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Spatiotemporal investigation of energy network patterns of agglomeration economies in China: Province-level evidence

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Abstract

China is currently in the fast track of urbanization and industrialization. This poses a series of challenges pertaining to environmental issues given the resultant boom in energy consumption and carbon emissions. To tackle these problems, this study explores the effects of economic agglomerations and geographic attributes on energy transmission patterns using multi-regional input-output model, complex network analysis, and exploratory spatial data analysis. The results show that Shandong, Jiangsu, and Zhejiang are the three leading regions with regard embodied energy consumption; they have distinct energy utilization models but can also provide instructive lessons for energy conservation at the provincial level. Energy interactions represent self-organizing agglomerative patterns, and the physical geographic clusters are highly consistent with the virtual administrative division of agglomeration economies. The in-depth investigation of major agglomerations has revealed that infrastructure construction remains a vital driver of local economies in developing areas, whereas more developed agglomeration economies have more balanced and service-oriented development. Bilateral connections in current major agglomeration economies have been enhanced, but multilateral connections are still rare. The findings of this study provide a bottom-up insight into the spatiotemporal effect on embodied energy system of China.

1. Introduction

China is currently in the fast track of urbanization and industrialization, which poses a longstanding challenge on environmental issues given the resultant boom in energy consumption and carbon emissions. The BP statistical review of world energy in 2018 revealed that China's primary energy consumption in 2013 accounted for 23.2% of global energy use; urban areas consumed more than 80% of the total [1].

Rapid urbanization has led to a threefold increase in the number of cities [2] along with the gradual emergence of urban agglomerations. Undoubtedly, the appearance of dynamic urban agglomerations is the result of agglomeration economies, which are the most active areas for economic activities and thus enhance geospatial connections and interactions [3]. As a result, agglomeration economies have become not only the engines of the national economy but also the drivers of adverse environment impacts, which has led to high environmental loads and extensive energy consumption. Several studies have explored the adverse environmental impacts of metropolitan areas that have arisen with the global agglomeration economy, including the energy history of Melbourne in Australia [4], the ecological footprint of Metro Vancouver in Canada [5], and Narragansett Bay in the United States [6]. In China, an increasing amount of research has focused on the energy, water, waste, and carbon aspects of agglomeration economies using various methodologies. These empirical studies cover most of the Chinese influential agglomerations that generate substantial impacts on the national economy, including JingeJineJi or BeijingeTianjineHebei (BTH) [7e10], SueXieChang [11], the Pearl River Delta (PRD) [12], and the Yangtze River Delta (YRD) [13,14]. In general, the noted increasing concern towards economic agglomerations implies that there has been a remarkable and growing role of urban agglomerations in environmental and climate issues.

China has promised to reduce its carbon emissions per unit of GDP by 60%e65% based on the 2005 levels reported in the United Nations Climate Change Conference in Paris (COP 21). Against this backdrop, the State Council of China has released a working plan for energy conservation and emission reduction for the 13th Five-Year Plan period. This plan targets the reduction of energy intensity per unit of GDP by 15% in 2020 against the 2015 level, with the total amount of energy being lower than 5 billion tons of coal equivalent. It follows, that appropriate scales and regional units are needed to bridge the top-down energy conservation target system between central government and local authorities in China; urban agglomerations should take more responsibility in reducing energy through industrial structure upgrading and advanced technology promotion.

Embodied energy, as an indicator describing virtual resource utilization, is the sum of direct and indirect energy used in the entire production process. The measurement of indirect energy consumption allows for the quantification of the by-product effects induced by the upstream supply chains of an economy. Several studies have demonstrated that indirect effects induced by iterations of trading processes are significant in China's modern economy [15,16]. Therefore, an embodied energy quantification can provide a holistic and fair insight into the real role and status of actors who should take responsibility for energy conservation.

As a burgeoning area of research, the characteristics of embodied energy consumption in the operation of economies has thus far been extensively studied at the global, national, and regional levels. Global studies have primarily explored international energy flows based on multilateral trading processes [17,18]. National scale investigations have emphasized industrial roles and their linkages to total embodied energy consumption [19,20], whilst Provincial level studies have included inter-provincial comparison by using multi-regional inputeoutput techniques [21,22], and intra-provincial investigations by using the energy metabolism method [23e25]. At the urban level, an extensive literature has explored the consumption mechanisms of embodied energy at different urban scales [26,27], as well as the different economic features that exist [28e30]. However, most research has been conducted on the basis of independent administrative divisions without considering the effect of geographical proximity on economic and industrial agglomerative structures. Studies that systematically consider the joint effects of geographic spatial distribution and industrial interactions on embodied energy consumption from an agglomerative economic perspective are comparatively rare [31]. In particular, the temporal comparison of intra- and inter-regional industrial linkages in terms of embodied energy consumption patterns of major agglomeration economies in China are scarce [7,9].

As urbanization accelerates, the role of agglomeration economies in determining the effectiveness of energy reduction becomes much more significant. Identifying the characteristics of industrial structure and the spatial connections of different agglomeration economies and effectively managing their embodied energy consumption has become urgent in terms of national level energy conservation. The review of prior research has revealed that certain issues must be addressed. First, given the broad terrestrial area and imbalanced socioeconomic development in China, examining the effect of agglomeration economies on embodied energy consumption from the perspective of spatial interaction is crucial. A comprehensive understanding of intra-regional industrial connections and cross-regional trade linkages is essential for adopting joint actions for alleviating inherent energy consumption burdens [12,32]. Second, identifying the self-organizing agglomerative patterns of industrial interactions and the spatial distributions of embodied energy fluxes is vital for optimizing energy transition processes and achieving the national five-year energy conservation target. Third, given the lag effect of top-down policy implementation, the time-series changes of industrial patterns on embodied energy consumption at the agglomeration scale should be investigated in detail to provide fundamental evidence and reference for decision making.

To tackle the abovementioned problems, this study first quantifies embodied energy flows at the provincial level by using MRIO techniques as these can differentiate the effects of regional disparities and technological differences on environmental interactions [18,33]. Then, community analysis is conducted on the basis of the spatial interactions of embodied energy consumption in the Chinese economy. Through so doing, the paper identifies the effects of agglomeration economies on energy transmissions from a bottom-up perspective by combining province-based statistical data. More importantly, and to further analyze agglomerative patterns based on embodied energy consumption, the geographic proximities of provinces are considered as weights of embodied energy flows for exploratory spatial data analysis (ESDA) to detect self-organizing patterns of spatial autocorrelation and heterogeneity. Subsequently, five major agglomeration economies, namely, the Beijing-Tianjin-Hebei (BTH), Liaoning-Jilin-Heilongjiang (LJH),

Pearl River Delta (PRD), Yangtze River Delta (YRD), and SichuaneChongqing (SY), are extracted and analyzed simultaneously to provide insights into the temporal effects of agglomeration on intra-regional industrial structure and cross-regional energy connections.

This study innovatively analyzes the agglomerative patterns of embodied energy consumption by detecting the spatial autocorrelation and heterogeneity from a self-organizing perspective. This, in turn, expands existing knowledge in a number of ways, Theoretically, the findings of this study can fill gaps in existent understanding of spatiotemporal variations of embodied energy consumption in the Chinese economy. In particular, the combination of the MRIO model, the complex network method, and the exploratory spatial data analysis provides a visualized technique to systematically analyze the effects of agglomeration economies on patterns of spatial heterogeneity and autocorrelation by using province-level data. Practically, the understanding of the spatiotemporal effects of interregional energy flow networks, and particularly the changing patterns of neighboring clusters, can facilitate stratified and fair policy implementations in energy conservation with due consideration of multi-scale control methods.

The remainder of this paper is organized as follows. Section 2 presents the methodology, including MRIO and ESDA. Section 3 introduces basic information on the target agglomeration economies. Section 4 presents the results from the aspects of energy quantification, community distribution, industrial structure investigation, and spatial correlation. Section 5 presents the discussion. Section 6 concludes the paper.

2. Methodology

2.1. MRIO method

According to the MRIO model, the basic equilibrium of monetary flows can be expressed as

$$X = (I - A)^{-1}V; \qquad (1)$$

where X is the total production vector, A is the intermediate coefficient matrix representing the monetary transaction per unit of products, V is the vector indicating the monetary value of total final use, and I is the identity matrix.

To link monetary transactions with environmental interactions, an environmental intervention vector (e.g., direct energy intensity in this study) $Q_{1(mn)}$ can be defined as

$$Q = C \cdot \hat{X}^{-1}; \qquad (2)$$

where C is the direct energy consumption vector obtained from statistical yearbooks.

Consequently, the vector embodied energy intensity E can be calculated as

E ¼ QðI AÞ^{1}: (3)

Therefore, the amount of embodied energy flow can be expressed as

F ¼ EAb Xb: (4)

2.2. Construction of embodied energy network

According to Equation (4), matrix F can be determined by a directed weighted network, which can derive the embodied energy interactions of sectors and regions. The network can be expressed by the set:

G ¼ ðN;PÞ; (5)

where G represents the embodied energy network. The node set is

N ¼ frk , wherenri g, wherepijrk nis the weighted directed edge connecting noteri is the sector i in province r. The edge set is P n¼ri tofpnijk$_j$g. If f ijrk > 0, then prkij ¼ 1 and its weight is equal to f rkij ; otherwise, prk$_{ij}$ ¼ 0.

Consequently, the weighted degree can be expressed as Equation (6), which is regarded as the key variable that determines the spatial association in the embodied energy flow system.

Dir ¼pf iri ¼ ⱣPpfinin þþ ^{P}Ᵽ fpoutout ¼ ⱣPrrⱣPiipijrkij þ$_þ$ ^{P}Ᵽkk^{P}Ᵽjjpf ijrkrkij ; (6) r f rk

where D^r_i is the weighted degree of sector i in province r representing the embodied energy connectivity of node n^r_i ; f^r_i is the amount of embodied energy flows connected to sector i in province r, including inflow and outflow; and p^r_i is the number of embodied energy flows connected to sector i in province r, including indegree and out-degree.

2.3. Community analysis

Community analysis is an approach to deconstruct the network G. The identification of communities is crucial, as it can help to uncover unknown functional modules. Nodes are comparatively homogeneous within communities but heterogeneous between communities. In the context of agglomeration economies, this community structure reflects regional agglomerative structures which generally comprise self-organized sectors in regions to optimize performance or productivity in collaborations.

The community analysis in this study is based on the iterative algorithm developed by Blondel and Guillaume [34]. First, different communities are assigned to each node of embodied energy network G with N nodes, in which N communities exist in the initial stage. Each node i is connected to node j. The gain is evaluated as DQ in Equation (7) by placing node i into community C that contains node j. Accordingly, the gain from the removal of node i from community C can be evaluated by a formula similar to Equation (7). In practice, removing i from its community and placing it into a neighboring community happens only if the change of the gain is positive. This process is applied repeatedly and sequentially for all nodes until no further improvement can be achieved. DQ ¼"PPP̶ðP$_2$ÞþPP$_D$ CðP^{i}Þi #P D$_2$^{C}Pþ$_D$P D^{i2}# "P$_2$ P̶CðDPÞ C

2 DC 2PP̶$_D$; (7) D 2 D ^{2}

where P CðPÞ is the sum of the weighted edges insideP $_i$ P P i C, P D$_C$ is the sum of the weighted degree of nodes in C, D is the sum of the weighted degree of node i, CðP Þ is the sum of the weighted edges between node i to nodes in C, and D is the sum of the weighted degree in network G.

2.4. Exploratory spatial data analysis

According to growth pole theory, regions can be considered to be spatially low-value clusters or random distributions until growth poles emerge. The polarization effects of growth poles initially dominate to form a coreeoutlier spatial structure. Then, the effects of spreading gradually become strong and drive neighboring areas to flourish, thereby forming a high-value clustering spatial pattern.

To detect and visualize spatial distributive patterns, this study uses exploratory spatial analyses, including the global Moran's I statistical analysis and the local indicators of spatial autocorrelation (LISA).

2.4.1. Global spatial autocorrelation

Global Moran's I is utilized in this study to detect the spatial correlation of energy transactions of different regions. We use D^r, which is the weighted degree of province r induced by the complex networkfl G (r2½1;n), as the variable of interest to comprehensively re ect the strength and breadth of the connections in each province in the embodied energy flow system. Consequently, a holistic map of the spatial correlations was produced. Global Moran's I can be calculated as

I ¼ nPPnr¼rn¼11PPknkn¼¼11wwrkrkPDrrn¼1DDr DkD2D ; r (8)

where I represents the value of global Moran's I; D is the sum of the

weighted degree of the nodes in region r; $\bar{D}$ is the mean of the weighted degree of a region; w_{rk} is the spatial weight between region r and region k; w_{rk} ¼ 1 when region r and region k share edges geographically, and w_{rk} ¼ 0 otherwise; and n is the total number of regions, which equates to 30 in our case.

For the result of the global Moran I analysis, a Z-test is used to examine the significance of spatial correlation. For statistically significant z-scores, a positive Moran's I index value indicates a tendency toward clustering, whereas a negative value suggests a tendency toward dispersion.

The equation for the Z-test can be expressed as

Z ¼ IþV^{E}ðð$_{I}^{I}$Þffiffi Þ; (9) 1 ; (10)

EðIÞ ¼ n 1

VðIÞ ¼ EI^{2} EðIÞ^{2}; (11)

where the Z value represents the multiple of the standard deviation.

2.4.2. Local indicators of spatial association

To capture the local patterns of spatial association, LISA statistics serve as indicators of local pockets of non-stationarity which assess the influence of individual locations on the magnitude of the global statistic and identify "cores" and "outliers" [35]. A positive value of I_r for region r indicates a clustering pattern with high or low value, while a negative value for I_r suggests a coreeoutlier pattern. In either instance, the significance of the cluster or outlier is tested by using the Z_{Ir} -score.

For the embodied energy network G, the local Moran's I_r statistics of spatial association for region r is given as:

Ir ¼ ðn 1ÞPDrnk¼1;DksPrwkn rk¼1;Dksk rwDrk2Dk D : (12)

Similarly, the Z_{Ir} -score for the statistics is computed as

ZIr ¼ rþVðIrrÞffiÞ; (13) I E I

where

EðIrÞ ¼ Pk¼n1;ks1rwrk ; n (14)

VðIrÞ ¼ EI_i^2 $EðI_iÞ^2$: (15)

Four spatial association forms are described in the LISA cluster map (Table 1).

2.5. Data collection and consolidation

To explore the spatiotemporal variations and patterns of embodied energy consumption in the Chinese economy, MRIO tables were collected as a time series. The MRIO tables in 2007, 2010, and 2012 were collected from the Chinese Academy of Sciences [36]. The MRIO table 2007 and 2010 contain monetary flow information of 30 regions (22 provinces, four autonomous regions, and four municipalities) with 30 sectors in each region (Appendix A, Table A1 and A2), while the MRIO table for 2012 adds the sectoral information of Tibet and changes the sectoral scale from 30 sectors to 42 sectors in each region. Therefore, some integrations are conducted to make MRIO tables consistent with each other. The sectoral direct energy consumption data were mainly collected from the provincial energy balance tables of the Chinese energy

Table 1

	Implication
HigheHigh (HH)	Positive association, indicating that regions with high values are surrounded by other regions with high values
LoweLow (LL)	Positive association, indicating that regions with low values are surrounded by other regions with low values
HigheLow (HL)	Negative association, indicating that regions with high values are surrounded by regions with low values
LoweHigh (LH)	Negative association, indicating that regions with low values are surrounded by regions with high values

Types of local spatial correlation.

statistical yearbook. To remove the effects of price fluctuations from the computation, the monetary flows in the MRIO tables were all converted into 2007 constant prices by using a GDP deflator. To bridge the data from the MRIO tables and the sectoral direct energy inputs, aggregation and disaggregation were performed for the sectoral energy statistics with the assumption that sub-sectoral energy consumption is proportional to economic output.

3. Study area

This study first captures the spatiotemporal variations of embodied energy consumption in China at the provincial level by using the MRIO technique. Then, the characteristics of industrial linkage and spatial distribution of major agglomeration economies are explored. The selection criteria are as follows. First, the selected area should generate a substantial impact on the national economy. Second, the target agglomerations should comprise a group of provinces which can be investigated through province-level data. Consequently, five major agglomeration economies were selected; LiaoningeJilineHeilongjiang (Northeastern China, LJH), BeijingeTianjineHebei (JingeJineJi, BTH), ShanghaieJiangsueZhejiang (Yangtze River Delta, YRD), Guangdong (Pearl River Delta, PRD), and SichuaneChongqing (ChuaneYu, CY). Table 2 shows the basic profile of the selected agglomerations.

Although these five agglomerations only account for one-third of the number of prefecture cities and less than 20% of the total national land area, they constitute more than half of the national total GDP and approximately 40% of the population in 2016. In fact, these five agglomerations are leading areas experiencing fruitful outcomes from the Reform and Opening Up policy in China, which have received abundant natural and capital resources with particular supportive policies for further development. Therefore, the selected five agglomerations are socio-economic centers and can be considered representative of the current Chinese economy.

4. Results

4.1. Province-level embodied energy quantification

Table 2

Basic profile of five agglomeration economies.

	Prefecture-level cities		Land area		GDP		Population	
	No.	Percentage (%)	10^4 sq.km	Percentage (%)	Trillion Yuan	Percentage (%)	10^8 Person	Percentage (%)
LJH	34	10.2	78.7	8.2	5.2	7.0	1.09	7.9
BTH	13	3.9	21.5	2.2	7.5	10.1	1.10	8.0
YRD	26	7.8	21.2	2.2	14.7	19.8	1.50	10.9
PRD	14	4.2	5.5	0.6	7.3	9.8	0.59	4.3
CY	16	4.8	24.0	2.5	4.8	6.5	0.98	7.2
China	334	100	963.4	100	74.4	100	13.70	100

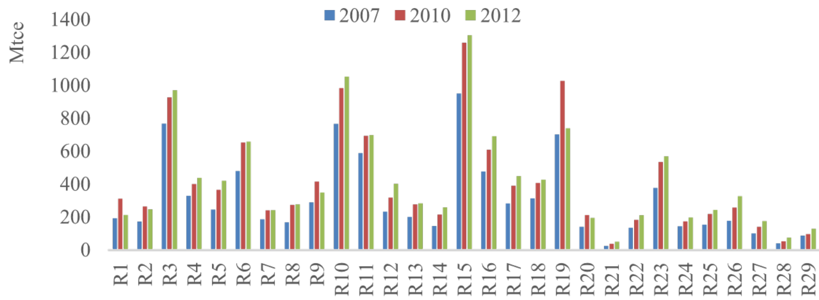


Fig. 1. Province-level embodied energy consumption from 2007 to 2012.

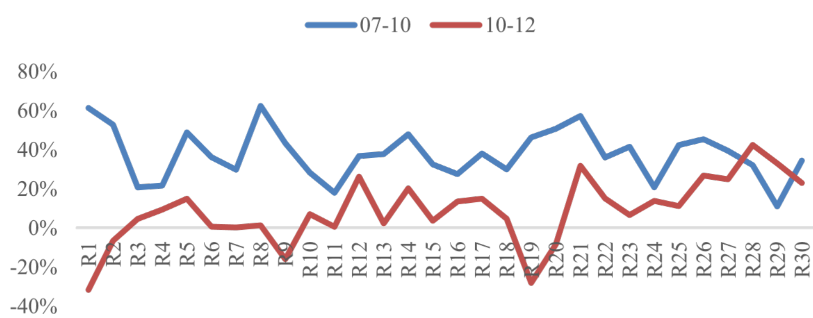


Fig. 2. changes of province-level embodied energy consumption.

Fig. 1 shows the trajectory of embodied energy consumption at the provincial level from 2007 to 2012. An increasing trend of embodied energy consumption is evident given the continued growth of the national economy. In particular, Shandong (R15), Jiangsu (R10), Hebei (R3), and Guangdong (R19) were the four leading regions with the largest embodied energy consumptions. Fig. 2, which summarizes the percentage change in the volume of embodied energy consumption at different time intervals, is presented to further illustrate temporal variations. Most provinces experienced comparatively high increase rates of approximately 40% from 2007 to 2012, with only three exceptions. The rapid growth of embodied energy utilization in Beijing (R1) from 2007 to 2010 sharply declined with an increase rate of 31.6% from 2010 to 2012. Furthermore, Shanghai (R9) and Guangdong (R19) experienced negative growth (e.g., 16.0% and 28.1%) in 2012 compared with incremental increase in energy use from 2007 to 2010. This was mainly because the time interval between 2010 and 2012 was the starting point of the 12th Five-Year Plan, during which regional authorities made concrete efforts to exceed the normal reduction targets in advance, thereby alleviating possible challenges and pressures that might hamper their achievement of specific targets. Such ambitious actions led to relatively high energy conservation at the provincial level. For instance, by reviewing the specific targets initiated at the beginning of the 12th Five-Year Plan (Table 3), it can be seen that the local governments of Beijing (R1), Shanghai (R9), and Guangdong (R19) became more aggressive in terms of renewable energy improvements, CO_2 emission reduction, and energy intensity reduction. This focused target setting further reinforced the short-term energy performances of these regions.

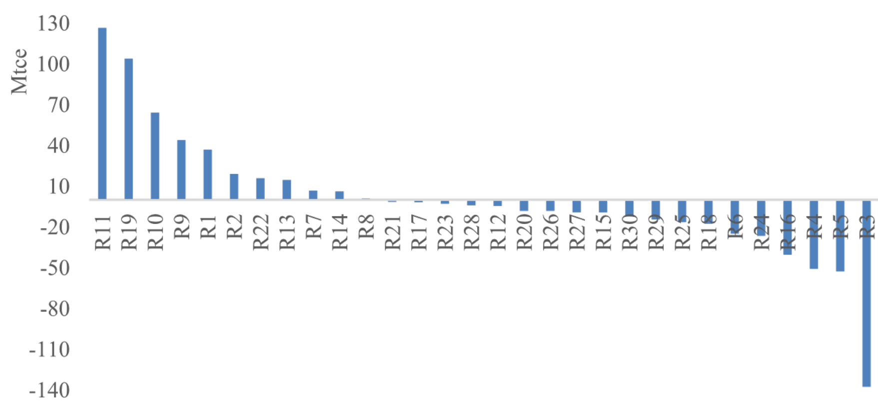
Fig. 3 presents the net inter-regional transactions of China's economy from 2007 to 2012. These regions had increasing trends for both the amount of imported energy and the number of energy receivers. These findings are related to the increasing strength and frequency of trading in these different regions. In general, Zhejiang (R11), Guangdong (R19), and Jiangsu (R10) were the leading regions in energy imports with net energy inflows of more than 100 million tones of coal equivalent (Mtce), followed by Beijing (R1) and Shanghai (R9) with net energy inflows of nearly 50 Mtce. Most energy receivers were located in coastal areas with comparatively

Table 3

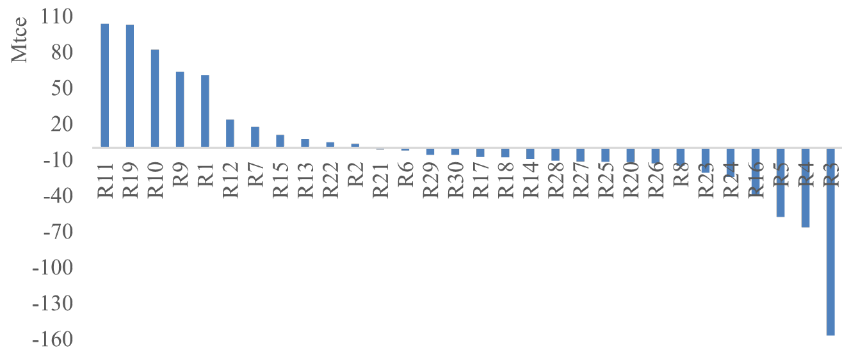
Province-level targets in the 12th Five-Year Plan.

	Ratio of non-fossil energy to total energy use (%)	Reduction rate of CO2 emissions[d] (%)	Reduction rate of energy consumption per GDP per capita[d] (%)
Beijing (R1)	6.1[a]	18	17
Shanghai (R10)	12[b]	19	18
Guangdong (R19)	20[c]	19.5	18
National	11.9	17	16

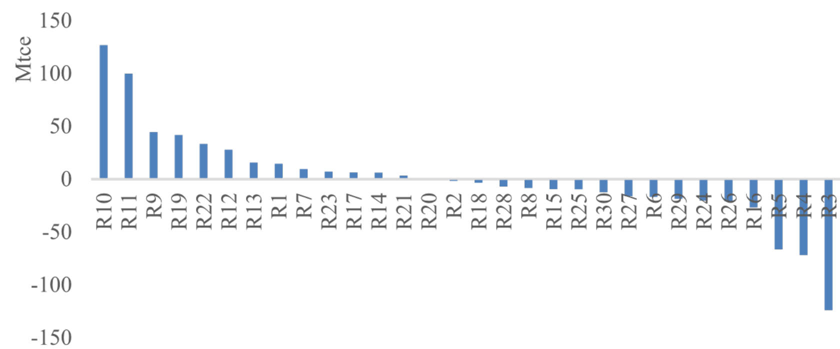
Sources: "a" 12th Five-Year Plan for the energy development and construction of Beijing; "b" 12th Five-Year Plan for the national economy and social development of Shanghai; "c" 12th Five-Year Plan for the energy development of Guangdong; and "d" 12th Five-Year action plan for energy conservation and emission reduction.



2007



2010



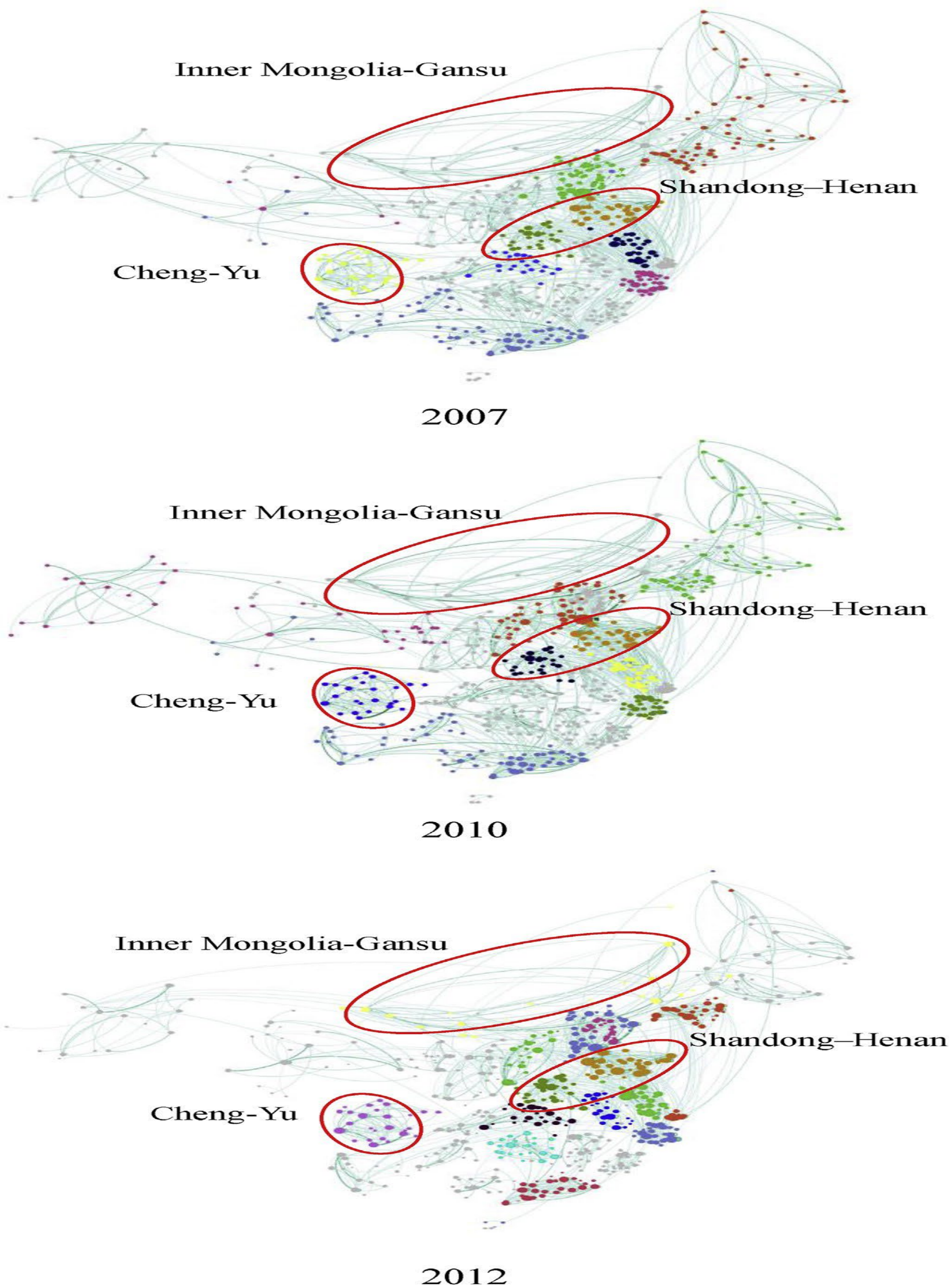
2012

Fig. 3. Net inter-regional transactions of China's economy from 2007 to 2012.

high economic levels. Their extensive participation in economic globalization generated intense energy demands and their need to import energy from foreign regions. In contrast, Hebei (R3) was the largest net embodied energy exporter, followed by Inner Mongolia (R5) and Shanxi (R4). These are all resource-abundant provinces, being rich in crude oil, raw coal, and metallic minerals [39]. Gao, Su [38] conducted similar research but they focused on regional total energy exports and imports. In their results, Guangdong, Jiangsu, Hebei, Beijing, Tianjin, and Shanghai were top importers whilst Jiangsu, Shandong, Hebei, Inner Mongolia, and Henan were leading importers. Given that the present study concentrated on net energy transactions, it can be seen that the results were in line with each other. Therefore, optimizing energy structures and alleviating the overspending of primary energy in resource-abundant provinces can effectively promote clean production nationwide.

4.2. Community analysis and path characteristics

Fig. 4 shows the results of the community analysis. Nodes with the same color imply that there is significant correlation of embodied energy fluxes. China can be divided into nine groups based on energy interaction. The first five groups are highly consistent with the national major agglomerations (Table 4). The proportions shown in the last three columns in Table 4 indicate



trading strengths in the national inter-regional relationship of energy flows. The trading processes of PRD, YRD, LJH, and BTH were the most active and together accounted for approximately half of the total national intermediate energy consumption. However, a declining trend can be observed in terms of the bridging role of agglomerations in China's embodied energy system. For instance, the proportions of intermediate energy use of BTH and LJH fell by 23.8% and 11.0%, respectively, from 2007 to 2012. On the one hand, this reduction was the result of the slight slowdown of the economic growth rate of China, whereby the GDP growth rate decreased from 14.2% in 2007 to 7.9% in 2012. On the other hand, it also reflected a broad change of energy interaction patterns. For instance, Inner Mongolia (R5) and Gansu (R27) were two clusters which were found to be significant in their inner sectoral energy connections in 2007 and 2010; then they gradually mutually interacted in 2012. Henan (R16) and Shandong (R15) functioned independently in terms of their spatial relationships with intermediate energy use during the entire investigated period. The CY area was comparatively insulated from other regions in 2007 and 2010 but established multiple connections with Guangdong (R19) and Guangxi (R20) provinces in 2012. Gao, Su [38] investigated interprovincial primary energy transfers and demonstrated similar regional divisions. According to their results, several agglomerations (e.g., LJH, BHT, YRD, and PRD) in primary energy transfer system were detected; and Shandong and Henan were found to be comparatively insulated with other regions. In summary, the results of community analysis can represent the self-organizing agglomerative patterns of energy interactions, and they were inclined to show the self-adaptive relationship between industrial structure and geographical proximity. In addition, energy interactions are, to a large extent, driven by national growth. Therefore, to explore how trends in GDP affect different clusters, this study summarized the GDP proportion of each cluster in Table 4. It is evident that GDP temporal changes were highly consistent with the trading strengths of each cluster. For instance, the change of trading strengths in YRD, PRD, and Shandong were a consequence of proportional changes in regional GDP. It is noteworthy that despite the slightly increasing trend of GDP proportion, the trading strength of CY and LJH was continuously decreased. In other words, CY and LJH obtained environmental benefits from structural upgrading and efficiency improvement from 2007 to 2012.

With respect to path characteristics, the strength of the energy path in 2012 was more intensive than in 2007. The number of paths increased in eastern coastal areas. The dense spatial connections implied enhanced regional connections in the most concentrated and developed areas of economic activities in China. Moreover, relative to the separated distribution of energy clusters in 2007 and 2010, the energy paths in 2012 suggested improved cross-regional connections, particularly in terms of multi-regional linkages which can overcome barriers of regional restriction and local protectionism.

4.3. Geographic attributes

Table 5, which presents the results of the global Moran's I index for the investigated period, was further analyzed to detect spatial correlations between regional embodied energy distribution. The Moran's I index from the spatial autoregressive model was used to interpret the spatial autocorrelation of the dependent variable. The value of Moran's I index ranged from 0.2347 to 0.3000 at the significance level of 1% for all years. This indicated a significant positive spatial interdependence in terms of province-level outflow and

Fig. 4. Clustering analysis visualization maps. inflow energy strengths.

Thus, when the geographical neighborhood effect is considered, the results can provide concrete evidence of the spatial agglomeration of embodied energy flows according to

Table 4

Group division of community analysis.

	Province	GDP proportion			Energy proportion		
		2007	2010	2012	2007	2010	2012
LJH	Liaoning (R6), Jilin (R7), Heilongjiang (R8)	9.4	9.3	9.7	10.0	9.7	8.9
BTH	Beijing (R1), Tianjin (R2), Hebei (R3), Part of Shanxi (R4)	11.3	10.9	11.1	10.5	7.7	7.5
YRD	Jiangsu (R10)	10.3	10.3	10.4	4.5	4.5	4.4
	Zhejiang (R11)	7.5	6.9	6.7	5.6	4.3	4.3
PRD	Guangdong (R19), Guangxi (R20), Yunnan (R25)	16.7	15.6	15.5	13.1	11.7	11.5
CY	Chongqing (R22), Sichuan (R23)	5.9	6.3	6.8	4.9	4.3	4.4
Others	Shandong (R15)	10.4	9.8	9.6	4.9	4.9	4.2
	Henan (R16)	6.0	5.8	5.7	4.5	4.5	4.4
	Qinghai (R28), Ningxia (R29), Xinjiang (R30)	3.2	3.1	3.4	6.2	6.3	6.0

Note: The exact percentage is unavailable given that the regional integration process occurred in 2012.

Table 5

Results of Moran's I index.

	2007	2010	2012
Moran's I	0.2347	0.3000	0.2942
Z value	2.4885	3.1923	2.4139
P value	0.0128	0.0014	0.0079

similar status and nature.

The results of the global Moran's I index may, to an extent, overshadow partial instability. Considering the unbalanced regional development of China, the LISA cluster map was utilized for spatial statistical analysis to further measure the spatial correlation between each region and its neighboring areas. Relative to the global Moran's I index, the LISA cluster map identified the type of spatial association that is formed between regional units and their neighbors.

Fig. 5 shows a set of LISA cluster maps which represent the spatial autocorrelation of regional energy out-degree and in-degree strengths at provincial level in 2007, 2010, and 2012. Different value ranges with the same color represent variations in confidence levels. The embodied energy transactions showed significant spatial agglomerations for nearly half of the provinces grouped into HH, HL, LH, and LL categories. The spatial distribution of energy transactions was unbalanced, which indicated an obvious regional inequality in the energy transaction system of China. Provinces in the HH and HL categories were mainly located in eastern coastal areas. In contrast, those provinces in the LH and LL categories tended to be concentrated in the northwest area. However, the spatial dependence of degree strength was insignificant in the northeastern area and in most parts of the central area. The results were highly consistent with the spatial correlation of emissions investigated by Jiang and Ji [40], where the LISA cluster map showed similar distributions. The regions with HH and HL status were Jiangsu, Anhui, and Shandong; located in the eastern area, whereas the regions labelled with LH and LL categories were concentrated in Gansu and Xinjiang, which were part of northwest China.

From a temporal perspective, the spatial agglomeration was consistent across different years without significant status changes; as represented by the sequence of values from eastern to western regions. In particular, southern China exhibited insignificant spatial agglomerations in 2007 but gradually entered the HL categories in 2010 and 2012. Furthermore, although no significant status changes occurred nationwide, the confidence levels varied for different areas. In general, the confidence levels of the northwestern areas indicated a distinct declining trend; this is consistent with the backward nature of the economies of these regions. In contrast, the confidence levels of Hebei (R3) and Henan (R16) improved from 90% to 95% in the HH category. In fact, given the effect of regional integration and agglomeration, the spatial linkages of the two regions were further enhanced. However, Anhui (R13), a neighboring province of the regions in the eastern coastal area (i.e., these regions are in the HH category), was categorized under LH, which indicated the failure of Anhui to participate in regional coordination development. Furthermore, this spatial characteristic became much more significant when the confidence interval was increased from 95% to 99% in 2012; implying that the regional gap has widened over time.

4.4. Industrial structural analysis of major agglomeration economies

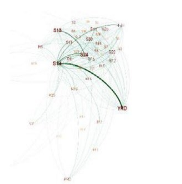
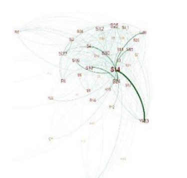
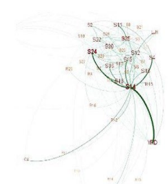
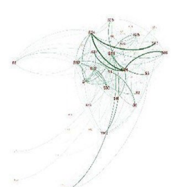
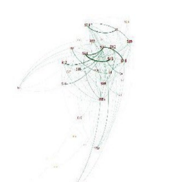
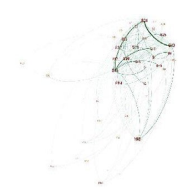
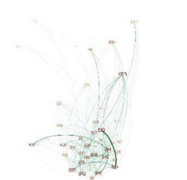
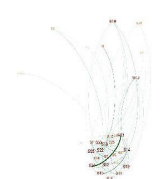
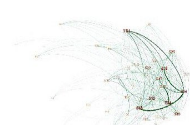
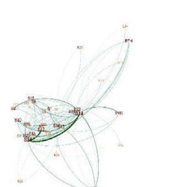
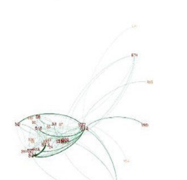
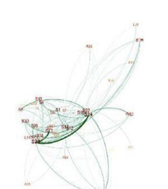
Table 6 summarizes the industrial energy transaction patterns of the major agglomeration economies (Please see supplementary file for high-resolution pictures). The embodied energy network of BTH was complicated by a large number of significant inflows and outflows. BTH experienced a closer relationship with YRD than the other agglomerations. This closeness is a possible consequence of the development of Beijing-Shanghai High-Speed Railway which has an annual passenger capacity of nearly 100 million. Easier accessibility to traffic networks greatly stimulates bilateral trading between agglomerations. The industrial energy linkage in the BTH area was comparatively balanced in terms of distribution and covered nearly the entire local economy without structural bias. Therefore, the energy consumption pattern of the BTH area was a result of the joint contributions of different industries in the entire economy rather than infrastructure-driven developments. This is mainly because BTH is the political center with highly developed economy, where the tertiary industry accounts for more than 60% of total regional GDP. Against this backdrop, the construction sector played a limited role in the regional energy transaction system compared to other sectors. This balanced economic structure can facilitate sustainable and rational economic growth.

LJH was strongly linked with the BTH cluster but had a weak relationship with the PRD area owing to spatial closeness and the urban gravity effect. S14 (smelting and pressing of metals) and S13 (manufacturing of non-metallic mineral products) played a dominant role and occupied a central position in the industrial energy flow system in the LJH area. This may have arisen due to the fact that LJH area is a traditional old industrial base area. The mineral reserves in this area are abundant, and it provides raw materials for industrial development nationwide. For instance, the crude oil supplied by the northeast of China accounts for approximately 40% of the total national amount. To mitigate energy-intensive production processes and achieve supply-side structural reform, the central government released a series of development programs to shift old growth drivers to new ones. With the continuous emphasis on reducing industrial overcapacity and restricting the mining of mineral resources, the amount of energy flows to manufacturing industries sharply declined in 2010 and 2012.

As an area with one of the most active economies, PRD had the most sectors with significant energy inflows and outflows. PRD is a pioneer of China's reform and opening up policy, thus being capable of gaining economic and technical advantages compared with other counterparts. The central government's Outline Development Plan for the Guangdong-Hong Kong-Macao Greater Bay Area is designed to further reinforce the growth-pole-effect of PRD for the national economy. Moreover, PRD is a centrally positioned region in the

Table 6

Industrial structural analysis of major urban agglomerations.

	2007	2010	2012
BTH			
LJH			
PRD			
YRD			
CY			

national economy that has established multiple connections with other agglomerations. According to Ref. [41], Guangdong (R19) is the most critical bridge in China's energy flow network and has tied relationships with other provinces. Therefore, any disturbance or interruption in the energy network of PRD may generate substantial impacts on energy transmissions nationwide. In particular, switching from energy-intensive heavy industries to serviceoriented framework in PRD area is vital for promoting clean production at regional and national levels. Furthermore, the reduced energy connections of PRD in 2012 further demonstrated that there was a negative growth of embodied energy consumption in Guangdong; a consequence of stern energy conservation policies.

Similar to the BTH agglomerations, the economy of YRD also has dense industrial connections. It is an important trade partner of the BTH area. YRD is regarded as an economic center of China, and has well-developed manufacturing industry. The total economic output of the manufacturing industry in this area accounts for approximately 20% of national total amount. As a result, the manufacturing sectors, including the chemical industry (S12), the manufacture of metal products (S15), the manufacture of general and special purpose machinery (S16), and the manufacture of electrical machinery and equipment (S18), were industries that dominate energy imports and exports in the regional energy flow network. Infrastructure construction played a limited role in this highly developed area, as the construction sector only generated a small proportion of total energy transfers.

S13, S14, and the construction sector (S24) were the most active sectors with significant inflows and outflows in the CY area. This is mainly because under the backdrop of the Go West Strategy, CY experienced a rapid urbanization process with intensive infrastructure constructions. Over time, the manufacture of transport equipment (S17) played an important role in the energy transaction system in the CY area. This may have arisen the fact that the motor industry is the dominant industry of Chongqing and accounts for more than 60% of regional GDP.

In summary, infrastructure construction was a key driver of the local economy in the developing agglomeration areas (e.g., the LJH and CY areas). The developed agglomeration economies, including those of BTH, PRD, and YRD, were characterized by comparatively balanced and service-oriented developments. Paired agglomeration partners were reinforced with enhanced cross-regional trading, including those of BTH and YRD, BTH and LJH, and CY and PYD. Sun, Li [42] demonstrated the similar balanced development modes in the BTH, YRD, and PRD areas and explored analogous strengthened trading connections between different agglomerations. However, significant multiple connections were still rare in the current major agglomerations.

5. Discussions

By combining their embodied energy consumptions and specific roles in interregional trading, the three leading consumers (i.e., Shandong (R15), Jiangsu (R10), and Zhejiang (R11)) can be seen to possess distinct characteristics in embodied energy utilization. Shandong, the province with the largest energy contribution, was distinguishable for its self-sufficiency supply pattern; this is the most common and dominant model in terms of regional energy utilization in China [15]. In comparison, Jiangsu was the top energy importer in inter-regional trading. Conversely, Hebei was the largest net energy exporter in China. Given the variations of energy consumption structures, tracing the origin of energy sources is crucial for improving reduction efficiency and for aiding the adoption of specific policy instruments. More specifically, considering diverse role of regions in energy flow network, the corresponding policies can be released for the future scenarios (See Table 7). Export-driven regions should pay great efforts on structural optimization in energy consumption while import-driven regions should enhance their ability for bargaining more energyefficient products. Generally, it is rational to link regional energy reduction performances with career advancement of local cadres given the political ecology in China. Only in this way can provide internal impetus for achieving green economic growth.

With regard to the spatial structure of embodied energy distribution, the functional modules of energy fluxes for industrial networks were inclined toward having agglomerative patterns with geographical proximities and highly self-adaptive characteristics. Given the global Moran I results pertaining to agglomerative patterns, further analysis was conducted on the combined effects of spatial proximities and industrial networks using the LISA maps. The HH agglomerations were all located in eastern coastal area, whereas the LL agglomerations were concentrated in the western area, this indicated an obvious trend of polarization. From a temporal perspective, the confidence level of the HH regions has increased, which implied sustained and strengthened radiation effects from the growth pole area to the surrounding economies. Conversely, Sichuan and Guangdong were the HL regions that failed to form growth poles and failed to provide fresh impetus for regional development. As a result, the HH agglomerations exerted positive effect on economic growth whereas the LL agglomerations suffered from long-term economic backwardness problems given the lack of driving effect from the surrounding growth pole areas. As a result, central government should pay more attention to alleviating such regional inequalities. On the one hand, crossregional coordination, in particular for the collaboration between eastern and western areas, is of importance for overcoming regional barriers. In fact, the central government has released a series of plans for strengthening cooperation in poverty alleviation and enhancing pairing-assistance between east and west of China in 2016. On the other hand, the Chinese central government should achieve high quality growth of urbanization by transforming the traditional quantity-led and resource-extensive urbanization mode into quality-oriented inclusive development mode. To achieve this, the irrational physical construction occurred in the traditional urbanization process should be steered onto a sustainable urbanization with the emphasis on alleviating urban-rural inequality.

Three trends can be observed from the temporal perspective.

Table 7

Types	Corresponding strategies
Self-sufficiency regions	Develop green capital market with greenfiscal and tax supports for sustaining long-term institutional mechanisms of energy reductionfinance
Export-driven	Provide
Import-driven	Develop clean economic growth mode by upgrading economy structure
	Supply-side structural reform
	Promote the sharing of renewable and clean energy to achieve energy structure upgrading
	Advance high-tech innovation for clean production
	Implement strict bilateral trading policy during energy bargaining process

	Charge additional high taxation for energy-intensive products
	Implement tax deductions or exemptions for foreign eco-friendly companies
	Develop a green labeling system for import products and goods

Specific energy reduction strategies for different types of regions.

First, several separate neighboring provinces involved in major economic agglomerations have gradually integrated with significant spatial clustering characteristics. For instance, Henan (R16) formed a significant spatial connection with the BTH area in 2012. Second, an increasing trend of energy connections was observed among the backward regions (e.g., Sichuan and Chongqing) and developed areas (Guangdong). Finally, the spatial connections of these agglomerated regions have been further strengthened over time. Dorosh and Thurlow [43] and Geppert and Stephan [44] demonstrated that although regional integration can enable slower regions to catch up, the agglomeration effect may be insignificant when their regional connections are weak. Therefore, both topdown vertical administrative control and bottom-up horizontal coordinated mechanism are needed to overcome regional protectionism and enhance effective regional integration.

More specifically, mandatory regulations released by central government can break the regional inequality among different communities. On the one side, intra-regional collaboration can encourage knowledge sharing and industrial-chain formation, thus reinforcing and advancing interregional coordination. On the other hand, it is imperative to highlight the active role of market in resource allocation, particularly in the context of regional integration, which can stimulate the formation of industrial specialization. This industrial circles are beneficial for developing a circular economy, in which renewable resources and solid waste are encouraged to be used as raw materials for producing energyintensive products, such as steel, nonferrous metals, and cement. Third, continuous efforts should be paid to further strengthening the radiation effect from growth pole areas to surrounding or even long-distance entities. Mandatory regulations are needed to bridge administrative linkages and form pairing-assistant mechanisms between growth poles and backward areas.

6. Conclusion

This study conducted a province-level investigation of the embodied energy consumption of the Chinese economy to explore the effects of economic agglomerations and geographic attributes on energy transmissions patterns using MRIO, complex network analysis, and ESDA methods. Shandong (R15), Jiangsu (R10), and Zhejiang (R11) were the three leading regions and have distinct energy utilization models. Nonetheless study of them can provide instructive implications for energy conservation at the provincial level. The results of the community analysis have shown that the physical geographic clusters were highly consistent with the virtual administrative divisions of agglomeration economies. Paired regions, including Inner Mongolia and Gansu, CY and Guangdong, possessed prominent trends of regional integration. The in-depth investigation of major agglomerations has revealed that infrastructure construction remains a vital driver of local economies in northwest China) has weakened, as depicted by the declining

Appendix A

confidence levels. In contrast, regional integration has been further enhanced in the eastern coastal area, as shown by the increasing

Table A1

Region division in MRIO table

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

Table A2

Sector division in MRIO table

S1Farming, forestry, animal husbandry and fishery	S16 Manufacture of general and special purpose machinery
S2Mining and washing of coal	S17 Manufacture of transport equipment
S3Extraction of petroleum and natural gas	S18 Manufacture of electrical machinery and equipment
S4Mining and processing of metal ores	S19 Manufacture of communication equipment, computers and other electronic equipment
S5Mining and processing of nonmetal ores	S20 Manufacture of measuring instruments and machinery for culture activity and office work
S6Manufacture of foods and tobacco	S21 Other manufacturing
S7Manufacture 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

developing areas, whereas developed agglomeration economies have more balanced and service-oriented development. Bilateral connections in current major agglomeration economies have been enhanced, but multilateral connections remain rare. The spatial correlations of energy interactions in backward economies (e.g.,

confidence level. The findings of this study provide a bottom-up insight into the spatiotemporal effects of embodied energy flows. This can in turn be used to enhance our understanding of spatial connection patterns and the spatial heterogeneity manifestations of the embodied energy system of China.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2019.115998.

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