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Unfolding interregional energy flow structure of China's construction sector based on province-level data.

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Abstract

The construction sector is a critical part in achieving energy conservation targets in China, as it accounts for approximately 30% of the annual national energy supply for building construction. Therefore, this study integrates multi-regional input–output analysis and ecological network analysis to track energy fluxes and pathways from the construction sector, aiming to facilitate the configuration of the energy-flow structure and improve understanding of the region's responsibilities. Results of a spatial distribution analysis show that the eastern area of China leads in fossil energy consumption (e.g., coal and crude oil), whereas western China is the largest consumer of natural gas. Spatial relationship analyss indicate that eastern areas are located at the top of the trophic structure, implying that these regions are prioritized in energy consumption over the surrounding regions. By contrast, most regions located in the northern parts of China are characterized by resource-abundant areas and are at the bottom of the trophic structure, thereby indicating their comparatively weak role in an exploitation relationship. An investigation of major metropolitan areas demonstrates that mandatory targets set by national instruments are stratified in accordance with their diverse role and status in energy consumption at the beginning of the 12th Five-Year Plan period. However, these targets remain insignificant in the context of the inner area.

1. Introduction

China is the largest CO_2 emitter in the world. Therefore, during the United Nations Climate Change Conference in Paris (COP 21), China pledged to reduce its carbon emissions per unit of GDP by 60%–65% by improving the sharing of non-fossil energy up to 20% on the basis of 2005 levels. On this basis, the State Council of China released a working plan for energy conservation and emission reduction during the 13th Five-Year Plan period. This plan has a target of reducing the energy intensity per unit of GDP in 2020 by 15% versus the 2015 level; the total amount of energy is lower than 5 billion tons of coal equivalent (tce). With the acceleration of urbanization, the construction sector will be a critical factor in achieving energy conservation targets. The sector accounts for approximately 30% of the annual national energy supply, as most of this energy originates from fossil fuel sources and, consequently, makes a significant contribution to global warming (Dixit et al., 2012; Hong et al., 2016a, 2017a). Therefore, maximizing energy reduction in the construction field is a critical component of the climate change responses required to mitigate global warming.

Embodied energy, as an indicator that describes virtual resource utilization, is the sum of the direct and indirect energy used during building construction. This energy includes energy consumption that occurs during material production and construction, the placement of materials for maintenance and refurbishment purposes, and a building's deconstruction process. Detailed investigations of the energy consumed by the construction sector can advance the interpretation and improve the understanding of the current status of energy utilization and provide insights into the feasibility of energy conservation. Such investigations are beneficial for understanding energy allocation and movement induced by construction activities. Moreover, given that China exhibits the largest floor area of newly built buildings and relatively short building lifespans (e.g., 25–30 years) on average (Feng et al., 2013; Liu et al., 2014a), the energy saving potential during a building's embodied phase can play a critical role in life-cycle energy conservation. Single-region input–output (SRIO) analysis is commonly used to quantify total embodied energy consumption nationwide (Chang et al., 2016; Hong et al., 2017b). However, this method fails to analyze the environmental pollution caused by interregional trade, because the computational process is conducted on the basis of a high level of aggregation with insufficient information on the regional production structure (Hong et al., 2016c; Liu et al., 2018; Zhang et al., 2013). Disparities in regional resource endowments, productivity, and economies are major factors in the characterization of the distribution of embodied energy flows.

To tackle this problem, a network model with region-specific characteristics is needed to quantify the interrelationships among different regions. Recent methodological improvements in multi-regional analyses allow quantification of cross-regional energy transmissions; the details of environmental interactions can be captured by considering regional characteristics and sectoral differences (Chen and Chen, 2013; Wang and Chen, 2016; Zhang and Anadon, 2014).

However, few studies have focused on the spatial analysis of embodied energy flows from the perspective of systematic configurations. Relevant studies involving multi-regional energy analyses have focused on quantifying energy distribution while ignoring the inner relationships among different regions, which can lead to a poor understanding of spatial effects on the energy dislocation structure and the interrelationships of energy utility. Therefore, in addition to quantitative assessment of interregional energy flows, the current role and status of provinces in the overall energy utilization and the structural properties of the energy flows should be portrayed.

In previous studies, ecological network analysis (ENA) has provided insights into sectoral interdependence and functional mechanisms by investigating a network's flow structure through intercompartmental relationship analyses (Ulanowicz, 2004). This method can identify the utility of compartments existing in specific relationships (e.g., exploitation, competition, and mutualism). ENA originated from the economic analysis of monetary flow has been widely used in numerous resource investigations addressing a broad range of topics, including virtual water network analysis (Fang and Chen, 2015; Yang et al., 2012), material flow analysis (Li et al., 2012), energy network analysis (Zhang et al., 2009), and analyses of land use changes (Zhang et al., 2016b). ENA is the primary method used to elucidate the structure and function of ecosystems by quantitatively analyzing intercompartmental flows and their directions, thus revealing the behavioral patterns of individuals in the system.

The contributions of the present study include the following aspects. First, to capture the inherent characteristics of the overall complex energy flow system, this study uses the network technique as a viable way for tracking energy fluxes and pathways from the construction sector. Second, the specific role of regions in the national overall energy utilization is portrayed by investigating its diverse functions in connecting to other counterparts in the energy flow network, in which a regional categorization system is developed. Third, apart from the exploration of the structural characteristics of embodied energy flows, this study captures the spatiality of regional interdependence by considering the effect of geographical proximity, in which the ecological structure of three major metropolitan areas is revealed. The findings of this study are beneficial for developing a specific and differentiated energy conservation responsibility system at the industrial level from multiple scales.

The purpose of this study is to uncover the spatial characteristics of the overall energy flows induced by the construction industry. Against this backdrop, this study concentrates on the interdependence and function of provinces in the energy flow network in China, which includes 22 provinces, 4 municipalities, and 4 autonomous regions. The remainder of this paper is organized as follows: Section 2 conducted a comprehensive review of ENA applications for environmental impact assessment in China. Section 3 introduces the computational framework for the spatial analysis of embodied energy use in China's construction sector. Section 4 presents the results of the spatial distribution and spatial relationship analysis. Section 5 contains the discussion and policy implications. Finally, Section 6 provides the conclusions drawn from the study.

2. Literature review

Currently, numerous studies that integrate multiple methods with ENA have been conducted to explore intercompartmental relationships in resource consumption. Table 1 summarizes the relevant applications of ENA for environmental impact assessment in the context of China. From a spatial perspective, extensive studies on China's modern economy have been conducted at national, agglomeration, basin, province and urban levels with multiple research subjects. Carbon, energy, and water are three hotspots commonly investigated by integrating the MRIO technique and ENA (Duan et al., 2018; Zhang et al., 2015b). By contrast, other ecological indicators, such as nitrogen, natural gas, crude oil, waste, particulate matter, and material, are mainly analyzed on the

Table 1
Basic information of ENA applications in the context of China.

Region	Subject	Method	Reference
China	Carbon	MRIO; ENA	Duan et al. (2018)
Beijing		ENA	Xia et al. (2017)
			Chen et al. (2018b)
			Xia et al. (2018)

		IOA; ENA	Zhang et al. (2015a)
China	Energy	IOA; ENA	Lin and Zhang (2018)
		MRIO; ENA	Zhang et al. (2015b)
Beijing–Tianjin–Hebei		MRIO; ENA	Zhang et al. (2017); Zheng et al. (2018)
Beijing–Tianjin–Hebei		ENA	Hao et al. (2018)
Beijing, Shanghai, Tianjin, Chongqing		IOA; ENA	Zhang et al. (2015a)
Beijing			
Beijing		ENA Haken model	Hu and Mu (2018)
Beijing		EFA; IOA; ENA	Chen and Chen (2015)
Beijing		ENA	Liu et al. (2011)
Guangdong		IOA; ENA	Zhai et al. (2018)
China	Water	ENA	Guo et al. (2016)
Beijing		IOA; ENA	Zhang et al. (2010)
Heihe River Basin		IOA; ENA	Fang and Chen (2015)
Baiyangdian Basin		ENA	Mao and Yang (2012)
China	Energy–water nexus	MRIO; ENA	Wang et al. (2018)
Beijing–Tianjin–Hebei			Wang and Chen

			(2016)
Beijing	Nitrogen	ENA	Zhang et al. (2016a)
China	Natural gas/crude oil supply security	ENA	Shaikh et al. (2017); Shaikh et al. (2016); Lu et al. (2014)
Guangdong	Solid waste		Guan et al. (2019)
Beijing	Particulate matter 2.5		Yang et al. (2016)
Wuxi	Material	MFA; ENA	Li et al. (2018)

basis of combining input-output analysis (IOA) and ENA. This methodological difference mainly occurs because the MRIO model approach is a data-intensive method that requires specific sectoral data at the province level, thus being only applicable to the most common ecological indicators. IOA alleviates the data restriction through high-level integration and is therefore adopted for multiple ecological impact assessments. Most of the relevant research addressing ecological analysis has concentrated on inner-regional analyses, rather than cross-regional investigations. In particular, previous research has focused on ecological flows that cover the whole economy, whereas few studies have involved industrial-level investigations, especially in the construction industry, which plays a dominant role in indirect energy consumption in China (Liu et al., 2012b).

From a methodological perspective, IOA-based ENA is the most commonly used method for ecological assessment. This method allows an in-depth investigation of functional relationships from a sectoral perspective but shows weakness in spatial analysis. Consequently, there is a clear trend of gradually combining ENA with other methods, such as MRIO, MFA, and Haken models, to enhance its ability in spatial analyses. However, these multi-region-based studies have explored spatial patterns by grouping provinces according to geographical proximity (e.g., seven-region division in Duan et al. (2018) and Zhang et al. (2015b); eight-region division in Zheng et al. (2018)), while failing to reveal provincial specificity nationwide.

Compared with previous research, this study identifies the unique role of a specific region by comprehensively considering its diverse functions in the national energy flow network using ENA as an underlying method. In addition, by integrating MRIO and ENA, the functional relationship is interpreted with provincial specificity to capture the spatial pattern of energy network. An uncertainty analysis is used to quantitatively demonstrate the potential deviations from ENA and give an intuitive grasp of the changing structure features of the interregional energy flow network.

3. Methodology

3.1. *Spatial distribution analysis*

In the MRIO table, the Chinese economy is represented as a composite of 30 regions, and each region has 30 economic sectors. To illustrate a general case, we assume *m* regions with *n* sectors in each region. An intermediate use matrix represents the regional or cross- regional monetary transaction (u^{rk}_{ij}) for endogenous consumption. The final use matrix represents the monetary value of the total final use (v^{rk}_{i}). Subsequently, the total production output (x^{r}_{i}) can be expressed for each *i*th sector of the economy as follows:

$$x_i^r = \sum_{k=1}^{m}\sum_{j=1}^{n} u_{ij}^{rk} + \sum_{k=1}^{m} v_i^{rk} \quad (1)$$

By defining the intermediate coefficient matrix (*A*) in Equation (2), the production balance in Equation (1) can be expressed in a matrix format (See equation (3)):

$$A_{(mn)\times(mn)} = U \cdot \hat{X}^{-1} \quad (2)$$

$$X = (I - A)^{-1} V \quad (3)$$

where U is the intermediate matrix with $(mn)\times(mn)$ dimensions; X is the total production vector with $(mn)\times 1$ dimensions; I is the identity matrix with the same scale of A; and V is the final use vector with $(mn)\times 1$ dimensions.

To link monetary transactions with environmental interactions, an environmental intervention vector (e.g., the direct energy intensity vector in this study) $Q_{1\times(mn)}$ can be defined (4) as follows:

$$Q_{1\times(mn)} = C \cdot \hat{X}^{-1} \quad (4)$$

where C is the sectoral direct energy consumption vector with $1\times(mn)$ dimensions. The direct energy input data for each sector can be obtained from provincial statistical yearbooks and energy balance tables in Chinese Statistical Yearbook. Consequently, the embodied energy matrix of the entire economy (E) can be calculated as follows:

$$E_{(mn)\times(mn)} = \hat{Q}(I - A)^{-1}\hat{V} \quad (5)$$

To understand the relative importance of region *r* to other compartments in the total embodied energy consumption of China's construction sector, a contribution analysis can be performed as follows:

$$W^r = \frac{\sum_{k=1}^{m} E^{rk}}{\sum_{r=1}^{m}\sum_{k=1}^{m} E^{rk}}; \quad (7)$$

where W^r represent the relative contributions of region *r* to China's construction industry; E^{rk} represents the energy contribution from regional economy *r* to the local construction sector in region *k*. E^{rk} can be expressed as follows:

$$E^{rk} = \sum_{i=1}^{n} e_{ic}^{rk} \quad (8)$$

where e^{rk}_{ic} represents embodied energy flows from sector i in region r to the construction sector of region k. The results of this contribution analysis can facilitate the investigation of support from different regions by decision makers. In turn, these regions can characterize their ecological trophic levels and provide a holistic map for the status and function of each region in the energy flow network of China's construction industry.

3.2. *Spatial relationship analysis*

In accordance with the ENA, the direct energy transfer flows within an entire network can be calculated via the MRIO method as follows:

$$P = \left(p^{rk}_{ij}\right) = \hat{Q} \cdot U \quad (9)$$

where p^{rk}_{ij} represents the direct energy transfer flow from sector i in region r to sector j in region k. To explore inter-regional energy flows induced by provincial construction sectors, this study integrates energy flows from the construction industry at the regional level:

$$w^{rk} = \sum_{i=1}^{n} p_{ic}^{rk} \quad (10)$$

$$w^{kl} = \sum_{j=1}^{n} p_{cj}^{kl} \quad (11)$$

where w^{rk} denotes the energy input from region r to the construction sector in region k, w^{kl} denotes the energy input from the construction sector in region k to region l, and p^{rk}_{ic} represents the direct energy transfer from sector i in region r to the construction sector in region k. Consequently, the inter-regional energy flow matrix can be defined as $W_R = \begin{bmatrix} W_{RC} \\ W_{CR} \end{bmatrix}$, where $W_{RC} = \{w^{rk}\}_{m \times m}$ and $W_{CR} = \{w^{kl}\}_{m \times m}$. Similarly, to explore inter-sectoral energy flows induced by provincial construction sectors, the energy flows have been integrated at the sectoral level:

$$w^{ic} = \sum_{r=1}^{m} p_{ic}^{rk} \quad (12)$$

$$w^{cj} = \sum_{l=1}^{m} p_{cj}^{kl} \quad (13)$$

where w_{ic} represents the energy flow from sector i to the construction sector in region k, and w_{cj} represents the energy flow from the construction sector in region k to the sector j. Consequently, the inter- sectoral energy flow matrix can be obtained by $W_S = W_{SC} W_{CS}$, where $WSC = \{w_{ic}\}_{nm}$ and $WCS = \{w_{cj}\}_{mn}$.

Accordingly, w_R and w_S denote energy flows among regions and sectors induced by provincial construction sectors. As a result, the whole network constructed based on MRIO can be simplified into region-based and sector-based networks. In the network, direct energy flows are edges, whereas regions or sectors are nodes. To determine the functional relationships among the nodes of the network, a utility analysis has been used to quantify the interaction effect that occurs when each node exchanges energy with other nodes during construction activities (Zhang et al., 2015b).

A direct utility matrix has been developed for the functional relationships between pairs of nodes in the network (Lu et al., 2015). For instance, the region-based direct utility intensity (d^{rk}) can be expressed as follows:

$$d^{rk} = \frac{w_R^{rk} w_R^{kr}}{\sum_{r=1}^{m} w_R^{rk} + c^k} \qquad (11)$$

where $(\sum_{r=1}^{m} w_R^{rk})$ represents the sum of interregional energy inputs into the region k. c^k denotes the boundary inputs of region k, which is equal to the amount of direct energy use of region k. By equation (11), d^{rk} denotes the direct utility of a specific energy flow from region r to region k.

Similar to the Leontief production model, the overall utility intensity matrix (O) can be calculated as follows:

$$O = o^{rk} = (I\ D)^{1} = D^{0} + D^{1} + D^{2} + D^{3} + \cdots \qquad (12)$$

where O denotes the utility of energy flows in a more integral level, which includes the utility of self-feedback effect (D^0), direct effect (D^1), and infinite indirect effect ($D^2 + D^3 + \cdots$). Thus, Matrix (O) is a reflection of the overall benefits and patterns between any pair of regions.

The sign of each element in this matrix represents the interaction pattern and functional relationship between a pair of nodes. The value of each element represents the utility intensity of energy transactions. According to Zhang et al. (2015b), there are three types of relationships based on the similarity of organisms in a natural ecosystem. The signs (+,) and (, +) represent an exploitation relationship from different directions; in such a relationship, predators gain benefits, whereas preys suffer negative effects from the relationship. The sign (,) represents a competitive relationship, where the nodes act as competitors. The sign (+, +) implies a mutualistic relationship where both nodes can benefit from the relationship.

This study also uses a mutualism index, which explores the overall relationships and properties of an entire network. The mutualism index can be defined as follows:

$$\sum_{rk} \max(sign(o^{rk}), 0)$$

$$M = \underline{\qquad\qquad\qquad} P_{rk}(\qquad \min(sign(o_{rk});0)) \qquad (13)$$

Given the functional structure and sign distribution, the spatial relationship of embodied energy use caused by construction activities can be identified. Consequently, potential directions are provided for configuring and optimizing the energy flow system of China's construction sector.

3.3. *Data collection and consolidation*

Given the methods used in this study, two types of data are required for further calculation. The first is the MRIO table. The most updated one is MRIO table 2012, which is compiled by Mi et al. (2017, 2018). In this study, to keep the data consistency with previous research, we use MRIO table 2010, which is compiled by the Chinese Academy of Science, to facilitate the comparative analysis conducted in the results and discussion sections (Liu et al., 2014b). These provinces are composed of 30 regions, which include 22 provinces, 4 municipalities, and 4 autonomous regions. In each region, there are 30 sectors. The detailed regional and sectoral division information are provided in the Appendix Table A1 and A2. The other type of data is the sectoral direct-energy consumption data at the regional level. This study collected four types of energy, namely total energy consumption, coal, crude oil, and natural gas, from Chinese Energy Statistical Yearbook and provincial statistical yearbooks. To avoid double counting in data consolidation process, the national energy balance tables were employed to exclude the energy consumption in conversion of the primary energy into the secondary energy and the loss in the process of energy transformation. To achieve structural consistency, the statistical energy data are mapped onto the MRIO table, given the conflicts of sector classification between the two systems. The direct energy consumption data collected from each region are then aggregated to match the sectoral divisions in the MRIO table.

4. **Results**

4.1. *Spatial distribution analysis*

Fig. 1 illustrates the embodied energy distribution of the construction sector based on regional divisions. Shandong (R15), Jiangsu (R10), and Guangdong (R19) were the leading provinces in terms of embodied energy consumption. These provinces were top three regions regarding their GDP performance nationwide in the past two decades. Apart from this, these regions have experienced large-scale construction activities and accelerated urbanization process, where the annual economic outputs of the local construction sectors were leading nationwide. By contrast, the distribution of energy intensity presented an inverse trend in comparison with consumption patterns; developing regions with a low volume of embodied energy consumption located in the north, center, and southwest of China were high in energy intensity. The three leading regions were Ningxia (R29), Guizhou (R24), and Shanxi (R4). According to Liu et al. (2012a) and Hong et al. (2016a), the embodied energy and greenhouse gas distributions exhibited a similar trend; the developed areas with a high economic output (e.g., Shandong, Zhejiang (R11), and Jiangsu) were leading in the amount of embodied energy consumption; the developing regions (e.g., Shanxi, Ningxia, and Guizhou) with backward production technologies were energy-intensive in the building construction.

Table 2 summarizes the embodied energy contributions in accordance with different primary energy sources. To explore the overall energy distributions of China's construction sector from a geographic perspective, all the regions were combined into three major areas (i.e., eastern, central, and western China). Hebei (R3), Henan (R16), and Shanxi (R4) were the primary areas that provide raw coal. Hebei (R3), Liaoning (R6), and Shaanxi (R26) were the major contributors of crude oil for national construction activities. Thus, it is urgent to implement clean production technology in these energy-intensive regions to alleviate adverse environmental impact caused by the fossil fuel consumption. Xinjiang (R30), Sichuan (R23), and Shaanxi (R26) were leading regions in the supply of natural gas to the construction sector in China, which is strongly related to the distribution of China's natural gas reserves because the three provinces account for approximately 80% of known national reserves (Ministry of Natural Resources of China, 2015). Moreover, the structure of raw coal consumption

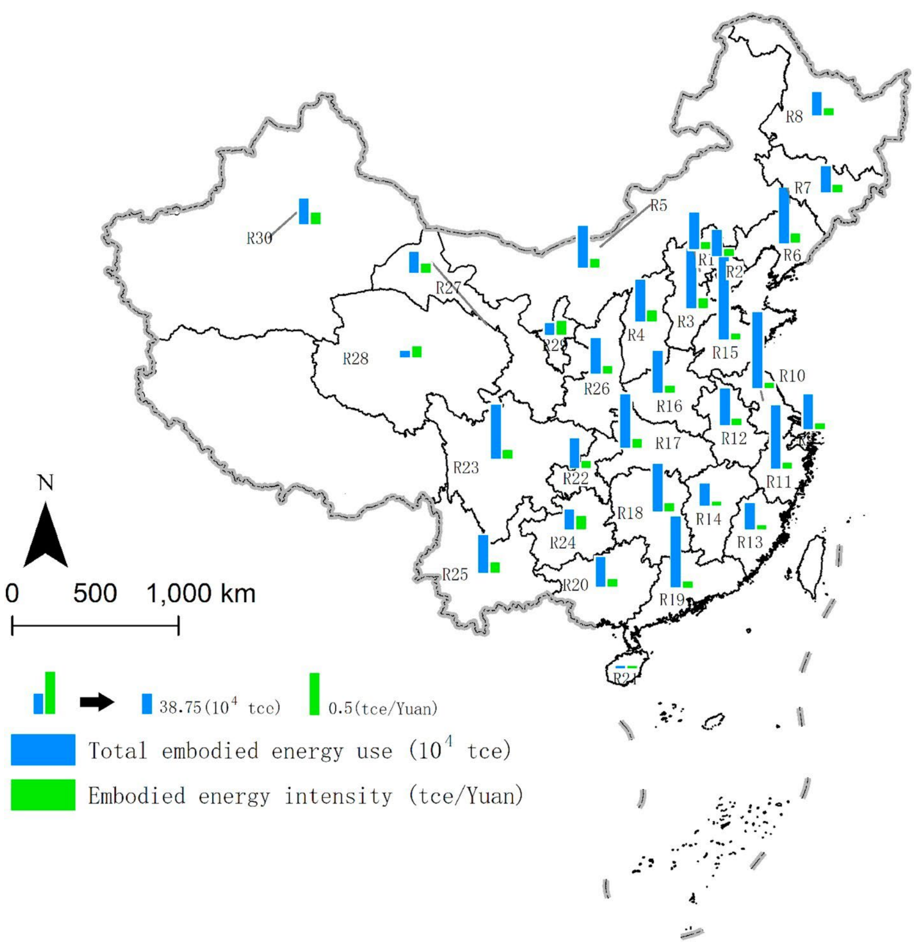


Fig. 1. Spatial distribution of the embodied energy consumption of provincial construction sectors.

corresponded to a typical inverted pyramid, with the largest proportion occurring in the eastern area, followed by the central and western areas. Similarly, the distribution of crude oil corresponded to an irregular, mostly inverted pyramid, in which the eastern area predominated (70.2%), followed by the western and central areas. By contrast, the structure of natural gas resembled an irregular pyramid, with the largest contribution coming from the western area followed by the eastern and central areas of China. The consumption of raw coal, as a typical fossil fuel, was dominant in China's construction sector, which can cause adverse environmental effects and present challenges for combating the impact of global warming. Capturing carbon dioxide from energy consumption is prominent for abating climate change challenges in China's construction industry, particularly in the medium to long term.

The net interregional transactions of China's construction sector are depicted in Fig. 2. A total of 16 regions were identified as net energy importers with positive values, whereas 14 regions were identified as net energy exporters, with negative values. Beijing (R1) was the leading region in importing energy, with a net energy inflow of 19.3 Mtce, followed by Zhejiang (R11) and Shanghai (R9). Most embodied energy receivers were located in coastal areas. Hebei (R3) was the largest net embodied energy exporter by exporting 42.3 Mtce. Henan (R16) and Liaoning (R6) followed as the two primary contributors to interregional energy exports.

4.2. *Spatial relationship analysis*

On the basis of the embodied energy flows among regions, an overall utility intensity matrix was derived through network utility analysis. The sign and value of each coefficient could then be used to explore the relationships among different regions in terms of the embodied energy consumption of China's construction sector (See Fig. 3a). An overview of overall utility intensity matrix shows that the negative value (cold color) was dominant, indicating an inactive environment in the current energy flow network in China's construction industry. The mutual relationship matrix in Fig. 3b shows that three types of relationships existed in all 435 pairs of regions. By excluding self-mutual values, these relationships were as follows: exploitation, with the utility sign for the pair of regions as (þ,) or (, þ); competitive relationship, where the sign was expressed as (,); and mutualistic relationship, with the sign expressed as (þ, þ). Among all pairs of relationships, exploitation was the most common (301), followed by competition (132) and mutualism (2). Consequently, the mutualism index for China's construction sector was 0.71, which was less than 1. The embodied energy consumption in the construction sector presented a negative relationship with the spatial distribution. We conducted a comparative analysis between the results obtained from the present study and previous research (Table 3). The proportions of relationships existing in the 30 regions were consistent among various studies. Specifically, the interregional relationships resulting from construction activities were more competitive than that of the whole economy. This situation is mainly because provincial construction sectors take priority in local energy use given their self- sufficiency characteristic, thus slightly mitigating exploitation relationships with surrounding regions. To quantitatively demonstrate the potential deviations and provide intuitive understanding of network changes, this study conducted uncertainty analysis based on ENA by examining variations in production structure and energy intensity (See supplementary file). The results showed that the production structure changes can lead to changes of functional relationship. The improvement in the sharing of tertiary industry can generate significantly.

Table 2

Volume of regional energy consumption and its contributions by different energy sources.

	Raw coal	Crude oil	Natural gas

East	R1	0.2%	38.4%	0.0%	70.2%	2.2%	25.0%
	R2	0.6%		1.1%		2.2%	
	R3	23.7%		39.1%		2.4%	
	R6	2.6%		23.6%		1.5%	
	R9	0.4%		0.1%		1.6%	
	R10	1.9%		0.2%		3.1%	
	R11	1.4%		0.0%		1.3%	
	R13	0.8%		0.1%		1.7%	
	R15	4.7%		5.0%		2.8%	
	R19	1.7%		0.3%		2.4%	
	R21	0.2%		0.8%		3.7%	
Central	R4	9.8%	34.2%	0.0%	2.9%	2.4%	15.5%
	R7	1.1%		0.8%		1.4%	
	R8	4.9%		0.7%		5.0%	
	R12	2.4%		0.0%		0.7%	
	R14	1.4%		0.0%		0.3%	
	R16	10.6%		0.6%		3.5%	
	R17	2.1%		0.3%		1.4%	
	R18	2.0%		0.5%		0.7%	
West	R5	6.9%	27.4%	0.4%	26.9%	5.6%	59.5%
	R20	1.5%		0.0%		0.1%	
	R22	1.4%		0.0%		5.0%	
	R23	2.2%		0.0%		14.3%	
	R24	3.8%		0.0%		0.5%	
	R25	2.8%		0.0%		0.4%	
	R26	2.3%		14.4%		7.8%	
	R27	1.6%		1.4%		2.1%	
	R28	0.4%		0.0%		4.1%	
	R29	3.3%		0.0%		1.8%	
	R30	1.3%		10.7%		17.8%	

positive impact on the energy-flow structure. On the other hand, although the change of energy intensity triggered the variations in utility intensity, the pairs of relationship still kept stable among different scenarios. Consequently, structural optimization should be more prioritized for improving the functional relationship of energy-flow network in China's construction sector. Given the computational structure of the MRIO analysis, a certain relationship exists between any pair of regions regardless of the strength of the connection. To provide insights into the inter-counterparts with the most substantial linkages, this study used a threshold of 0.01 for the utility intensity to exclude pairs with weak connections, to concentrate on the most substantial relationships among different regions. Under this scenario, 120 pairs were extracted with two types of relationships; exploitation accounted for 78.3% of the total number of relationships, followed by competition (21.7%).

In accordance with the specific role that a region played in a relationship, all the provinces were further divided into six categories. In the present study, a critical region was defined as an area whose roles include predator, prey, and competitor roles simultaneously; and whose absence can cause a crisis within the entire energy flow network of the construction sector given its functional relationship to energy transaction. Hub regions could act as both predator and prey in energy transactions and were regarded as nodes exhibiting energy inflow and outflow for energy transfer purposes. A strong region plays an active role as a predator and competitor simultaneously, whereas a weak region suffers from exploitation and competition relationship with other regions. The parasitic and host regions only played a single role (e.g., predator or prey) in the energy transaction system. Table 4 summarizes the regions in accordance with their types and roles.

Overall, predator regions with an intensity of more than 0.2 for China's construction sector were primarily distributed in eastern areas (e.g., Shanghai (R9), Jiangsu (R10), and Zhejiang (R11)) and northeastern areas (e.g., Beijing (R1), Tianjin (R2), Jilin (R7), and Heilongjiang (R8)); most of these places are highly developed in China. This finding was demonstrated by the fact that the embodied energy consumed by these regions is prioritized over the energy consumed by the surrounding regions in terms of construction activities. Prey regions with an intensity higher than 0.2 occurred in northern regions of China (e.g., Hebei (R3), Shanxi (R4), Inner Mongolia (R5), Liaoning (R6), and Shandong (R15), Henan (R16)). These places are characterized by resource-abundant areas. Competitive relationships (>0.1) occurred in regional pairs with intensive exploitative relationships (e.g., Beijing (R1), Zhejiang (R11), Shaanxi (R26), Hebei (R3), and Henan (R16)), primarily due to regional intense energy use behaviors, such as utilizing foreign energy for local construction or supplying domestic energy for export purposes, thus possibly causing competition with other regions simultaneously.

More specifically, critical regions were not the leading or sink regions in embodied energy use. In contrast, they mostly served as second- tier areas in the surrounding regions with regard to their economic volume. For example, in the Beijing–Tianjin–Hebei metropolitan area, Beijing (R1) was the leading region in terms of economic development. However, according to the results, Tianjin (R2) played a critical role in sustaining and improving the efficiency of embodied energy use of the construction sector in the area. Hub regions acted as transfer centers for energy flows and can facilitate the indirect exploitation of energy from other areas by energy-intensive regions. For example, Inner Mongolia (R5) and Liaoning (R6) received energy fluxes from Hebei (R3) to support construction activities occurring in northern China (e.g., Beijing (R1), Tianjin (R2), Jilin (R7), and Shaanxi (R26)). Guangdong grabbed energy from the central and western areas (e.g., Henan (R16) and Ningxia (R29)), eastern coastal areas (e.g., Shanghai (R9) and Zhejiang (R11)), and southwest part of China (e.g., Chongqing (R22) and Yunnan (R25)). The strong and parasitic regions were provinces on track for

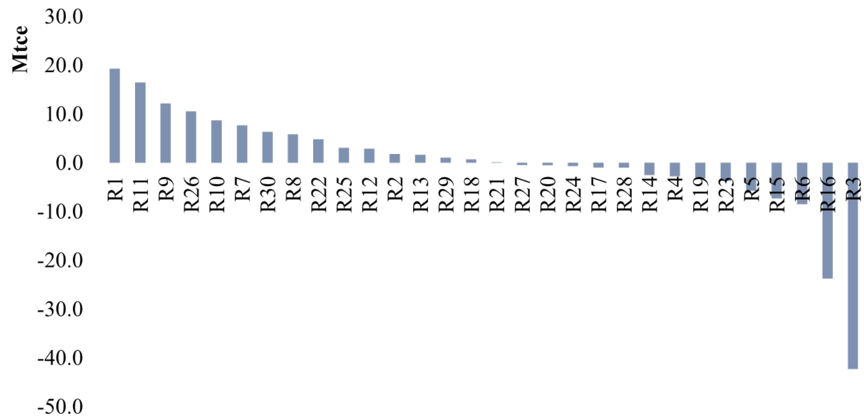


Fig. 2. Net interregional embodied energy transactions of the construction sector. (Note: The positive value represents the net import and negative value represents the net export).

Fig. 3. Overall utility intensity matrix and functional relationships among different regions. (Note: In Fig. 3 (a) the cold colors represent negative values and the warm color represent positive values; a darker color represents a higher value of utility intensity). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3

A comparative analysis between the present study and previous research.

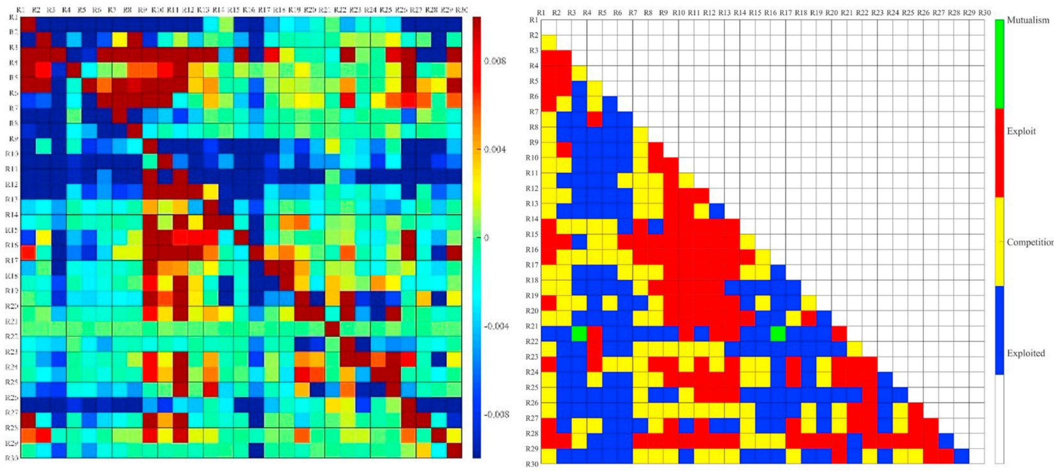
	Year investigated	Exploitation	Competition	Mutualism	Scale
Present study	2010	301 (69.2%)	132 (30.3%)	2 (0.5%)	China's construction sector (30 regions)
Zhang et al. (2015b)	2002	386 (88.7%)	36 (8.3%)	13 (3.0%)	China's economy (30 regions)
	2007	365 (83.9%)	64 (14.7%)	6 (1.4%)	China's economy (30 regions)

Table 4

Function and role of 30 regions in the energy flow network of China's construction industry.

Function	Role	Region
Predator, prey, and competitor	Critical region	Tianjin (R2) Jiangsu (R10) Anhui (R12) Shandong (R15) Ningxia (R29)

Predator, prey	Hub region	Inner Mongolia (R5) Liaoning (R6) Hubei (R17) Hunan (R18) Guangdong (R19) Yunnan (R25)
Predator, competitor	Strong region	Beijing (R1) Jilin (R7) Heilongjiang (R8) Shanghai (R9) Zhejiang (R11) Shaanxi (R26) Xinjiang (R30)
Prey, competitor	Weak region	Hebei (R3) Henan (R16) Shanxi (R4)
Predator	Parasitic region	Fujian (R13) Hainan (R21) Chongqing (R22)
Prey	Host region	Jiangxi (R14) Guangxi (R20) Sichuan (R23) Guizhou (R24) Gansu (R27)



(a) (b)

Qinghai (R28)

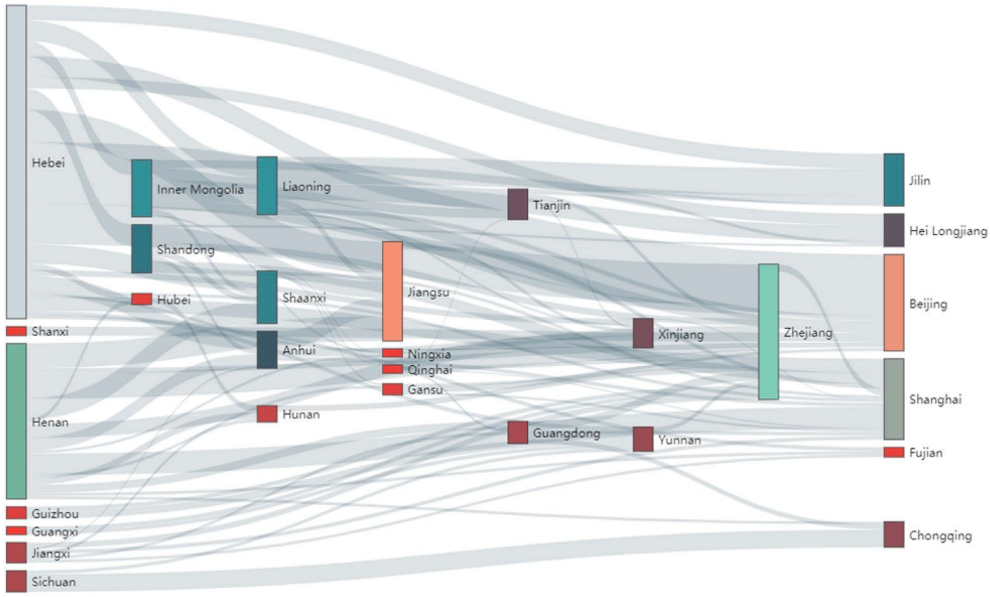
rapid urbanization, but have limited natural resources. Given the requirement for large-scale construction activities, these regions should seek out energy supplies from surrounding regions. The weak and host regions were provinces with abundant natural resources, most of which were major suppliers of the primary energy consumed during the building material production process, such as raw coal and coke.

To explore the regional hierarchical map of embodied energy flows in China's construction sector, this study only considered the energy inflows and outflows of a region that matched its role and status in a specific relationship. The results are demonstrated in Fig. 4. Beijing (R1), Jilin (R7), Heilongjiang (R8), Shanghai (R9), Fujian (R13), and Chongqing (R22) were located at the top of the trophic structure, which indicated that these provinces are leading energy receivers in the surrounding regions without significant energy outflows. In other words, they functioned as predators in the interregional relationship. For instance, Jilin (R7) and Heilongjiang (R8) were identified as the typical exploiters in the northeast area. In contrast, Hebei (R3), Shanxi (R4), Jiangxi (R14), Henan (R16), Guangxi (R20), Sichuan (R23), and Guizhou (R24) were located at the bottom. Specifically, the bottom-layer regions served as basic energy suppliers for different areas. For example, Hebei (R3) and Shanxi (R4) supplied energy for Northern China; Henan was the largest energy contributor for the central area; and Sichuan (R23) and Guizhou (R24) exported energy to Southwest China. Thus, for these demand-led regions located at the top of the trophic structure, in addition to control the volume of construction activities, efforts should be paid on implementing subsidies and tax exemptions to encourage a clean energy supply. For the supply side, mandatory administrative measures, carbon-clean techniques, and market-driven approaches should be implemented to achieve clean construction.

5. Discussions and policy implications

Given that network terminology can provide new insights in depicting the changing structure features of the inter-sectoral energy flow network (Chen et al., 2018a; Kagawa et al., 2015; Liang et al., 2015), this study also investigated the functional relationship of other

Fig. 4. Regional hierarchical map for energy flow network of China's construction sector. (Note: Energy inflows and outflows of a region depicted in this figure are



the flows with utility intensity higher than the threshold).

construction related sectors (See Fig. 5). It can be found that there were 226 pairs of exploitation relationship, 133 pairs of competition, and 76 pairs of mutualism, in which the mutualism index was equal to 0.76. Compared with negative relationship in the regional connections, the sectoral relationship was more positive. More specifically, the relationship between the chemical industry (S12), manufacture of non-metallic mineral products (S13), and smelting and pressing of metals (S14), which were the major energy suppliers for the construction industry, were more mutualism than the other economic sectors, accounting for 35.5% of the total pairs of relationships. Given China's construction industry developed complicated and multiple connections covering the entire economy, it is of necessity to enhance and spread such mutualism relationship into the whole supply chain.

According to the findings of this study, the interregional trophic structure of the construction industry represents discrepancies in comparison to the economy-wide investigation. The regional categorization based on diverse role of regions in the national energy flow network provides an additional insight to explore the status of a specific region. A detailed analysis of the major metropolitan areas can provide a holistic understanding of the current ecological structure of China's forefront

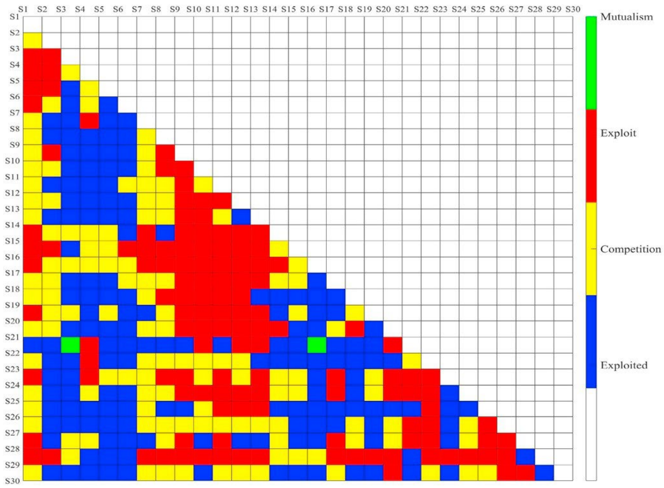


Fig. 5. Relationship matrix of sectors.

regions. In this study, the Jing–Jin–Ji agglomeration, the northeast area, and the Yangtze River Delta are selected for a detailed investigation (Fig. 6).

The Jing–Jin–Ji agglomeration and the northeast area of China presented a similar structural relationship. Beijing and Tianjin exhibited internal competition but exploited Hebei province. Jilin and Heilongjiang were competitive with each other; nonetheless, Liaoning was the primary energy supplier for both regions. Such a trophic structure reflected the spatial conflicts between the rapid development of urbanization and the restrictions imposed by natural conditions. This fact impeded the regional integration process and minimized the benefits of coordinated development. Therefore, reducing friction from resource competition between resource-abundant provinces were effective means of optimizing the energy structure of the construction sector at the regional level.

In contrast, the spatial relationships in the Yangtze River Delta represented an inverse situation; Jiangsu and Zhejiang not only faced external energy exploitation from Shanghai but simultaneously suffered from internal competition. As Shanghai is the economic center of China, with a relatively high urbanization rate, the embodied energy use of Shanghai was prioritized and is therefore located at the top of the trophic pyramid. However, such an ecological relationship may restrict the development of Zhejiang and Jiangsu, given the exploitation and competition that occurs in the two regions. These imbalanced resource priorities should be adjusted by transforming negative relationships into mutualistic relationships within the inner area. As a short-term strategic plan, actions should be formulated to minimize the negative effects of the current relationships. For example, predators should seek improvements of energy efficiency to alleviate the pressures of energy demands. Prey should improve the sharing of clean and renewable energy to create a low-carbon structure in energy production. The competitive relationship was, however, relatively complicated, similar to a coin with two sides: these relationships could increase the cost of embodied energy use, thereby impeding the development of regional integration, while they could also enforce and catalyze the local construction sector to upgrade the energy structure and implement advanced technologies to gain advantages in resource competition. Relevant actions should be formulated to enhance the driving forces, while at the same time minimizing the negative effects of the competitive relationship. In a long- term strategic plan, spatial relationships should be optimized into m utualism to an overall degree. Such transformations could lead to a positive and efficient atmosphere in the ecosystem of embodied energy use in China's construction sector.

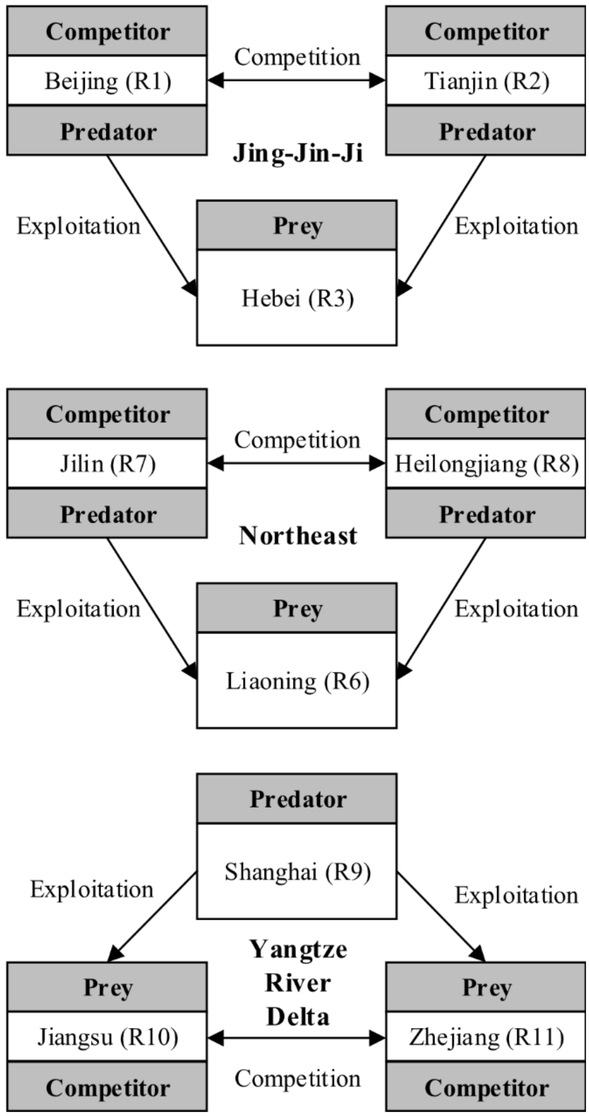


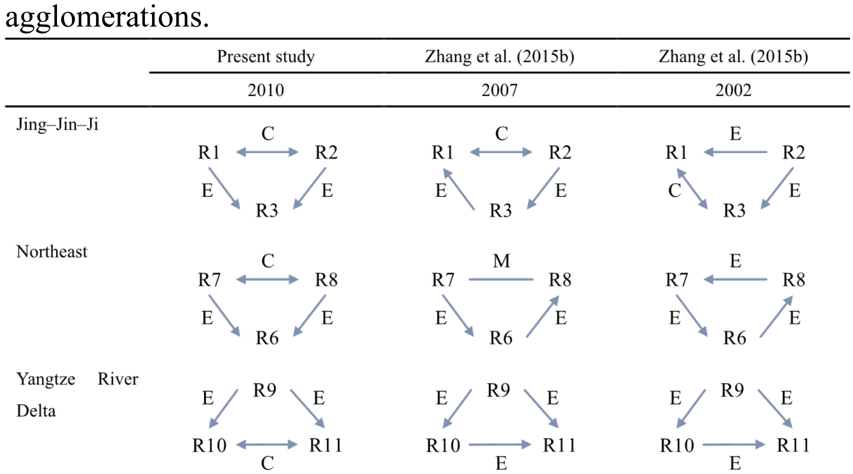
Fig. 6. flow network induced by regional construction sectors.

To validate the results of this work and identify the difference in interregional functional structure between the construction sector and the entire economy, this study compares the trophic relationships of three major agglomerations with previous research (Table 5). The functional relationships obtained in 2002 and 2007 are a result of energy interactions induced by the whole economy. Notably, the trophic relationships identified in this study are slightly different from those found in previous research given the industrial-level structural characteristics involved. For instance, due to its resource restrictions, Beijing is found to exploit Hebei Province to support local construction development in this study. In contrast, according to Zhang et al. (2015b), the direction of such an exploitation is inverted at the whole economy level. Jilin and Heilongjiang, in northeastern China, can mutually benefit each other through the bilateral trading process. However, this relationship becomes competitive in an industrial-level investigation. These structural differences further emphasize the importance of making mandatory and stratified policies to achieve clean production in the construction industry. More importantly, the unified national energy conservation plan needs to adjust to capture the real functional relationship and structural characteristics at the industrial level.

Furthermore, to link the findings of this work with policy practice, this study summarizes the relevant policies and mandatory targets released at the beginning of the 12th Five-Year Plan (See supplemental file, Table S1). According to the results of this study, both strong and parasitic regions should take more responsibility for controlling the volume of energy consumption. Additionally, the energy consumption structure should be primarily optimized in negative regions (e.g., weak and host regions). Such an emphasis is highlighted in the national instruments when mandatory targets are set. For example, in the Yangtze River Delta area, Jiangsu (R10) and Zhejiang (R11) exert further effort into improved sharing of non-fossil energy in primary energy consumption given their weak status in this area. Accordingly, Shanghai (R9) has prioritized improvement of the percentage of newly built floor areas of energy conserving buildings, to restrict the volume of energy demand. However, although these targets are stratified in accordance with their diverse roles and statuses in energy consumption at the beginning of the 12th Five-Year Plan period, they are still insignificant within the inner area context.

Ecological structure of three typical agglomerations regarding energy cations for regions at different scales according to their specific roles in To address this issue, this study reveals corresponding policy impli-

Table 5
A Comparative analysis between present study and previous research regarding the trophic relationships of three major agglomerations.



the nationwide energy flow network (Table 6). The achievement of energy reduction targets in the regional construction sector will require joint collaborations involving both economy-wide actions and precise industrial-level implementation because the energy consumption embodied in the construction sector is the result of energy interactions throughout the entire industrial chain. In fact, economy-level policies, which are designed from the institutional, technical, and managerial aspects, focus on the transition from the traditional energy-intensive, low-efficiency mode to a low-carbon, high-efficiency mode throughout the regional economy. Industrial-level energy reduction actions are organized on the basis of the production characteristic of the construction sector, in which advanced construction methods, high-tech energy- efficient products, and green management strategies aimed at environmental protection are commonly adopted to achieve construction efficiency. For instance, offsite construction (OSC) offers an innovative approach for improving productivity efficiency at both supply and demand sides. From a production or supply perspective, a factory-based production takes advantages in energy conservation and waste reduction (Hong et al., 2016b), which is beneficial for alleviating the overspending of primary energy in the regional construction industry. From a consumption or demand perspective, the superiority in reuse and recycling of building component in OSC poses a big potential of energy savings during building demolish phase. Moreover, establishing a building energy audit system is urgent for building energy conservation. Such a solid data foundation can facilitate local authorities to implement data-driven policies at the consumption side. The critical and hub regions determine the source and destination of embodied energy flows, thereby requiring the implementation of energy conservation strategies from both the demand and supply sides. More specifically, as the second-tier entities in the surround regions, Tianjin, Jiangsu, and Anhui exert unexpected important impact on sustaining energy flow transactions in Jing-Jin-Ji, Yangtze River Delta, and Central-plain agglomerations. This condition entails specific political concern on energy optimization in these “hidden” regions. Strong and parasitic regions face huge challenges in mitigating primary energy demands, given their priorities in the exploitation relationship. Therefore, the local authorities should trade off the byproduct effect of urbanization growth on energy increase. The mechanism of interregional technical conversion and communication should be established to lubricate the regional competition and reduce transaction cost owing to information asymmetry. This mechanism bears importance in reallocating the responsibility of energy reduction. In addition to restriction of the volume of construction activities, efforts should also be exerted on implementing subsidies and tax exemptions, to encourage a clean energy supply. Weak and host regions are typical supply-led regions. Mandatory administrative measures and market-driven approaches should be implemented to improve energy efficiency, thereby achieving low-carbon clean production. In addition to the top-down mandatory target system, a bottom-up market-oriented mechanism should be developed to enhance the engagement of energy service suppliers in building energy conservation through political instruments. Specifically, Clean Development Mechanism (CDM) should be elaborated to bridge the mutual assistance between energy- and technology-intensive re-

Table 6
Regional and industrial-level energy conservation strategies based on different roles of regions.

Regions	Regional-level strategy	Industrial-level strategy

Demand	CR, HR, SR, PR	Implement restrictions on import policies by encouraging the import of clean products; Implement tax deductions or exemptions for clean energy supplying enterprises Provide subsidies for energy efficient products Improve the sharing of renewable energy by implementing energy contract management Build a green capital market by restricting loan growth for energy- intensive enterprises	Build pilot construction projects for energy conservation Adopt advanced construction techniques (e.g., lean and off-site construction) Develop a building energy audit system
Supply	CR, HR, WR, OR	Regional coordinated innovation in energy conservation Implement renewable energy Enhance clean coal utilization Develop low-carbon technology Develop advanced technologies for energy efficiency improvements Prioritize the development of high-tech and energy-efficient industries Establish interregional technical conversion and communication mechanism	Release mandatory targets for energy conservation in the regional construction sector Develop a green labeling system for building materials Provide energy services with energy contract management Adopt offsite construction technique Implement Clean Development Mechanism

Note: CR is the critical region; HR is the hub region; SR is the strong region; WR is the weak region; PR is the parasitic region; OR is the host region.

gions, which can not only realize technology transformation from highly-developed regions to under developed regions, but also avoid lock-in effect in the backward regions.

Authorities should investigate the differences in energy utilization relationships among regional counterparts. Given the current trophic relationships in different economic circles, customized strategies should be implemented to address core energy problems in regional construction sectors. The top-down Energy Conservation Target Responsibility System (ECTRS) initiated in 2010 is used as an effective mechanism for enforcing the delivery of targets by local governments. However, this system has only been implemented at national and industrial levels, while ECTRS is still scarce in the provincial economic sector. Thus, the energy conservation targets set for China’s construction sector by the central government are non-mandatory at the regional level because the top-down administrative system in the ministries is likely to provide guidance than to exert authority. Consequently, provincial protocols and codes for energy conservation in buildings are optional; they only play a limited role in overall energy reduction in the construction sector (Lo and Wang, 2013).

6. Conclusion

In this study, a spatial analysis of the embodied energy use in China's construction sector is conducted by integrating MRIO analysis and ENA. The results provide an efficient method for analyzing the spatial distribution of embodied energy flows and the current status of regions within the entire energy flow system. The regions are divided into six categories (i.e., critical, hub, strong, weak, parasitic, and host regions) given their diverse roles in the embodied energy flow system of China's construction sector. However, although the mandatory targets set by national instruments are stratified in accordance with the regions' diverse roles and statuses in energy consumption at the beginning of the 12th Five- Year Plan period, they remain insignificant within the inner area context. The findings of this study allow exploration of the differences in energy utilization relationships among regional counterparts in China's construction sector, which is a clear improvement in elucidating the functional relationships and pathways of the embodied energy use of the construction sector. Notably, integrating MRIO with ENA by using the latest public data is still rare in energy consumption investigation at the national level. This limitation can be further addressed by conducting a time-series investigation in the future to depict the evolution patterns of embodied energy flow network in China's construction industry. In addition, network terminology is beneficial for depicting the changing structure features of the inter-sectoral energy flow network. Therefore, it is of necessity to make an in-depth investigation of structural characteristics and functional mechanisms of sectors in the future research.

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Appendix A

Table A1
Regional 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
Sectoral division in MRIO table

S1	Farming, forestry, animal husbandry and fishery	S16	Manufacture of general and special purpose machinery

S2	Mining and washing of coal	S17	Manufacture of transport equipment
S3	Extraction of petroleum and natural gas	S18	Manufacture of electrical machinery and equipment
S4	Mining and processing of metal ores	S19	Manufacture of communication equipment, computers and other electronic equipment
S5	Mining and processing of nonmetal ores	S20	Manufacture of measuring instruments and machinery for culture activity and office work
S6	Manufacture of foods and tobacco	S21	Other manufacturing
S7	Manufacture of textile	S22	Production and distribution of electric power and heat power
S8	Manufacture of textile wearing apparel, footwear, caps, leather, furs, feather(down), and related products	S23	Production and distribution of gas and water
S9	Processing of timber, manufacture of furniture	S24	Construction
S10	Manufacture of paper, printing, manufacture of articles for culture, education, and sports activity	S25	Transportation, storage, posts and telecommunications
S11	Processing of petroleum, coking, processing of nuclear fuel	S26	Wholesale trade and retail trade
S12	Chemical industry	S27	Hotel and restaurants
S13	Manufacture of non-metallic mineral products	S28	Tenancy and commercial services
S14	Smelting and pressing of metals	S29	Research and experimental development
S15	Manufacture of metal products	S30	Other services

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