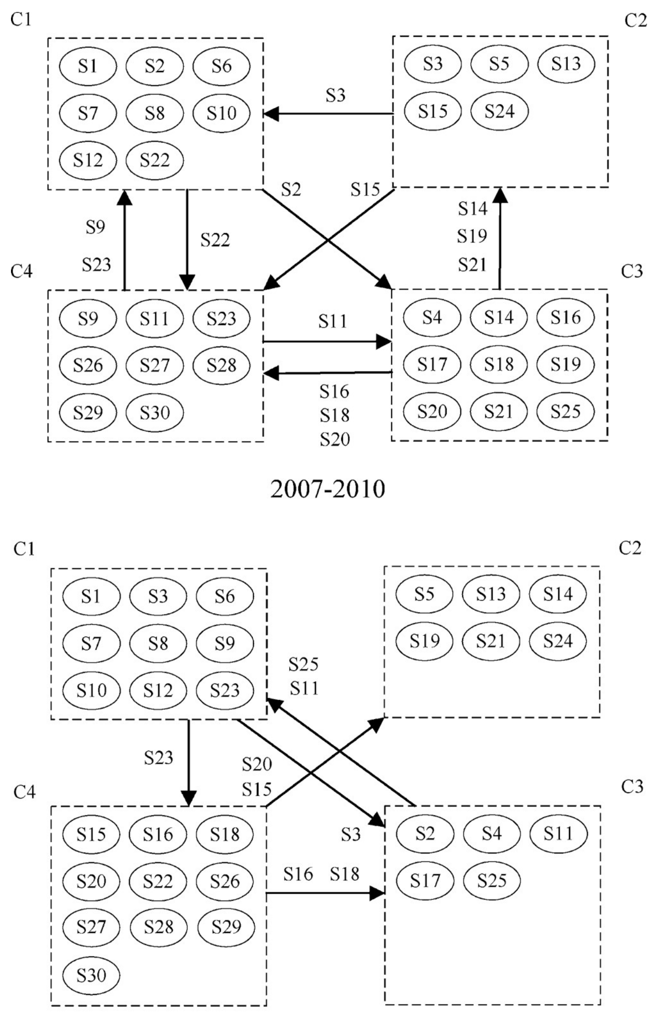


Fig. 4. Community division in SEEFN.

4. Discussions and policy implications

By considering consumption patterns and dominant sectors in existent energy flow networks, this study has revealed the emergence of structural upgrading in China's present-day economy from a temporal perspective. However, this trend has remained insignificant as a consequence of the stability of network patterns. The regional and sectoral networks represented the small world nature, within which several key regions and sectors could substantially impact the Chinese economy. From a regional perspective, the leading regions can be divided into consumption-based regions (e.g., Jiangsu (R10), Zhejiang (R11), and Guangdong (R19)) and production-based regions (e.g., Hebei (R3), Inner Mongolia (R5), and Henan (R16)), based on their consumption behaviors. Given the important status of Hebei in connecting other regions in REEFN and its production-based nature, the adoption of restricted policies with regard to energy efficiency improvements, production structure upgrading, and clean technologies may be considerably effective in achieving energy conservation nationwide. From a sectoral perspective, the construction sector played an influential and central role in connecting the most energy-intensive sectors in addition to its significant role in receiving large volumes of energy flows. This finding indicates a large potential for energy savings within the sector. It follows, *ceteris paribus*, that a strict energy audit process should be adopted to minimize the use of energy-intensive materials and products, while an easing policy should also be implemented to encourage

Table 7

Indicators for major urban agglomerations.

Degree

In-degree						Out-degree					
2007		2010		2012		2007		2010		2012	
YRD	21	YRD	21	BTH	21	BTH	20	BTH	19	BTH	20
PRD	21	PRD	21	YRD	21	NTP	20	NTP	19	NTP	20
BTH	20	BTH	20	CY	21	YRD	20	YRD	19	YRD	20
NTP	16	NTP	17	PRD	20	R16	18	R16	18	R16	20
R15	16	R15	16	NTP	20	PRD	16	PRD	16	R18	19
R16	16	R18	16	R26	20	R26	16	R15	15	PRD	19
CY	16	CY	16	R16	19	R15	15	CY	15	CY	19
R18	15	R13	15	R18	19	CY	14	R26	15	R26	19
R13	14	R16	15	R15	17	R18	13	R18	13	R25	17
R14	12	R20	12	R25	16	R20	12	R24	12	R8	16

Strength

In-strength						Out-strength					
2007		2010		2012		2007		2010		2012	
YRD	37016	YRD	39733	YRD	43316	BTH	25704	BTH	25656	BTH	23527

PRD	18346	PRD	18330	BTH	15541	NTP	15947	NTP	13998	NTP	22065
BTH	17580	BTH	16359	PRD	11747	YRD	13942	YRD	12429	YRD	15119
NTP	8902	NTP	9748	NTP	11683	R16	9422	R16	8998	R16	12227
R15	6280	R15	7358	CY	9243	PRD	7948	R4	8219	R4	9311
R16	5399	R16	5063	R16	8951	R15	7197	PRD	8058	R26	8328
CY	5305	R26	3948	R15	7544	R4	6600	R15	6276	R8	5772
R26	4327	CY	3594	R26	6445	R26	5129	R26	5237	R18	5615
R8	3464	R18	2865	R18	4652	R18	4294	CY	5212	PRD	5539
R13	3209	R8	2802	R8	4007	CY	3976	R8	4307	CY	5340

Centrality

Betweenness centrality						Eigenvector centrality					
2007		2010		2012		2007		2010		2012	
YRD	49	YRD	45	YRD	67	YRD	1.00	YRD	1.00	YRD	1.00
PRD	44	PRD	43	NTP	30	PRD	1.00	PRD	1.00	PRD	1.00
BTH	37	BTH	33	PRD	29	BTH	0.99	BTH	0.99	NTP	0.91
NTP	23	NTP	25	BTH	26	R18	0.86	NTP	0.92	CY	0.90
R16	16	R27	21	R16	16	CY	0.85	R18	0.91	BTH	0.90
R15	9	R16	17	CY	14	R13	0.84	R13	0.89	R18	0.86
R26	6	R15	11	R26	13	R15	0.84	R15	0.83	R16	0.86
CY	6	CY	9	R18	6	NTP	0.83	CY	0.83	R26	0.83
R18	6	R18	6	R27	3	R16	0.82	R16	0.77	R25	0.68
R27	2	R26	5	R25	3	R14	0.73	R20	0.74	R20	0.62

the use of less energy intensive products as well as clean goods and services. It is also important to note, given the important role of construction activities in the operation of China’s economy, that any disruption in the construction sector might lead to supply overcapacity and an energy crisis in the embodied energy flow network.

The results of the community analysis showed that the embodied energy flow network possessed a spatial heterogeneity; the trend of community divisions presented the form to be expected of agglomeration economies. Given this an in-depth investigation on the current status of major agglomerations in the embodied energy flow system needed to be conducted. To achieve this goal, we selected five major agglomeration economies that could be studied through province-level data: Liaoning–Jilin–Heilongjiang (NTP), Beijing–Tianjin–Hebei (JingJin-Ji, BTH), Shanghai–Jiangsu–Zhejiang (the Yangtze River Delta, YRD),Guangdong(the Pearl River Delta, PRD), and Sichuan–Chongqing (Chuan-Yu, CY) (See Table 7). Evidently, agglomeration economies generate a considerable impact on embodied energy flow systems; indeed, nearly all of them were at the forefront of importance indexes during the investigated period. YRD was undoubtedly the most important agglomeration, received the largest amount of embodied energy, andwas located at the most central position in the entire network with a wide range of connections to other regions. YRD, PRD, and BTH performed important roles in sustaining the embodied energy flow network of China. However, a growing trend in NTP and CY occurred in terms of their importance in the operation of the network based on their increasing values of betweenness and eigenvector centrality from 2007 to 2012.

According to the results, regional integration was reinforced between 2007 and 2012. Moreover, the spatially evenly distributed four clusterings shifted to a vertical distribution from north to south (See Fig. 3). It was further found that the formation of communities aggravated the toughness of regional competition and this leads to individual regions wavering between different communities over time (e.g., Hubei province). In fact, the noted evolution of the spatial pattern was a result of top-down administrative instructions that were focused, by central

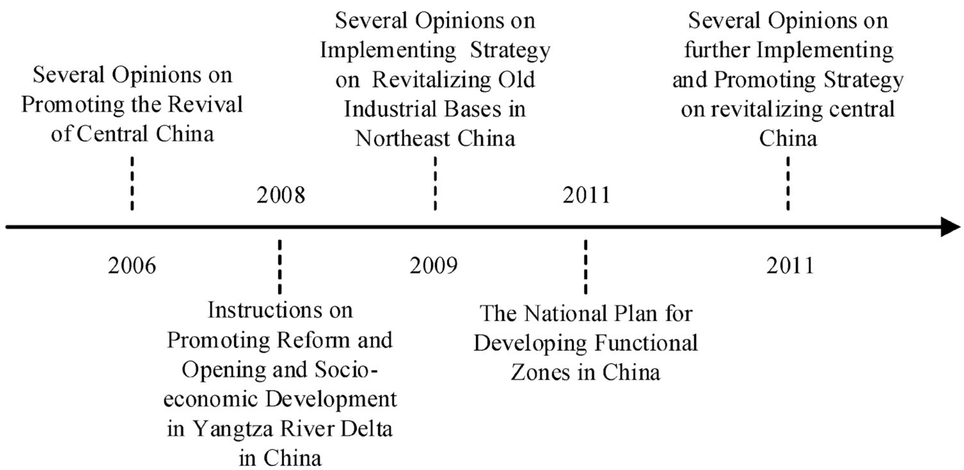


Fig. 5. Overview of national policies related to regional development from 2005 to 2012.

government, upon issues of regional coordination. To further link such spatial distribution changes to current policy practices, the national policies relevant to regional development promulgated between 2005 and 2012 were reviewed (See Fig. 5). Obviously, two policies, including the revival of the central area released in 2006 and the revival of the old industrial bases in the northeast area released in 2008, generated significant impact on the formation of community division in 2010, which caused the regional segmentation and connection taken place in the central and northern China. Thereafter, the national plan for developing functional zones which was initiated in 2011 has played a major role in region-building in 2012.

Despite the policy instruments initiated by central government, the implementation processes may be weakened by local authorities due to a lack of enforcement powers. Regional protectionism and administrative fragmentation can impede the fostering of functional economic linkages. Therefore, continuous administration-led efforts and mandatory political interventions for achieving regional integration are needed. On the one hand, economic unification can enhance the toughness of competition, and improve productivity efficiency (Melitz & Ottaviano, 2008). On the other, regional integration can advance knowledge exchange and experience sharing, and highlight industrial comparative advantages. All these advantages can be used to promote industrial specialization and improve resource allocation efficiency; each is a major driving force in moving forward productivity growth. Therefore, and considering the dominating role of vertical hierarchical control in the current Chinese administrative system, horizontal connections should be further enhanced to crystallize socioeconomic developments. Moreover, the evolution pattern of community divisions in SEEFN represents an explicit tendency for industrial specialization in which the whole economy has gradually become grouped into light industries, energy-intensive heavy industries, machinery manufacturing industries, and high value added service sectors. Generally, the process of industrial transfer and specialization may scarify local economic interests and establish invisible walls for regional integration (Li & Wu, 2018). Such regional protectionism may lead to industrial homogeneity and, through so doing, excessive competition and additional resource depletion. Therefore, regionally coordinated development is beneficial for industrial specialization. At the same time, the formation of crossregional economic connections to break administrative boundaries and fragmentation with due consideration being given to national and regional interests is important for achieving industrial specialization.

5. Conclusion

This study integrated the MRIO method and complex network theory to investigate the evolutionary pattern of REEFN and SEEFN in China's modern economy from a spatiotemporal perspective. The key findings of this study are as follows.

(1) The economic scale and trading frequency have increased in the REEFN, while sectoral energy connections remained stable from 2007 to 2012 with comparatively small changes being recorded in industrial structure and sectoral interrelationships nationwide.

(2) REEFN and SEEFN presented the small world nature, and demonstrated that several key regions and sectors in China's modern economy played vital roles in sustaining the operation of the entire embodied energy network.

(3) A temporal examination of REEFN uncovered that Guangdong (R19) was the most vital region for bridging the whole regional energy network and that it was located at the center of the network with regard to energy flow transfers. Furthermore, Jiangsu (R10) was vital in connecting and transferring energy flows in primary consumers, whereas Hebei (R3) was the key region that sustained the operation of the supply side of the network. Sectoral investigation uncovered the fact that infrastructure construction remained dominant in the current Chinese economy. It was also noted that the development of a service-oriented economy also emerged because of structural upgrading in China. The results of betweenness and eigenvector centrality imply that although the construction sector was not located in the center of network, it nevertheless possesses importance in connecting to sectors which have the most impacts on the network.

(4) Through undertaking regional community analysis, it was found that a split trend exists in the northern regions whilst there is a trend towards integration in the central areas. The

sectoral community analysis unveiled that there is an evident process of industrial differentiation and economic agglomeration in existence.

This study explored the changes in patterns and functions in the embodied energy flow system from a network perspective and, through so doing, provided a new angle by which to understand spatial heterogeneity and industrial structures in a time series manner. This initiative can, in turn, facilitate better policy-making for national energy conservation from a spatiotemporal perspective.

Acknowledgement

The authors wish to express their sincere gratitude to the Fundamental Research Funds for the Central Universities (No. 2017CDJSK03XK05), the Natural Science Foundation of China (Grant No. 71801023), Chongqing Science & Technology Commission (No. cstc2018jcyjAX0099), Humanities and Social Sciences Grant of Ministry of Education (No. 17YJCZH191), and the Research Grants Council of Hong Kong (No. 15276916) for funding this research project. Appreciation is also due to all members of the research team for their invaluable contributions.

Appendix A

Table A1

Regional division in MRIO table.

R1	Beijing

R2	Tianjin
R3	Hebei
R4	Shanxi
R5	Inner Mongolia
R6	Liaoning
R7	Jilin

R8 Heilongjiang

R9 Shanghai R10

Jiangsu

R11 Zhejiang R12

Anhui

R13	Fujian
R14	Jiangxi

R15 Shandong R16

Henan

R17	Hubei
R18	Hunan

R19 Guangdong R20

Guangxi

R21	Hainan

R22 Chongqing R23

Sichuan

R24	Guizhou
R25	Yunnan
R26	Shaanxi
R27	Gansu
R28	Qinghai
R29	Ningxia
R30	Xinjiang

Table A2

Sectoral division in MRIO table.

S1	Farming, forestry, animal husbandry and fishery
S2	Mining and washing of coal
S3	Extraction of petroleum and natural gas
S4	Mining and processing of metal ores
S5	Mining and processing of nonmetal ores
S6	Manufacture of foods and tobacco
S7	Manufacture of textile
S8	Manufacture of textile wearing apparel, footwear, caps, leather, furs, feather(down), and related products

S9	Processing of timber, manufacture of furniture
S10	Manufacture of paper, printing, manufacture of articles for culture, education, and sports activity
S11	Processing of petroleum, coking, processing of nuclear fuel
S12	Chemical industry
S13	Manufacture of non-metallic mineral products
S14	Smelting and pressing of metals
S15	Manufacture of metal products
S16	Manufacture of general and special purpose machinery
S17	Manufacture of transport equipment
S18	Manufacture of electrical machinery and equipment
S19	Manufacture of communication equipment, computers and other electronic equipment
S20	Manufacture of measuring instruments and machinery for culture activity and office work
S21	Other manufacturing

S22	Production and distribution of electric power and heat power
S23	Production and distribution of gas and water
S24	Construction
S25	Transportation, storage, posts and telecommunications
S26	Wholesale trade and retail trade
S27	Hotel and restaurants
S28	Tenancy and commercial services
S29	Research and experimental development
S30	Other services

References

An, H., Zhong, W., Chen, Y., Li, H., & Gao, X. (2014). Features and evolution of international crude oil trade relationships: A trading-based network analysis. *Energy, 74*, 254–259.

An, Q., An, H., Wang, L., Gao, X., & Lv, N. (2015). Analysis of embodied exergy flow between Chinese industries based on network theory. *Ecological Modelling, 318*, 26–35.

Barrat, A., Barthélemy, M., Pastorsatorras, R., & Vespignani, A. (2004). The architecture of complex weighted networks. *Proceedings of the National Academy of Sciences of the United States of America, 101*, 3747–3752.

Barrat, A., Barthélemy, M., & Vespignani, A. (2004). The architecture of complex weighted networks: Measurements and models. *Proceedings of the National Academy of Sciences of the United States of America, 101*, 3747–3752.

Blondel, V. D., Guillaume, J. L., Lambiotte, R., & Lefebvre, E. (2008). Fast unfolding of communities in large networks. *Journal of Statistical Mechanics, 2008*, 155–168.

Brandes, U. (2001). A faster algorithm for betweenness centrality. *The Journal of Mathematical Sociology, 25*, 163–177.

Chen, B., Li, J. S., Wu, X. F., Han, M. Y., Zeng, L., Li, Z., et al. (2018). Global energy flows embodied in international trade: A combination of environmentally extended input–Output analysis and complex network analysis. *Applied Energy, 210*, 98–107. Cui, L.-B., Peng, P., & Zhu, L. (2015). Embodied energy, export policy adjustment and China's sustainable development: A multi-regional input-output analysis. *Energy, 82*, 457–467.

Du, R., Dong, G., Tian, L., Wang, M., Fang, G., & Shao, S. (2016). Spatiotemporal dynamics and fitness analysis of global oil market: Based on complex network. *PloS One, 11* e0162362.

Du, R., Wang, Y., Dong, G., Tian, L., Liu, Y., Wang, M., et al. (2017). A complex network perspective on interrelations and evolution features of international oil trade, 2002–2013 ☆. *Applied Energy, 196*, 142–151.

Dunn, S., Wilkinson, S., & Ford, A. (2016). Spatial structure and evolution of infrastructure networks. *Sustainable Cities and Society, 27*, 23–31.

Fan, Y., Ren, S., Cai, H., & Cui, X. (2014). The state's role and position in international trade: A complex network perspective. *Economic Modelling, 39*, 71–81.

Gao, C. X., Su, B., Sun, M., Zhang, X. L., & Zhang, Z. H. (2018). Interprovincial transfer of embodied primary energy in China: A complex network approach. *Applied Energy, 215*, 792–807.

Geng, J. B., Ji, Q., & Fan, Y. (2014). A dynamic analysis on global natural gas trade network. *Applied Energy, 132*, 23–33.

Hao, X., An, H., Qi, H., & Gao, X. (2016). Evolution of the exergy flow network embodied in the global fossil energy trade: Based on complex network ☆. *Applied Energy, 162*, 1515–1522.

Holme, P., Park, S. M., Kim, B. J., & Edling, C. R. (2007). Korean university life in a network perspective: Dynamics of a large affiliation network. *Physica A Statistical Mechanics and Its Applications, 373*, 821–830.

Hong, J., Gu, J., Liang, X., Liu, G., & Qiping Shen, G. (2019). Characterizing embodied energy accounting with a multi-dimensional framework: A study of China's building sector. *Journal of Cleaner Production, 215*, 154–164.

Hong, J., Shen, G. Q., Li, C. Z., Liu, G., Wu, Z., & Zhong, X. (2018). An integrated framework for embodied energy quantification of buildings in China: A multi-regional perspective. *Resources, Conservation, and Recycling, 138*, 183–193.

Hong, J., Shen, G. Q., Guo, S., Xue, F., & Zheng, W. (2016). Energy use embodied in China′s construction industry: A multi-regional input–Output analysis. *Renewable and Sustainable Energy Reviews, 53*, 1303–1312.

Hong, J., Shen, Q., & Xue, F. (2016). A multi-regional structural path analysis of the energy supply chain in China's construction industry. *Energy Policy, 92*, 56–68.

Ji, Q., Zhang, H. Y., & Fan, Y. (2014). Identification of global oil trade patterns: An empirical research based on complex network theory. *Energy Conversion and Management, 85*, 856–865.

Kitamura, T., & Managi, S. (2017). Driving force and resistance: Network feature in oil trade. *Applied Energy, 208*, 361–375.

Lenzen, M. (2007). Structural path analysis of ecosystem networks. *Ecological Modelling, 200*, 334–342.

Li, Y., & Wu, F. (2018). Understanding city-regionalism in China: Regional cooperation in the Yangtze River Delta. *Regional Studies, 52*, 1–12.

Liu, Z., Geng, Y., Lindner, S., Zhao, H., Fujita, T., & Guan, D. (2012). Embodied energy use in China's industrial sectors. *Energy Policy, 49*, 751–758.

Liu, Z., Guan, D., Crawford-Brown, D., Zhang, Q., He, K., & Liu, J. (2013). A low-carbon road map for China. *Nature, 500*, 143.

Melitz, M. J., & Ottaviano, G. I. P. (2008). Market size, trade, and productivity. *The Review of Economic Studies, 75*(1), 295–316.

Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y.-M., et al. (2017). Chinese CO2 emission flows have reversed since the global financial crisis. *Nature Communications, 8*.

Shi, J., Li, H., Guan, J., Sun, X., Guan, Q., & Liu, X. (2017). Evolutionary features of global embodied energy flow between sectors: A complex network approach. *Energy, 140*, 395–405.

Shi, W., Zhou, W., Liu, Q., Ye, X., & Zhang, Y. (2014). The evolution of communities in the international oil trade network. *Physica A Statistical Mechanics and Its Applications, 413*, 42–52.

Su, B., & Ang, B. W. (2010). Input–Output analysis of CO2 emissions embodied in trade: The effects of spatial aggregation. *Ecological Economics, 70*, 10–18.

Su, B., & Ang, B. W. (2011). Multi-region input–Output analysis of CO2 emissions embodied in trade: The feedback effects. *Ecological Economics, 71*, 42–53.

Su, B., Huang, H. C., Ang, B. W., & Zhou, P. (2010). Input–Output analysis of CO2 emissions embodied in trade: The effects of sector aggregation. *Energy Economics, 32*, 166–175.

Sun, X., & An, H. (2018). Emergy network analysis of Chinese sectoral ecological sustainability. *Journal of Cleaner Production, 174*, 548–559.

Sun, X., An, H., Gao, X., Jia, X., & Liu, X. (2016). Indirect energy flow between industrial sectors in China: A complex network approach. *Energy, 94*, 195–205.

Tang, M., Hong, J., Liu, G., & Shen, G. Q. (2019). Exploring energy flows embodied in China's economy from the regional and sectoral perspectives via combination of multi-regional input–output analysis and a complex network approach. *Energy, 170*, 1191–1201.

Wang, M., Tian, L., & Du, R. (2016). Research on the interaction patterns among the global crude oil import dependency countries: A complex network approach. *Applied Energy, 180*, 779–791.

Yang, Y., Ng, S. T., Xu, F. J., & Skitmore, M. (2018). Towards sustainable and resilient high density cities through better integration of infrastructure networks. *Sustainable Cities and Society, 42*, 407–422.

Yang, Y., Poon, J. P. H., Liu, Y., & Bagchi-Sen, S. (2015). Small and flat worlds: A complex network analysis of international trade in crude oil. *Energy, 93*, 534–543.

Zhang, Y., & Qi, S. (2012). *China multi-regional input–Output models for 2002 and 2007.* Beijing, China: China Statistics Press.

Zhang, B., Chen, Z., Xia, X., Xu, X., & Chen, Y. (2013). The impact of domestic trade on China's regional energy uses: A multi-regional input–Output modeling. *Energy Policy, 63*, 1169–1181.

Zhang, B., Qiao, H., Chen, Z., & Chen, B. (2016). Growth in embodied energy transfers via China's domestic trade: Evidence from multi-regional input–Output analysis. *Applied Energy, 184*, 1093–1105.

Zhang, B., Qu, X., Meng, J., & Sun, X. (2017). Identifying primary energy requirements in structural path analysis: A case study of China 2012. *Applied Energy, 191*, 425–435.

Zhang, H. Y., Ji, Q., & Fan, Y. (2014). Competition, transmission and pattern evolution: A network analysis of global oil trade. *Energy Policy, 73*, 312–322.

Zhang, B., Qiao, H., & Chen, B. (2015). Embodied energy uses by China's four municipalities: A study based on multi-regional input-output model. *Ecological Modelling, 318*, 138–149.

Zhang, Y., Zheng, H., Yang, Z., Su, M., Liu, G., & Li, Y. (2015). Multi-regional input–output model and ecological network analysis for regional embodied energy accounting in China. *Energy Policy, 86*, 651–663.

Zhong, W., An, H., Shen, L., Fang, W., Gao, X., & Dong, D. (2017). The roles of countries in the international fossil fuel trade: An emergy and network analysis. *Energy Policy, 100*, 365–376.

Zhou, M., Wu, G., & Xu, H. (2016). Structure and formation of top networks in international trade, 2001-2010. *Social Networks, 44*, 9–21.