An-embodied energy perspective of urban economy: A three-scale analysis for Beijing 2002-2012 with headquarter effect

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Abstract: As the typical characteristic of globalization, large-scale agglomeration of headquarters in urban economies exerts extensive cross-border trade links, and inevitably generates energy use outside their boundary. Therefore, studies about urban economies' energy use profiles should pay special attention to the tremendous energy transfers embodied in their trade connections along the whole supply chain. In this regard, a three-scale input-output model which distinguishes local, domestic and foreign activities is devised to reflect cross border embodied energy perspective for urban economies, with an intensive case study for Beijing during 2002-2012. The results show that domestic imports dominate Beijing's total embodied energy use, while local energy exploitation accounts for less than one-tenths of the final use. Regarding to energy use embodied in trade, headquarter effect contributes significantly to the rapid growth of embodied energy inflows and outflows. Embodied

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energy transfers induced by headquarter effect almost doubled in the case period. Different industries show distinct embodied energy redistribution evolution characteristics. Moreover, the complete source-to-sink budget is constructed, implying that coal use still dominates Beijing's total embodied energy inputs. Analysis in this study highlights the importance to consider the impacts of headquarter effect on Beijing's embodied energy use and redistribution pattern, pointing the potential room for policy implications aimed to realize collective and inclusive governance of global energy supply chain.

Keywords: Urban economy; embodied energy; three-scale input-output analysis; domestic and international trade; headquarter effect

1. Introduction

Extensive population gathering and corporate industry aggregation (Creutzig et al., 2015; Viladecans-Marsal, 2004) make urban economies at the center of global economic growth. Due to the expanding industrial and human activities, urban economies also dominate global energy consumption, contributing to about 64% of global primary energy use (IEA, 2016). With the predicted addition of 2.5 billion people, urban population is expected to occupy 68% of the world total by 2050 (UN, 2018). It is bound to cause high-speed urban expansion and climate change in the coming decades. As the leading actions of the world, urban economies are considered the key roles to alleviate environmental stressors by energy management in pursuit of sustainable socioeconomic development (Seto et al., 2011).

Recent decades have witnessed the widening, deepening and accelerating of globalization (Chen et al., 2018a; Li et al., 2020). As the important driving force of economic globalization, transnational corporations (TNCs) reconstruct global economy through cross-border investments and trade (Yun and Yoon, 2019). TNCs tend to locate their headquarters in a few key cities, such as New York, Paris and London (Taylor and Csomós, 2012; Taylor et al., 2009). Large-scale concentration of headquarters in giant cities gives birth to a new economic development model for city, i.e., headquarter economy. This economy model exerts crucial impacts on the progress of globalization and urbanization, and also reshapes urban economies' trade pattern. As the command center of firms, headquarters are in charge of strategic management and sales business. Numerous products required by different regions outside the urban economies' administrative boundary are uniformly sold and re-distributed by headquarters in these urban economies. These part of income and revenue by selling products are attributed to the location of headquarters. Therefore, income taxes of many sub-companies are partly converged to their headquarters. However, these commodities' energy-intensive production activities carried out by the sub-companies are usually located in other regions outside the urban economy where headquarters are located (Zhang, 2011; Zhao, 2004). Consequently, headquarter effect requires little on-site direct and large off-site indirect energy use that rely on domestic and global imports. At the same time, products required by regions all over the world need being redistributed through the unified selling business by headquarters, leading to large indirect energy use exported to fulfill the demand of other regions worldwide. In summary, the headquarter effect contributes significantly to urban economies' close and extensive trade links with other regions outside their boundaries, making them get involved in global and domestic supply chain more deeply (Meng et al., 2018b; Parnreiter, 2010), and also drives tremendous inflows and outflows of energy use embodied in trade. Therefore, influenced by the increasingly prominent headquarter effect, studies about urban economies' energy use profiles should pay special attention to the large-scale energy transfers embodied in their trade connections along the whole supply chain.

Numerous works have been carried out to evaluate the total energy use profiles at different scales. Some are mainly conducted from the traditional production perspective, i.e., solely focusing on energy directly consumed or emissions directly emitted by the human industrial production activities (Dhakal, 2009; Li et al., 2010; Sugar et al., 2012). These studies just account direct energy use from end users, ignoring indirect energy use embodied in intermediate and final inputs. Accompanied by the emergence of headquarter economy, urban economies become more dependent on imports of energy resource to maintain daily operation. Owing to headquarters' control on products selling, large amount of energy use is embodied in urban economies' exports to fulfill the demand of other regions worldwide. Given that, based on the concept of embodied energy originating from the theory of systems ecology (Costanza, 1980; Odum, 1983), numerous studies try to depict the holistic picture of urban energy use by investigating total embodied energy use covering both direct (on-site) and indirect (off-site) energy use throughout the whole supply chain (Chen and Chen, 2015; Chen et al., 2017c; Collins et al., 2006; Larsen and Hertwich, 2010; Li et al., 2014b; Li et al., 2019b; Mahjabin et al., 2020; Zhang et al., 2014b). Similarly, integrated with historical and off-site formation process, embodied analysis can provide a systematic perspective of resource use at global (Chen and Chen, 2011a; Wu et al., 2019; Wu and Chen, 2017) and national (Guo et al., 2020; Jianyi et al., 2015; Li et al., 2019a; Tang et al., 2012; Wang and Yang, 2020; Zhang et al., 2020a) scales.

Input-output analyses, which possess unique sensitiveness in capturing accurate economic relationships among all the studies, play important roles in tracking energy flows embodied in urban economies' domestic and foreign trade (Hu et al., 2016; Li et al., 2018b; Sun et al., 2017; Zhang and Lahr, 2014; Zhang et al., 2020b). Concretely, single-region input-output (SRIO) model, which only requires relatively tiny amount of economic and direct natural resource data, is commonly used in urban economies' energy use accounting (Guo et al., 2012; Zhou et al., 2010). Limitations of SRIO-based analysis locates in the indiscriminate intensities of imported and local products, making the evaluation of energy use embodied in urban economies' inflows less exhaustive. Based on complete data support at national level, energy use that is embodied in international trade have been successfully analyzed and estimated by MRIO analyses (Chen et al., 2018b; Chen and Chen, 2011b; Cui et al., 2015). Yet, for urban economies where the detailed sectoral and geographical trade data are difficult to obtain, a comprehensive energy resource MRIO still presents difficulties. For instance, some scholars solely focus on energy use or emissions embodied in domestic interregional trade, with international items removed or ignored (Wang et al., 2019b; Zhang et al., 2013; Zhang et al., 2015; Zhang et al., 2014a). However, the increasingly intensified headquarter effect of TNCs in recent decades makes urban economies get involved in global supply chains more deeply. Energy use embodied in regional-international trade is playing a more important role than ever-before. Therefore, to shed light on the full picture of the rapidly increasing energy inflows and outflows embodied in urban economies' trade, some researchers choose the hybrid life-cycle based MRIO analysis (Chen et al., 2017b; Heinonen and Junnila, 2011; Ramaswami et al., 2008), which requires detailed geographical lists for goods and services. Both data collection and model development are challenging missions. Moreover, numerous studies build the large-scale nested multi-regional input-output table (Wang et al., 2015), emphasizing on transnational highly-connecting between urban agglomerations (Chen et al., 2016), city-centric regional-international relationships (Lin et al., 2017) and urban economies' multi-layer trade connections with all cities in China and all economies in the world (Feng et al., 2013; Meng et al., 2018a; Mi et al., 2017). However, this set of nested methods are based on the assumption that the international exports/imports of an urban economy are distributed among all foreign economies in the same proportion as China's total exports/imports. Such simplified processing of urban trade structure may lead to some uncertainty when the analysis is focusing on detailed exports/imports.

Given that, a compromise method for regional ecological element modeling influenced by the headquarter effect is to employ the multi-scale input-output (MSIO) model, which is proposed by Chen and his colleagues (Chen et al., 2011). It can distinguish different energy intensities of same products from different scales, which is superior to SRIO. In addition, the applying of averaged embodied energy intensity databases for the global and national economies make the data requirements be much lower than a complete MRIO analysis. In this sense, the MRIO method is extraordinarily suitable for estimating the resource use of a sub-national or even a smaller economy.

As the capital of China, Beijing's exports climbed 15.41 percent year on year to 396.25 billion CNY for 2017, while imports hit 1796.14 billion CNY, up 18.02 percent from the previous year (BMBS, 2017). Such tremendous capital transfers are actually controlled by headquarters of large TNCs. In retrospect, to enhance Beijing's competitiveness in a globalized world economy, the government has endeavored to attract headquarters of both domestic giant firms and regional headquarters of TNCs by virtue of its special advantages as the heartland of superior information administrative advantage (Wang et al., 2011). These measures have exerted dramatic influences on the overall economic structure of Beijing. Until 2013, Beijing has surpassed Tokyo to become the No. 1 city housing the most headquarters of Global Fortune 500 companies (Pan et al., 2015). It's reported that income taxes for enterprises shared nearly 50% of Beijing's total tax revenues in 2017 [1]. The GDP

1 http://industry.people.com.cn/n1/2018/0108/c413883-29750136.html

created by headquarters enterprises is 865.54 billion CNY, accounting for 48.4% of the total GDP of the whole city in 2012 [1]. With 0.4% of the total enterprise quantity in Beijing, the headquarter enterprises in Beijing have realized nearly 60% of the city's income, created nearly half of the city's added value and profits, and become an important force in promoting Beijing's economic development (BSB, 2014a). Moreover, during the recent decades, power economy with distinctive Chinese characteristics has become increasingly prominent in Beijing, representing by the expediting centralized control to large state-owned enterprises' headquarters (Hu and Jefferson, 2004; Wang et al., 2008). These all provide an intriguing setting to select Beijing as a typical city for research. In view of the closely coupled economic development and energy use (Chen et al., 2017a; Su and Ang, 2017; Wang et al., 2019a; Wesseh and Lin, 2018), a serious of questions emerge: how much energy is needed to support a city boosted by headquarter economy such as Beijing? how do the headquarters play crucial roles in energy redistribution and uniform management along Beijing's domestic and foreign supply chains?

Our past literatures that estimate resource use profiles of Beijing by the MSIO method convey several ecological elements, including energy (Li et al., 2016), carbon emissions (Chen et al., 2013; Shao et al., 2016) and water resources (Han et al., 2015; Shao et al., 2017). To compare with Li et al.'s study which also conducts the MSIO method on the energy resource use of Beijing, the present study has the following further contributions. Firstly, this study differs from Li et al.'s study in that Li et al.

1 http://news.hexun.com/2014-03-08/162835786.html

focus towards comprehensive estimation of Beijing's overall embodied energy consumption, while this study lays emphasis on tracking Beijing's cross-border energy trade patterns with domestic and foreign scales. Considering Beijing's role of consumer, Li et al.'s previous study tracks upstream sources (direct input, domestic and foreign import) of Beijing's total embodied energy consumption, finding that the picture of real energy consumption in terms of embodied energy consumption is in stark contrast to the nominal energy use in terms of only direct energy input. Yet, in the context of a global economy characterized by deep level of industrialization and globalization, giant cities like Beijing with headquarter effect are inclined to become embodied energy transfer centers in complex supply chains. To fill in the gaps, this present study probes into how embodied energy is collected from upstream sources and then redistributed to downstream consumers, paying due attention to Beijing's energy inflows/outflows and the transfer patterns. The MSIO method is extended in this study for analyzing the headquarter dominated energy profiles. With the improvement of the model's quantification level, the impacts of headquarter effect on urban economies' embodied energy use are discussed for the first time. Secondly, different from Li et al.'s study that only shows basic results for a single benchmark year, this study focuses on the dynamic evolution patterns of Beijing's energy use profiles by a time series analysis from 2002 to 2012. The estimation under long-term horizon is not only ex post measurement of past performance but also ex ante measurement of future expected or anticipated changes, making it possible to do timely policy adjustments with the goal of sustainable energy use. Thirdly, distinguished from Li et al.'s study uses the energy input inventory showing where it was used (burnt), this study adopts the energy input inventories showing where it was extracted. This makes it possible to present a holistic picture of Beijing's energy use from source to sink.

Given these, this study constructs a multi-scale assessment framework, taking Beijing as an example, to completely account energy use by a typical headquarter economy along the entire domestic and foreign supply chain. Interactions and synergism along the entire supply chain are given enough consideration. The remainder of the paper is organized as follows: the methodology and data sources are explained in Section 2; Section 3 presents the empirical results. Discussions and implications are listed in Section 4 and concluding remarks are illustrated in Section 5.

2. Methodology and data source

2.1 Embodied energy accounting model

A three-scale diagram of urban energy flows are described in Fig. 1. Sectoral inputs for Beijing are originated from three scales of the urban, domestic and international systems. Induced by different industrial structures and technical levels, the three scales possess distinct energy intensities. Given that, three energy flows originating from the urban, domestic and international systems should be accounted for influencing the three-scale destinations of outputs, including EEF (energy use embodied in final consumption), EEDE (energy use embodied in domestic export) and EEFE (energy embodied in foreign export).

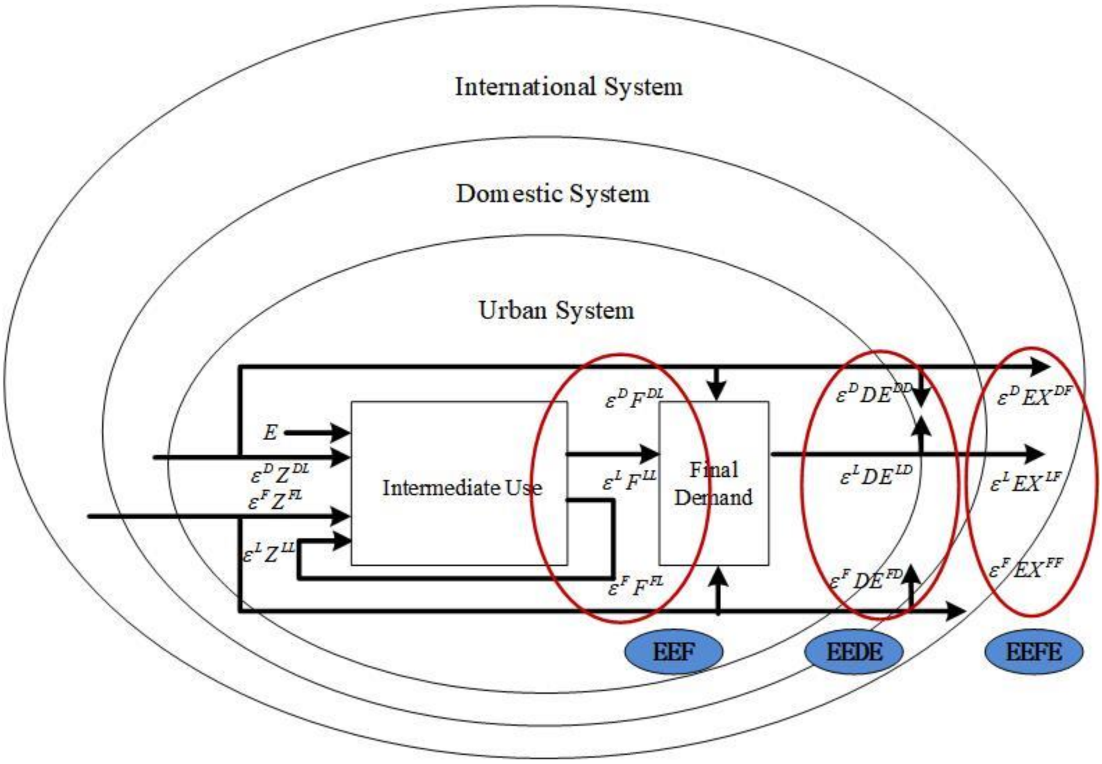

Fig. 1. Three-scale diagram of urban energy flows. (The arrow represents the flow direction and energy flow destination in the corresponding region. ε^L, ε^D, ε^F represent embodied energy intensity matrix of local, national and global scales, respectively. Z^{LL}, Z^{DL}, Z^{FL} denote local products and imported products originated from the three scales that are used as intermediate inputs for Beijing. F^{LL}, F^{DL}, F^{FL} denote the local products and imported products of the three scales to satisfy the local final demands. DE^{LL}, EX^{LL} represent local products that satisfy domestic and foreign use in the external economies. DE^{LD}, DE^{LF} represent products imported from domestic and foreign scales to satisfy domestic exports. EX^{DF}, EX^{FF} denote products imported from domestic and foreign scales to satisfy foreign exports.)

The three-scale input-output model used in this study has been extended based on previous conventional accounting framework of previous study by Chen and Guo (Chen et al., 2013) and Li et al. (Li et al., 2016). It is the most detailed one in history in terms of the quantification of Beijing's embodied energy trade turnover. To completely illustrate the multi scales energy use of Beijing and distinguish between the energy flows embodied in local and imported products from other scales, the official competitive economic input-output tables, which do not distinguish between local and imported products, are transformed into a non-competitive input-output table, which is considered as the basis of the MSIO analysis. Table 1 shows the general form of the multi-scale non-competitive input-output table of an economic system. The direct energy investment of Sector j are denoted by e_j. z_{ij}^{LL}, z_{ij}^{DL} and z_{ij}^{FL} denotes local products and imported products originated from the three scales from Sector i that are used as intermediate inputs for local Sector j. f_i^{LL}, f_i^{DL} and f_i^{FL} represent the local products and imported products of the three scales from Sector i to satisfy the local final demands. de_i^{LD} and ex_i^{LF} denotes the local products from local Sector i that satisfy domestic and foreign use in the external economies.

Dominated by the ever-increasing headquarter effect, large amount of communities that produced by the sub-companies outside of Beijing are unified sold by their headquarters locating in Beijing, and then be used to satisfy the final demand of other economies. In this procedure, the gradually prominent headquarter effect drives large amount of capital and embodied energy inflows and outflows. Beijing plays a pivotal hub in transferring and redistributing the embodied energy along the supply chain. In the extended three-scale model designed in this study, abundant consideration and attention have been given to energy embodied in the imported products from domestic and foreign economies which are also re-exported to economies outside Beijing's boundary. Exactly, the origins of energy embodied in imports and exports are accounted and elaborated in more details in this study than the previous paper. These detailed structures have been neglected by previous works, and their evolution characteristics would contribute special significance to the evaluation of headquarter dominated energy use perspectives. In this study, energy embodied in de_i^{DD}, de_i^{FD} and ex_i^{DF}, ex_i^{FF} is transferred via Beijing but not processed or used by Beijing. They are mainly dominated by the headquarter effect. For instance, in Beijing's 2012 input-output table, the total import of oil and natural gas industry was 1.08 trillion CNY, accounting for 75.52% of China's total oil and natural gas imports (BSB, 2014b; Liu et al., 2014). This also explains why Beijing's oil and gas industry will have a larger volume of outflows. Therefore, the striking headquarter effect could lead to significant increase of energy embodied in these four parts. In the following analysis, the total volume and proportion shared by the energy embodied in these four parts in total energy inflows and outflows are discussed in details.

Table 1. Multi-scale input-output table

Input/Output		Intermediate use			Final use		
		Sector 1	⋯	Sector n	Final demand	Domestic export	Foreign export
Local intermediate inputs	Sector 1	z_{ij}^{LL}			f_i^{LL}	de_i^{LD}	ex_i^{LF}
	⋯						
	Sector n						
Domestic imported intermediate inputs	Sector 1	z_{ij}^{DL}			f_i^{DL}	de_i^{DD}	ex_i^{DF}
	⋯						
	Sector n						

Foreign imported intermediate inputs	Sector 1	z_{ij}^{FL}	f_i^{FL}	de_i^{FD}	ex_i^{FF}
	…				
	Sector n				
Direct energy input		e_j			

According to the general model purposed by Chen et al. (Chen et al., 2013) for multi-scale input-output analysis of a regional economy, the biophysical balance of energy of Sector i in Beijing based on multi-scale input-output model can be described as:

$$e_j + \sum_j^n \varepsilon_j^F z_{ji}^{FL} + \sum_j^n \varepsilon_j^D z_{ji}^{DL} + \sum_j^n \varepsilon_j^L z_{ji}^{LL} = \varepsilon_i^L x_i \tag{1}$$

Where e_j denotes the direct energy input into Sector j, ε_j^L, ε_j^D and ε_j^F stand for the corresponding embodied energy intensity of local intermediate input, domestic intermediate import and foreign intermediate import from Sector i to j. x_i is the vector of total output of Sector i.

The corresponding equation can be expressed in a compressed matrix form as:

$$E + \varepsilon^F Z^{FL} + \varepsilon^D Z^{DL} + \varepsilon^L Z^{LL} = \varepsilon^L X^L \tag{2}$$

Where $E = [e_i]_{1\times n}$, $\varepsilon = [\varepsilon_i]_{1\times n}$, $Z = \lfloor Z_{ij} \rfloor_{n\times n}$, and diagonal matrix $X = \lfloor x_{ij} \rfloor_{n\times n}$, where $i, j \in (1,2,\cdots, n)$, $x_{ij} = x_i (i = j)$, and $x_{ij} = 0 (i \neq j)$. Therefore, the three-scale embodied energy intensity matrix ε^L is obtained as:

$$\varepsilon^L = \left(E + \varepsilon^F Z^{FL} + \varepsilon^D Z^{DL}\right)\left(X^L - Z^{LL}\right)^{-1} \tag{3}$$

Given this, the energy use embodied in final demand $\left(EEF^L\right)$, domestic imports $\left(EEDI^L\right)$, domestic exports $\left(EEDE^L\right)$, foreign imports $\left(EEFI^L\right)$, foreign exports

$\left(EEFE^{L}\right)$, domestic balance $\left(EEDB^{L}\right)$ and foreign balance $\left(EEFB^{L}\right)$ can be obtained as:

$$EEF^{L} = \sum_{i}^{n} EEF_{i}^{L} = \sum_{i}^{n} \left(\varepsilon_{i}^{L} f_{i}^{LL} + \varepsilon_{i}^{D} f_{i}^{DL} + \varepsilon_{i}^{F} f_{i}^{FL} \right) \tag{4}$$

$$EEDI^{L} = \sum_{i}^{n} EEDI_{i}^{L} = \sum_{i}^{n} \left(\varepsilon_{i}^{D} \left(\sum_{j}^{n} z_{ij}^{DL} + f_{i}^{DL} + de_{i}^{DD} + ex_{i}^{DF} \right) \right) \tag{5}$$

$$EEDX^{L} = \sum_{i}^{n} EEDX_{i}^{L} = \sum_{i}^{n} \left(\varepsilon_{i}^{L} de_{i}^{LD} + \varepsilon_{i}^{D} de_{i}^{DD} + \varepsilon_{i}^{F} de_{i}^{FD} \right) \tag{6}$$

$$EEFI^{L} = \sum_{i}^{n} EEFI_{i}^{L} = \sum_{i}^{n} \left(\varepsilon_{i}^{F} \left(\sum_{j}^{n} z_{ij}^{FL} + f_{i}^{FL} + de_{i}^{FD} + ex_{i}^{FF} \right) \right) \tag{7}$$

$$EEFX^{L} = \sum_{i}^{n} EEFX_{i}^{L} = \sum_{i}^{n} \left(\varepsilon_{i}^{L} de_{i}^{LF} + \varepsilon_{i}^{D} de_{i}^{DF} + \varepsilon_{i}^{F} de_{i}^{FF} \right) \tag{8}$$

$$EEDB^{L} = \sum_{i}^{n} EEDB_{i}^{L} = \sum_{i}^{n} \left(EEDI_{i}^{L} - EEDX_{i}^{L} \right) \tag{9}$$

$$EEFB^{L} = \sum_{i}^{n} EEFB_{i}^{L} = \sum_{i}^{n} \left(EEFI_{i}^{L} - EEFX_{i}^{L} \right) \tag{10}$$

Besides, the transformation from official competitive economic input-output tables to the non-competitive input-output tables is based on the assumption that the imported products have been distributed to intermediate input and final use with the same ratio as local products (Shao et al., 2017; Shao et al., 2016). The first order approximation is presented as follows:

$$z_{ij}^{L} = z_{ij} \left(x_i / x_i + x_i^{D} + x_i^{M} \right) \tag{11}$$

$$z_{ij}^{D} = z_{ij} \left(x_i^{D} / x_i + x_i^{D} + x_i^{M} \right) \tag{12}$$

$$z_{ij}^{M} = z_{ij} \left(x_i^{M} / x_i + x_i^{D} + x_i^{M} \right) \tag{13}$$

$$f_{ik}^{L} = f_{ik} \left(x_i / x_i + x_i^{D} + x_i^{M} \right) \tag{14}$$

$$f_{ik}^{D} = f_{ik}\left(x_i^D / x_i + x_i^D + x_i^M\right) \quad (15)$$

$$f_{ik}^{M} = f_{ik}\left(x_i^M / x_i + x_i^D + x_i^M\right) \quad (16)$$

Where x_i^D is the domestic imported monetary flow in Sector i and x_i^F is the foreign imported economic flow in Sector i. z_{ij} denotes the total intermediate input from Sector i to Sector j and f_{ik} is the total final demand of category k in Sector j.

2.2 Data sources

During the ten years from 2002 to 2012, Beijing has witnessed the hosting of Olympic Games and global financial turmoil. Moreover, large-scale industrial restructuring has been implemented thoroughly, which leads to the profound influence on economic structure adjustment. Therefore, the time period from 2002 to 2012 is chosen as a great research sample. The official competitive economic input-output tables for Beijing are obtained from Beijing Statistical Bureau (BSB, 2004; 2007; 2009; 2012; 2014). These input-output tables for Beijing published are year-apart, only the input-output tables for 2002, 2005, 2007, 2010 and 2012 can be obtained from Beijing Statistical Bureau. Therefore, these five years are selected as the representative years during this period to reflect evolution features of Beijing's basic energy perspective. The Eora database is selected as the supporting data to evaluate the embodied energy intensities of Beijing's foreign/domestic imported goods and services in terms of its relative high resolution (189 economies, 26 sectors) and the long time-series coverage (Lenzen et al., 2012; Lenzen et al., 2013). Notably, price changes induced by the long time-series constant-price input-output tables using the double-deflation method (Almon, 2009). The price indices of all sectors needed for double-deflation method are collected from various sourced, as presented in Appendix Table A2 (BSY, 2003; 2006; 2008; 2011; 2013). The statistical data contributed by the International Energy Agency extended energy balances are referred to for energy production by different economies globally. The energy exploitation data of Beijing are derived from China Statistical Yearbook (CESY, 2003; 2006; 2008; 2011; 2013).

2.3 Uncertainty analysis

The identification and management of uncertainty and variability for MRIO analysis and three-scale analysis is crucial. These uncertainties would induce the fluctuations of results. There are several main factors that contribute significantly to the uncertainties and variabilities of this study, such as temporal price fluctuations, average intensity deviation, sectoral aggregation errors and custom statistical errors of enterprise trade. Since long time span evolution investigation requires unified price metrics, the double subtraction method was taken in this study to eliminate the influence of price fluctuation on the monetary flows in the input-output table, especially at urban scale (Almon, 2009). Moreover, the three-scale model introduces average intensities of domestic scale and global scale to distinguish intensities of import products and local products. Owing to the lack of detailed sectoral trade data, the weighted average processing is based on the output value of each country's different sectors. These limitations created deviations in the results. However, compared with artificially constructing inaccurate sectoral trade links based on the assumption that the international exports/imports of an urban economy are distributed among all foreign economies in the same proportion as China’s total exports/imports. The three-scale model has minimized the inaccuracy. Furthermore, there exists aggregation errors in the process of MRIO table construction, as well as the process of connecting 26 sectors-based Eora intensity database to 42 sectors-based Beijing input-output data. Based on the original data resolution in the heterogeneous global system, different economies have different sector classifications that ranges from 26 to 511. Yet, this study adopts the simplified model in which all economies have been aggregated to a 26-sector system. This aggregation error has been investigated by numerous studies (Lenzen et al., 2010; Steen-Olsen et al., 2014; Su and Ang, 2010). Finally, the evaluation of Beijing’s headquarter dominated energy use pattern is based on the statistical principle of “legal person's places of business” when compiling input-output tables for cities. However, the missing statistics of some micro-enterprises, possible repeated accounting induced by cross-regional attribution of headquarters, as well as confused classification owing to complex integrated industrial structures all can exert different fluctuation errors (Yan and Li, 2009). These deviations in statistical process are usually controlled within 10%, that can not influence the overall headquarter dominated economic and energy use profiles.

3. Results

3.1 Energy embodied in final use

The variation trend of energy embodied in final use of Beijing from 2002 to 2012 is portrayed in Fig. 2. The total energy embodied in final use is more than doubled during the accounting period, increasing from 1260 PJ in 2002 to 3040 PJ in 2012. Owing to the economic depression induced by the decrease in employment, Beijing's total final demand witnessed a decline under the widespread influence of global financial crisis (Li et al., 2014a). Therefore, the growth rate of energy embodied in Beijing's final use decelerates during 2007-2010. After Chinese government implementing a series of stimulus plans to increase domestic demand and fight against the crisis, this growth rate experiences a rebound during 2010-2012. In the contrary, the respective direct energy exploitation declines from 259 PJ to 146 PJ, showing a decoupling tendency. The heavy dependence on embodied energy outside the city boundary to meet its own requirements manifests that only taking direct energy input into consideration can lead to significant spillover effects.

As for the contributions of original sources from each scale, energy use originally from domestic imports occupies the largest share of the total amount in final use averagely, with a proportion of 83.13%, followed by foreign imports (12.15%) and local exploitation (4.73%). Notably, the embodied energy use from foreign scale witnesses a persistent growth from 5.36% in 2002 to 14.09% in 2012, compensating the share loss of energy use from local scale, which decreases from 11.85% in 2002 to 0.10% in 2012. Besides, Energy embodied in three kinds of final use, namely, household consumption including both rural and urban household consumption, government consumption and total capital formation, including fixed capital formation and inventory change, is also compared in Fig. 2. Fixed capital formation is the top final user, contributing more than half to the total embodied energy use during the accounting periods, followed by the household consumption, consecutively sharing a quarter of the total energy use in final demand during the studied ten years.

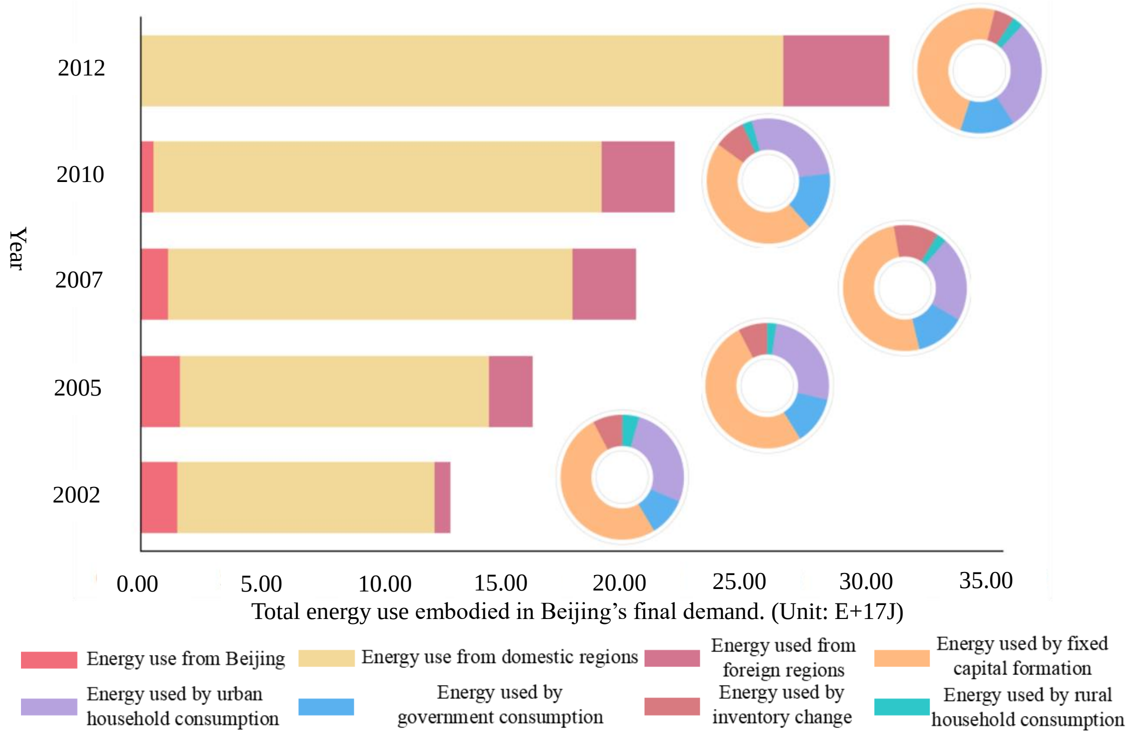

Fig. 2. Energy resources embodied in the final use of Beijing economy from 2002 to 2012

3.2 Energy embodied in trade

Fig. 3 expounds on the overall energy use embodied in Beijing's trade with domestic and foreign sources. Total amount of net embodied energy imports is 1340 PJ per year averagely, which is 6.56 times of energy directly exploited. Disparities depicted above indicate that energy use in Beijing is far much significantly dependent on trade transfers than local exploitation. Therefore, detailed energy profiles along domestic and foreign supply chain are discussed as follows.

3.2.1 Energy embodied in domestic and foreign trade

As portrayed in Fig. 3(a) and (b), energy use embodied in domestic trade is far much larger than the amount embodied in foreign trade, indicating that Beijing has closer relationships with domestic economies than foreign economies. Generally, Beijing is a typical energy receiver of domestic and foreign supply chain, net importing total embodied energy from 1180 PJ in 2002 to 28400 PJ in 2012. As demonstrated in Fig. 3(a), energy use embodied in domestic imports and exports are identical in order of magnitude and shows consistent changing trend, which slightly increase from 2180 PJ and 989 PJ in 2002 to 3810 PJ and 1580 PJ in 2007 but grow substantially to 3660 PJ and 2900 PJ in 2012. Correspondingly, the net domestic imported energy also grows modestly from 1190 PJ in 2002 to 2220 PJ in 2007. It begins to accelerate in the following five years and significantly jumps to 7560 PJ in 2012. That can be explained by the ever-increasing domestic imports and exports, owing to selling and re-location businesses' shifting to enterprises' headquarters in Beijing.

Energy use embodied in foreign imports also grows sluggishly from 190 PJ in 2002 to 699 PJ in 2007. Accompanied by headquarters of multinational corporations' (MNCs) intruding into Beijing, a huge jumping occurs in the next five years, which reaches the pinnacle at 223 PJ in 2012, 21.01 times higher than that in 2007. For instance, American Amazon Group, with its cloud computing center, formally settles in Beijing in 2012, bringing 250 billion dollars into the account annually. However, energy embodied in foreign exports continuously maintains a low-level from 203 PJ in 2002 to 1420 PJ in 2012. The intensifying headquarter functions are reflected by the sudden reverse of embodied energy in foreign trade from net exporting 73.5 PJ in 2007 to net importing 20900 PJ in 2010. During 2010-2012, due to the surge of foreign imported energy, the net foreign imported energy increases more than tenfold.

The results of the pie charts illustrate that the ratio between energy embodied in domestic intermediate imports and final imports witnesses a sharp decline from 1.03 in 2002 to 0.19 in 2012. Corresponding ratio of foreign part also drops from 0.57 in 2002 to 0.06 in 2012, manifesting Beijing’s transformation from a productive city dominated by manufacturing to a consumptive city. Besides, as portrayed in the inner ring of the pie charts, embodied energy used for exports is mainly through local production in 2002, contributing 65.09% of domestic exports and 62.84% of foreign exports. However, this proportion decreases to 15.32% and 33.15% in 2012. Instead of exporting energy intensive products manufactured by local factories to other domestic regions, Beijing is becoming more enthusiastic in selling goods and services that have been processed completely by regions outside. Its control and command functions from energy perspective are emerging accompanied by the development of headquarter economy.

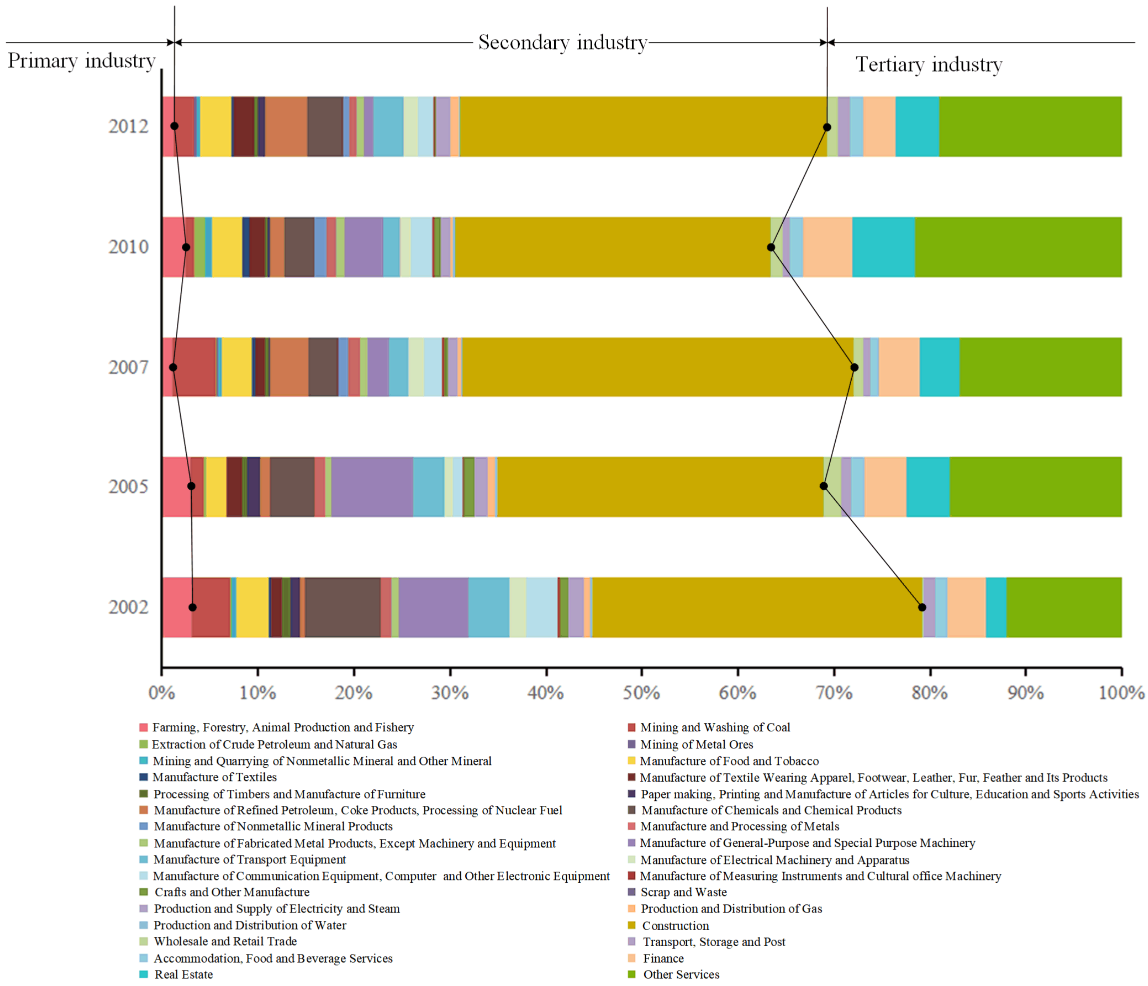

Fig. 3. Energy embodied in the final use divided by sectors

To sum up, what kind of characteristics can fully reflect the significant influences put by the headquarter economy on energy requirements of Beijing? As illustrated in section 2.1, energy structure that is dominated by the headquarter economy should possess large amount of energy use embodied in de_i^{DD} (domestic imported products that used to domestic exports), de_i^{FD} (foreign imported products that used to domestic exports), ex_i^{DF} (domestic imported products used to foreign exports) and ex_i^{FF} (foreign imported products used to foreign exports). The outstanding rise of total energy use embodied in imports and exports has already been shown in Fig. 3, therefore, a significant increase in proportion of energy use embodied in these four parts is the distinctive salience of headquarter economy. Energy use embodied in these four parts, which are carried by products imported from non-local regions and then exported to other regions denotes the energy transfer ability of Beijing. From a holistic perspective, as portrayed in Fig. 4, the proportion mentioned above firstly witnesses a slight decline from 17.76% of imports and 35.30% of exports in 2002 to 16.72% and 32.24% respectively in 2005, and experiences a continuous ascent from 2005 to 2012, reaching the pinnacle at 43.37% and 83.85% respectively in 2012. Since when the headquarter economy concept been firstly come up in China, the growth rate for the share of energy use embodied in these four parts gets bigger every year.

Concretely, the rapidly increasing proportion of energy embodied in ex_i^{DF} (domestic imported products used to foreign exports) from 6.38% of imports and 12.20% of exports in 2007 to 15.83% and 28.34% in 2010 respectively, contributes the most for the total four parts' growth range. However, in time range from 2010 to 2012, the skyrocketed share of energy embodied in de_i^{FD} (foreign imported products that used to domestic exports) from 4.00% in imports and 7.16% in exports to 17.52% and 33.87% respectively dominates the overall proportion's increasing. These results demonstrate different driven forces of headquarter economy during different time ranges. As "The World Factory", large amounts of manufacturing products are processed in Chinese boundary, and are allocated through uniform trading business of headquarters during the period from 2007-2010. However, changing trend from 2010 to 2012 is profoundly influenced by headquarter functions of large state-owned enterprises such as China National Petroleum Corporation (CNPC) and Sinopec Group. Energy requirements especially oil and natural gas, that highly dependent on imports from foreign world, are purchased in and then re-located to domestic regions across China thanks to the headquarter functions of these enterprises.

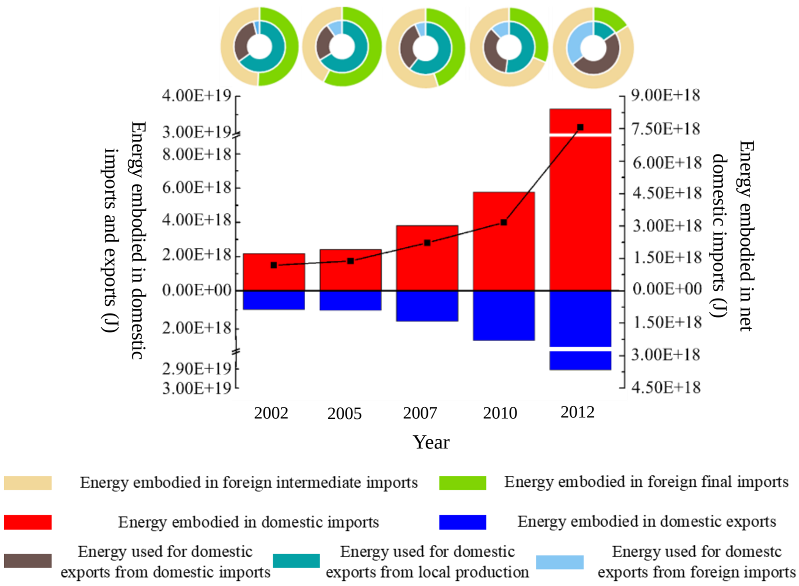

Fig. 4(a). Energy embodied in domestic trade

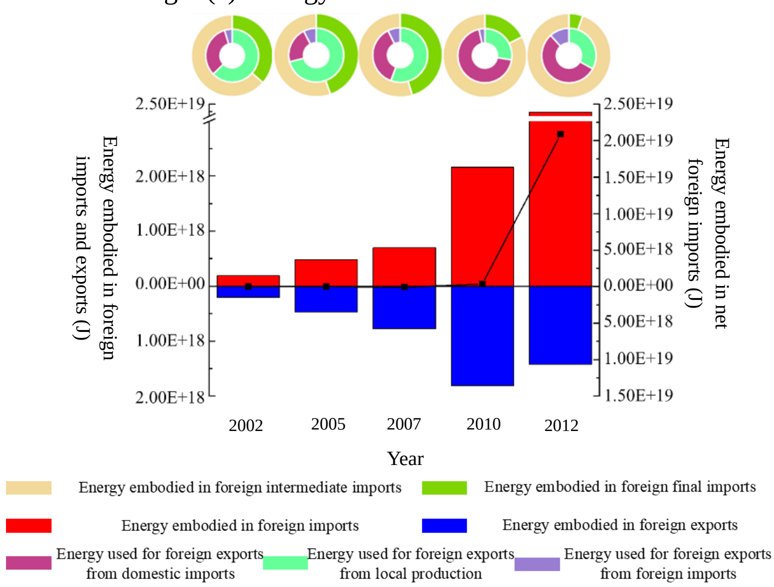

Fig. 4(b). Energy embodied in foreign trade

Fig. 4. Temporal evolution for energy use embodied in domestic and foreign trade (The columns above the abscissa axis denote energy embodied in domestic or foreign imports, while the below columns stand for exports; lines represent energy embodied in net domestic or foreign imports. The outer ring represents the contributions of energy embodied in intermediate and final imports,

and the inner ring shows the original sources from local production, domestic imports and foreign imports for Beijing's exports)

3.2.2 Energy use embodied in trade of typical industries

To explicate the full range influence induced by the gradual growing headquarters in Beijing, three typical sectors are selected. Total amount of energy use embodied in trade of the three typical sectors are depicted in Fig. 5 (Detailed values see in the Appendix). Fig. 6 focuses on the composition of energy embodied in domestic and foreign trade, which varies significantly during the accounting period. The total imports and exports of *Manufacture of Communication Equipment, Computer and Other Electronic Equipment Sector* both have an inverted-U trend as they firstly rise from 150 PJ and 158 PJ in 2002 to 397 PJ and 387 PJ in 2007, then drop to 297 PJ and 248 PJ in 2010, and reach the pinnacle at 835 PJ and 758 PJ in 2012. From perspective of composition, de_i^{LD} (the local products used to satisfy domestic use in external economies) occupies 45.34% of the total exports in 2002. That manifests the ability of producing electronic elements during early stage. Notably, the sharp skyrocketing proportion of ex_i^{DF} (domestic imported products used to foreign exports) in total energy embodied in imports and exports grow rapidly from 4.63% and 6.24% in 2002 to 21.97% and 33.97% in 2007, respectively. Owing to the large-scale annexation and reorganization of enterprises, as well as headquarters' relocation in domestic regions, occupations of de_i^{DD} (domestic imported products that used to domestic exports) in the total imports and exports also increases dramatically from 12.89% and 17.37% in 2007 to 27.17% and 48.12% in 2012, respectively.

Remarkable changes induced by headquarter economy in typical energy intensive sectors, such as *Steam and Extraction of Crude Petroleum and Natural Gas Sector* and *Production and Supply of Electricity Sector,* contribute most to the total energy use alteration induced by headquarter economy. It’s interesting to note that almost all energy resource embodied in imports of *Steam and Extraction of Crude Petroleum and Natural Gas Sector* is supplied by domestic regions in 2002, with an amount of 2.47 PJ. However, embodied energy imported from foreign regions begins to take up a large slice of the total imports, accounting for 16.99% of total imports in 2007. Owing to the monopoly of oil and gas industry in China, the oil and gas required by mainland China is virtually distributed almost only by the headquarters of state-owned oil and gas enterprises in Beijing, while the physical term may not even appear in Beijing. Therefore, de_i^{FD} (foreign imported products that used to domestic exports) dominates the imports by roughly half in 2012, which exceeds the level of 2007 by 2.39 times. Embodied energy requirements of *Production and Supply of Electricity Sector* also vary in the accounting period, with the similar trend as that of *Steam and Extraction of Crude Petroleum and Natural Gas Sector*. Transmission and distribution of electricity are controlled consistently by the headquarter of State Grid in Beijing, leading to de_i^{DD}’s (domestic imported products that used to domestic exports) soaring to 472 PJ in 2012, which is 29.16% of the total imports.

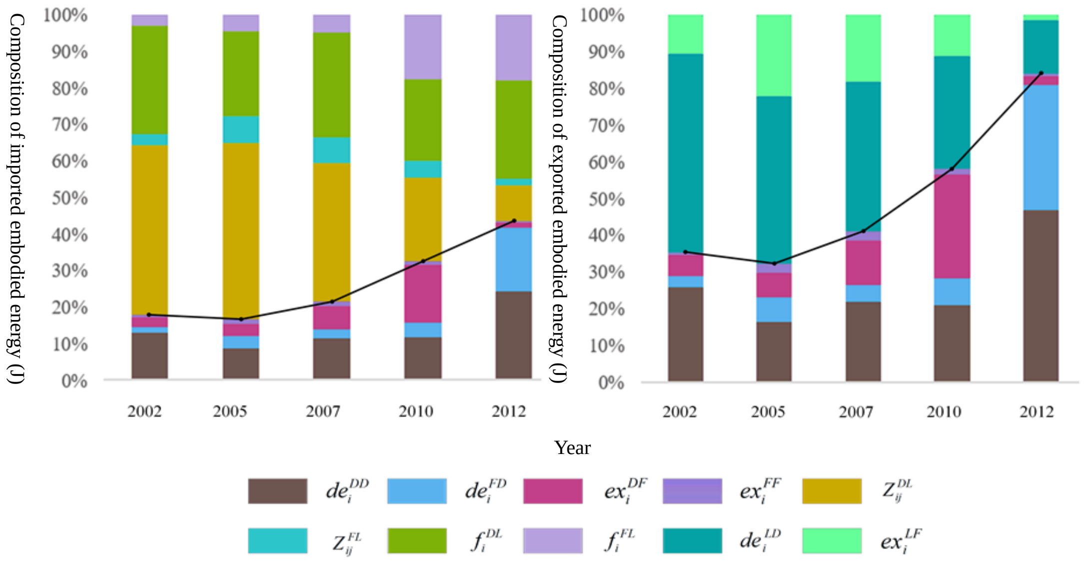

Fig. 5. Energy use composition embodied in domestic and foreign trade (de_i^{DD} denotes imported products that used to domestic exports, de_i^{FD} denotes foreign imported products that used to domestic exports, ex_i^{DF} denotes domestic imported products used to foreign exports, ex_i^{FF} denotes foreign imported products used to foreign exports, z_{ij}^{DL} denotes domestic imported products that are used as intermediate inputs for local sector, z_{ij}^{FL} denotes foreign imported products that are used as intermediate inputs for local sector, f_i^{DL} denotes the domestic imported products to satisfy local final demands, f_i^{FL} denotes the foreign imported products to satisfy local final demands, de_i^{LD} denotes the local products used to satisfy domestic use in external economies, ex_i^{LF} denotes the local products used to satisfy foreign use in external economies. The evolution for energy use composition of imports (de_i^{DD}, de_i^{FD}, ex_i^{DF}, ex_i^{FF}, z_{ij}^{DL}, z_{ij}^{FL}, f_i^{DL}, and f_i^{FL}) and exports (de_i^{DD}, de_i^{FD}, ex_i^{DF}, ex_i^{FF}, de_i^{LD} and ex_i^{LF}) are showed in this figure. Lines in the figure denote the total proportion of energy use embodied in de_i^{DD}, de_i^{FD}, ex_i^{DF} and ex_i^{FF} in imports and exports respectively, which represents embodied energy transfers induced by headquarter economy)

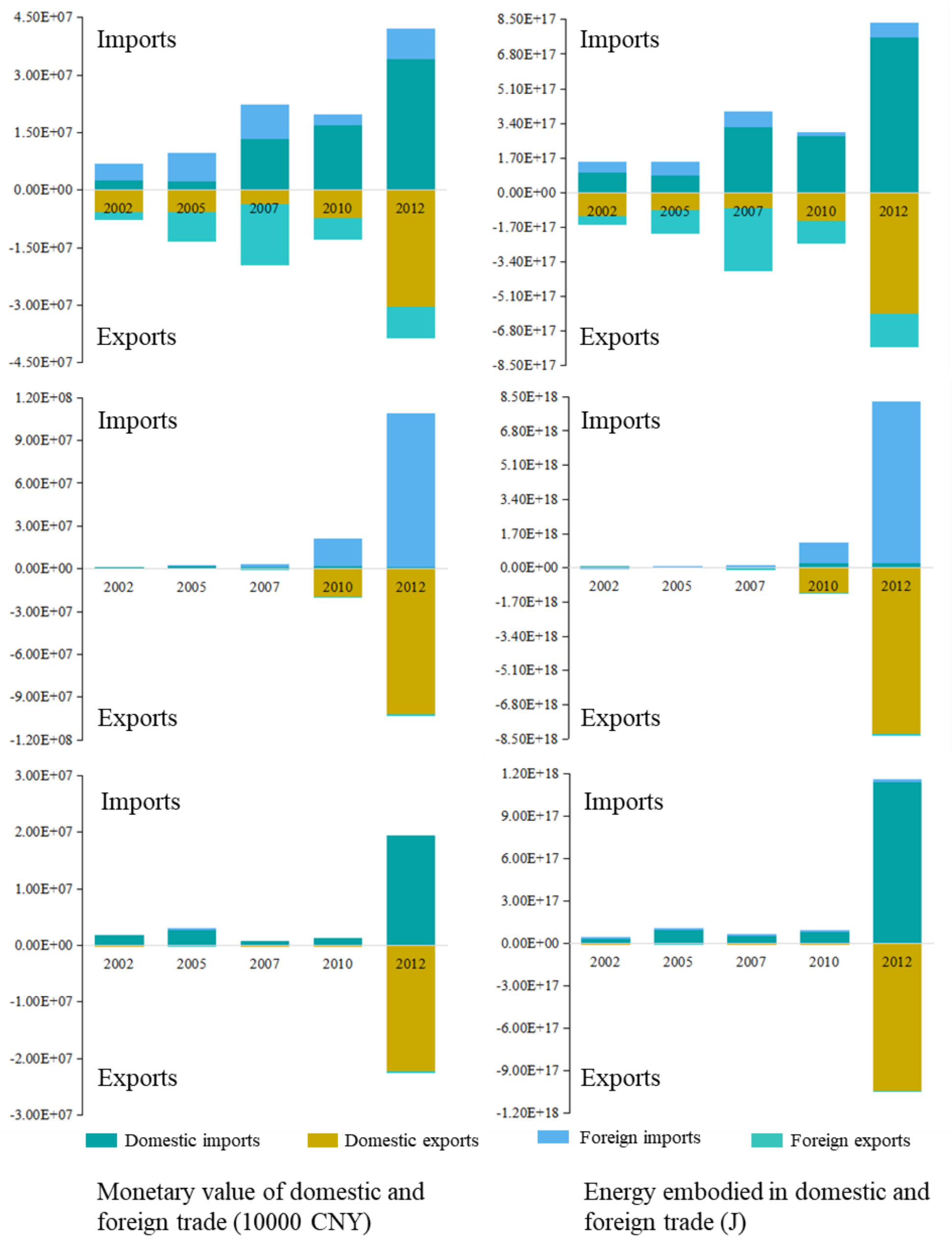

Fig. 6. Total monetary value and energy use embodied in trade of the three typical sectors (Corresponding detailed data see in the Appendix)

3.3 Source-to-sink budget

Energy embodied in the total energy use of Beijing consists of direct inputs from local exploitation and indirect inputs from domestic and foreign scales (Coulter, 2012). Original sources of energy embodied in Beijing's final use and trade activities has been analyzed in section 3.1, 3.2. However, how much pressure the total energy outputs in Beijing put on different kinds of original energy sources is still unidentified. To explore the origination of energy requirements divided by oil, coal, natural gas, hydro power and nuclear power in Beijing, the source-to-sink budget is established in Table 2.

On one hand, raw coal use in Beijing occupies more than three-quarters of the total energy use. The booming construction infrastructure leads to the total amount of coal resources use almost tenfold during 2002-2012. It’s originated mainly from domestic imports (83.32%), followed by direct energy exploitation (13.94%) in 2002. Owing to headquarter functions, importing coal resources from international market is tend to be responsible by headquarters of coal companies in Beijing. Coal use originated from foreign imports shares 32.55% of its total use in 2012. Crude oil and natural gas, without local supply, is heavily relies on imports. Headquarters of oil and natural gas companies make crucial effects in importing resources from foreign world and distributing them to meet energy requirement across regions in China. That leads to total use of oil and natural gas, which originated from foreign imports, changing from 91 PJ (18.07%) in 2002 to 2990 PJ (50.07%) in 2012.

On the other hand, energy used for domestic exports dominates energy demand during the accounting period, of which the domestic import items contribute the most. Notably, policies aimed to attract headquarters of large transnational corporations stimulate the rising share of foreign imports, which compensate the share loss of energy originated by local exploitation. The occupation of energy embodied in foreign imports used for domestic exports, raises in ever-increasing quantities from 16.20% to 38.29% during 2007-2012. That underlines the intensified energy transfers and turnovers of Beijing induced by the headquarter economy.

Table 2. Evolution of source to sink budget of energy use in Beijing from 2002 to 2012. Unit: PJ

Source to sink flows	2002	2005	2007	2010	2012
Direct exploitation → Coal	257.87	276.65	189.91	146.39	144.33
Direct exploitation → Hydro power	1.48	1.70	1.77	1.58	1.58
Domestic imports → Oil	327.44	311.60	477.08	550.39	2116.48
Domestic imports → Coal	1541.55	1874.41	2811.47	3540.80	17541.84
Domestic imports → Natural gas	85.29	99.57	131.06	186.13	865.20
Domestic imports → Hydro Power	52.41	56.79	60.66	91.61	488.11
Domestic imports → Nuclear Power	26.08	35.11	58.48	76.74	291.10
Foreign imports → Oil	63.86	133.62	250.87	382.10	1791.64
Foreign imports → Coal	50.69	164.81	235.84	1284.61	8535.37
Foreign imports → Natural gas	27.16	65.21	94.04	229.40	1198.18
Foreign imports → Hydro Power	2.12	5.17	7.52	13.88	65.85
Foreign imports → Nuclear Power	13.79	25.18	48.20	56.70	218.71
Domestic imports → Household consumption	332.44	366.39	392.85	519.90	785.82
Domestic imports → Government consumption	97.14	146.75	205.63	269.55	59.15
Domestic imports → Total capital formation	612.42	741.83	1046.94	1029.24	1521.60
Domestic imports → Domestic exports	821.53	771.79	1269.63	1948.79	17781.32
Domestic imports → Foreign exports	169.25	350.73	623.71	678.18	1155.30
Foreign imports → Household consumption	20.20	42.76	68.22	106.45	173.88
Foreign imports → Government consumption	6.39	20.10	46.13	53.47	23.01
Foreign imports → Total capital formation	40.86	113.51	141.47	135.21	201.65
Foreign imports → Domestic exports	71.82	134.56	256.42	1507.65	11119.83
Foreign imports → Foreign exports	18.35	83.06	124.23	163.91	261.87
Direct exploitation → Household consumption	41.88	46.18	30.70	23.00	1.28

Direct exploitation ⟶ Government consumption	22.41	31.03	7.77	7.74	0.80
Direct exploitation ⟶ Total capital formation	84.85	83.24	71.63	252.31	3.64
Direct exploitation ⟶ Domestic exports	95.36	81.16	57.14	61.86	138.54
Direct exploitation ⟶ Foreign exports	14.86	36.75	24.43	33.06	1.65

Note: Both original different kinds of energy use and the total energy use embodied in Beijing's total outputs are supplied by local exploitation, domestic imports and foreign imports.

4. Discussions and policy implications

The ever-increasing energy embodied in Beijing's inflows and outflows reveal the fact that the headquarter effect is gradually reshaping energy profiles of cities, which locate at the apex of new global hierarchy (Godfrey and Zhou, 2013; Rice and Lyons, 2010). As our results imply, total energy use embodied in Beijing's imports and exports grow from 2370 PJ and 1190 PJ in 2002 to 26000 PJ and 4320 PJ in 2012, respectively. Moreover, share for energy use which is accumulated along upstream supply chain and then redistributed by Beijing's headquarter effect–increases from 17.76% of imports and 35.30% of exports in 2002 to 43.37% and 83.85% respectively in 2012, indicating that the headquarter effect in Beijing has posed great impacts on the prominent transfers of embodied energy.

Owing to the economic growth boosted by enormous financial gains from giant enterprises' headquarters, governments in Beijing have implemented a series of preferential measures to attract headquarters depending on the superiorities of capital city (Zhao, 2013). They firstly propose "energetically develop the headquarter economy" in *The 11th Five-Year Plan for Economic and Social Development* (2006-2010), and vigorously implement the policy of "further expand the advantage of headquarter economy" in *The 12th Five-Year Plan for Economic and Social Development* (2011-2015). As reported, the headquarters base constructed in Fengtai has successively attracted more than 200 headquarters of enterprises till 2008 (Tan et al., 2008). Such implications promote the peak period's arrival of embodied energy layout dominated by the headquarter effect. By the end of 2012, headquarter enterprises owned 70.4 trillion yuan of assets, accounting for 63.5% of the city's total assets, and realized a revenue of 7.3 trillion CNY, accounting for 59.9% of the city's total income. By collecting data about enterprises' assets, business income and total profits, the contributions of headquarters to Beijing's sectoral monetary gains can be accounted as demonstrated in the Table 3.

Table 3. Company-scale data for headquarters of each sector's enterprises in 2013. Unit: one thousand CNY

Sectors	Total assets of HQs	Total assets of all companies	Proportion	Total business income of HQs	Total business income of all companies	Proportion	Total profits of HQs	Total profits of all companies	Proportion
Manufacture	9.54	17.83	53.53%	8.53	#	#	0.58	0.86	67.84%
Construction	14.44	18.00	80.21%	8.02	10.20	78.56%	0.40	0.44	91.71%
Wholesale and retail	25.68	40.40	63.57%	35.73	55.35	64.55%	0.88	1.02	85.64%
Information transmission, software and information technology services	22.39	28.00	79.97%	3.12	5.69	54.87%	1.66	1.83	90.83%
Finance	622.66	873.34	71.30%	14.49	16.73	86.64%	10.21	10.96	93.15%
Leasing and business services	80.93	116.95	69.20%	6.34	10.10	62.75%	2.98	3.19	93.35%
Scientific research and technical services	10.56	20.33	51.92%	3.58	5.80	61.81%	0.47	0.67	70.74%

Through accelerating the separation of upstream manufacturing bases and downstream sales market (Alderson and Beckfield, 2004), the prominent headquarter effect has contributed significantly to Beijing's stunning economic output while keeping its direct energy exploitation at a relatively low level. As our results imply, when the total energy embodied in final use increases from 1260 PJ in 2002 to 3040 PJ in 2012, the respective direct energy exploitation declines from 259 PJ to 146 PJ, showing a decoupling tendency. At the same time, the extraction regions sacrifice enormous environmental benefits in the mode of headquarter effect to obtain much smaller economic benefits. Therefore, energy regulation strategy originating from the current energy abatement responsibility assignment mechanism need more consulting to the scientific evaluations that are influenced by the headquarter effect, rather than solely following the current energy abatement policies that are confined in the framework of the direct energy accounting. Nevertheless, previous misleading policies released by The 11th/12th Five-Year Plan for Economic and Social Development of Beijing still mainly focus on direct energy consumption, leading to precious information loss of indirect energy use. For instance, in order to reduce local energy intensity, measures like simply displacing the energy-intensive industries to other regions and even replacing electricity from local coal power plants by imported electricity from other regions have been implemented by the government. These policies may even lead to an increase in energy consumption nationwide. Given that, we suggest Beijing's headquarters with enriched capital and technology and production base with affluent labor and natural resources carry out synergetic measures in energy conservation. Environmentally sound technology diffusion and clean energy financing for production base should be encouraged to realize greater cooperative engagement in overall energy conservation.

Distinguished with previous consumption-based analysis, this study pays due attentions to Beijing's transboundary embodied energy trade features. In addition to policies mentioned above, the empirical results obtained in this study can provide valuable references for market-oriented policies that can give full paly to Beijing's role in the cooperative governance of upstream production activities and downstream consumption demand. When the headquarters in Beijing allocate goods/services to economies around the world, they also redistribute energy resources embodied in these goods/services which are exploited along the supply chain and consumed in their production processes. The rationally planning for cities' energy use dominated by headquarter effect, and collective and inclusive governance of energy supply chain by headquarters would contribute significantly to global reduction of energy exploitation. Concretely, headquarters should choose suppliers intensive in low carbon technologies, and choose more environmentally friendly downstream distributors with less energy consumption. Sharing of information among headquarters and sub-companies along the supply chain is in urgent need to realize energy conservation from the overall national or even global perspective. The headquarters can also transmit the upstream energy consumption structure to stakeholders on the one hand and to consumers on the other hand who are able to guide the global economy onto the path of sustainability across their consumption decisions.

For the *Manufacture of Communication Equipment, Computer and Other Electronic Equipment Sector*, it should be noted that “Cultivating and expanding high-tech service industry” is purposed by government in *The 12th Five-Year Plan for Economic and Social Development*. As a result, the sharing of de_i^{DD} soars in ever-increasing quantities from one-tenth to almost half of the total transferred energy during 2010-2012. This amazing growth rate is far in excess of the occupation for de_i^{FD} (foreign imported products that used to domestic exports), indicating the more prominent influence of headquarter effect on domestic electronic products companies than foreign enterprises. For instance, LINPO LCFC, Lenovo’s largest PC manufacturing and R&D base that locates in Hefei, manufactures nearly 30 million computers for its headquarter in Beijing recently[1] and simultaneously contributes a lot to the large amount of de_i^{DD} (domestic imported products that used to domestic exports) in Beijing. Owing to the geographical aggregation of different industries’ headquarters, information exchange and knowledge spillover among industries become more convenient. Given that, headquarters in Beijing are suggested make full use of this advantage to investigate high energy efficiency technologies along the supply chain. They can also create sectoral standards that use incentives or sanctions to help energy conservation across the whole supply chain, or design products to improve existing ones to minimize material and energy use. For special industries such as *Manufacture of Communication Equipment, Computer and Other Electronic*

1 http://www.sohu.com/a/167022312_254578

Equipment Sector, enterprises should coordinate the quantitative supply of electronic products manufactured by factories in other regions and the whole sales volume by the headquarters in Beijing to realize the balance between energy use supply and demand, and to avoid the overcapacity or waste of energy.

Besides, the headquarter economy is reflected thoroughly in state monopolized industries, whose products are consistently redistributed by their headquarters. It is exactly these parts of headquarters that most significantly influence energy embodied in trade. As for the *Production and Supply of Electricity and Steam Sector*, the reform of electricity system emphasized on the separation of factories and power grids was finished in 2012. As a result, it can be clearly shown that energy embodied in domestic trade has been surging from 77.7 PJ in 2010 to 2180 PJ in 2012 (see in Table 2). The *Steam and Extraction of Crude Petroleum and Natural Gas Sector* dominates large amount of energy supply across China, which accounts for 27.78% of the total energy use embodied in trade. Headquarters in Beijing, China National Petroleum Corporation (CNPC), control the allocation and sales of oil and gas resources through various online trading platforms. Actually, the products selling and its capital incomes, which are originally controlled by local subsidiaries, transfer in large proportion to enterprises' headquarters. For bulk energy commodities, the energy benefits brought by these headquarters' (like China National Petroleum Corporation) overall management and redistribution effects can prevent energy excessive use induced by malicious competition among regional subcompany and achieve optimal energy allocation nationwide.

Generally, Beijing's overall embodied energy abatement should be subjected to the whole nation's policy framework. Coordination of relationships among headquarters and their upstream subsidiaries can realize the most objective energy conservation from national perspective. Such policies can make contribution to preventing overall energy waste induced by blindly scrambling for headquarters, as well as the maximized energy rational re-location. Concretely, the local government should break through the traditional view in direct energy consumption reduction focused policies, and broad their eyesight to cooperation in Beijing-Tianjin-Hebei Region. Efficiently integrate technology advantages, caliber candidates in Beijing, low cost labor and production materials in Hebei, and convenient port passage in Tianjin, to build the green energy supply chain around Beijing featured by headquarter economy. Inversely, as expected, the "Orderly dissolving non-capital functions" and "selective optimal development of headquarter economy" have been stressed in *The 13th Five-Year Plan for Economic and Social Development*. Energy requirements changes to support such a typical headquarter economy in Beijing may slacken in the near future. Then, headquarters of several enterprises may move from Beijing to the newly established Xiong'an New Area. That may bring new changes to the overall energy use evaluation for Beijing, which can be discussed in further studies.

In particular, the measures provided above only rely on the MSIO method, which is dependent on a basic three-tier structure and applied in this study to give a preliminary overview of Beijing's headquarter dominated energy trade structures, before moving towards more detailed investigation. It must be pointed out that the conclusions obtained by this method have certain limitations. For instance, the MSIO method is not compatible to differentiate every single region with different production technology, resource use and pollution intensities (Wiedmann, 2009). The introduction of domestic and global scales' average intensities for every sector also creates inevitable deviations. In this sense, if accurate and detailed custom data were available to support urban economies' tele-connecting trade analysis or high-resolution MRIO modelling, future studies could go one step further to capture the full spectrum of embodied energy flow patterns by considering all the specific trade partners along the complex global supply chains (Chen et al., 2019; Hubacek et al., 2009; Li et al., 2018a). Moreover, the hybrid life-cycle-based approach could also track trans-boundary energy flows embodied in detailed trade lists for goods and services. The data collection and model development are still challenging missions for some cities. If expenditure data at the level of metropolitan statistical areas are available, a hybrid life-cycle-based approach could be adopted by future studies for developing more holistic energy use pictures for cities (Chen et al., 2020). Besides, to spur materials recycling and conservation as well as alternative materials policies, further works could concentrate on tracking trans-boundary energy flows embodied in key materials and different industries' trade in parallel.

5. Concluding remarks

Intensifying globalization exacerbate a new economic development model called headquarter economy. Numerous previous studies have evaluated the influence on economic gains put by the typical economic phenomenon. However, systematical assessment from energy perspective is conducted for the first time in our study, combined with the three-scale input-output analysis which distinguishes local, domestic and foreign transfers in light of the energy intensities for the average world and national economies. To further understand total amount of energy required by a typical headquarter economy and the energy reallocation at micro-scale, detailed energy embodiment influxes are analyzed targeted on sectors as *Manufacture of Communication Equipment, Computer and Other Electronic Equipment, Production and Supply of Electricity and Steam* and *Extraction of Crude Petroleum and Natural Gas.*

As our results imply, energy requirements embodied in trade grow much more significantly than energy required by final use. Total proportion of headquarter dominated energy flows embodied in imports and exports witnesses a consistent rise from 17.76% and 35.30% in 2002 to 43.37% and 83.85% in 2012, proving that such rapid growth of energy requirements embodied in trade is dominated by the gradually prominent headquarter effect in Beijing. The headquarter dominated energy use patterns are analyzed in micro results of different sectors. The monopoly control of oil, natural gas by CNPC improves the volume of energy embodied in foreign imported products that use for domestic exports, whose sharing in *Steam and Extraction of Crude Petroleum and Natural Gas Sector's* total imported energy embodiment fluxes reaches pinnacle at 48.27% in 2012. The reform of electricity system by State Grid

Corporation further accelerates the separation of power generation and distribution, leading to the significantly increasing of energy embodied in domestic imported products that used to domestic exports. Besides, for rapidly developing *Manufacture of Communication Equipment, Computer and Other Electronic Equipment Sector*, headquarters' migration of giant companies and uniform sales businesses' transferring from sub-companies to headquarters also lead to great changes to the energy use profiles along the global supply chain.

Our results prove headquarter effect's vital influence on reshaping Beijing's energy trade profiles. They could support significant references for policy makings under the background of the intensifying headquarter effect. Based on the accelerating separation of upstream manufacturing bases and downstream sales market induced by the headquarter effect, environmentally sound technology diffusion and clean energy financing along the supply chain for production base are encouraged to realize greater cooperative engagement in overall energy conservation. Considering headquarters' ability of redistributing energy resources accumulated along the global supply chain to downstream economies, a series of policy suggestions have been proposed to help realize more rationally planning for cities' energy use dominated by headquarter effect as well as collective and inclusive governance of energy supply chain. Concrete policy implications include selecting suppliers with low energy consumption technologies, choosing downstream distributors with less energy consumption, sharing of information among headquarters and sub-companies along the supply chain to prevent energy excessive use induced by malicious competition among regional subcompany and achieve optimal energy allocation nationwide. For different sectors with distinct characteristics of energy use influenced by headquarter effect, headquarters are suggested make full use of knowledge spillover among different sectors and create sectoral standards that use incentives or sanctions to help energy conservation across the whole supply chain. Besides, the framework proposed in this work could also be applied to investigate other urban economy's evolution of energy embodiment fluxes.

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