Embodied Energy Use of China’s Megacities: A Comparative Study of Beijing and Shanghai

Highlights

- A comprehensive comparison of energy use perspectives of Beijing and Shanghai is investigated.
- The substantial energy use of Beijing is attributed to government activities.
- The energy use of Shanghai is more dependent on foreign regions compared with Beijing.
- Distinct energy use evolution features and directions of Beijing and Shanghai are presented.
- Just and effective energy conservation policies on the basis of megacities’ distinct functions and development plans are proposed.

Abstract

Previous studies presenting city energy use profiles generally disregard the indirect energy use across global supply chains. Moreover, the distinct energy-use patterns of megacities in China remain unclear, particularly attributable to various urban functions and development strategies associated with China's urbanization. Therefore, a multi-scale single-region input-output model was devised to depict patterns of energy use in two representative Chinese megacities—Beijing and Shanghai. This model highlights the distinct upstream sources of the city energy use, elucidating regional-international connections. The distinct evolutionary features of the two cities' energy-use structures are presented from a consumption-based perspective. Results show that the growth of Beijing and Shanghai depended heavily on embodied energy resources from other domestic or foreign regions. Further, as Beijing is the country's political center, its substantial energy use is attributed to government activities. In contrast, Shanghai, China's financial center, 6.05% of its energy consumption depends on foreign energy sources, while that of Beijing is only 4.2%. During 2002–2012, the growth rate of Beijing's energy use was notably lower than Shanghai's due to their different development modes. The comparison of the cities' different energy use profiles highlights the urgent need for globally oriented and inclusive governance and the formulation of energy conservation policies based on distinct city functions and development plans.

Keywords: China; megacities; embodied energy use; multi-scale input-output analysis

1. Introduction

Urban centers dominate global economic growth and energy use. Approximately 70%

of the world's energy use is consumed by urban economies (Seto et al., 2014). Therefore, it is widely considered that they play a key role in conserving energy (Guo et al., 2019; Rao et al., 2019) and alleviating environmental stress (Fang and Chen, 2018; Wang et al., 2019). Meanwhile, ever-increasing globalization has made urban economies more deeply embedded in fragmented global supply chains. In light of this new phase of globalization, researchers must look beyond direct energy consumption by end-users to the total embodied energy use along global supply chains. Moreover, diverse development models and strategies complicate the assessment of urban energy-use profiles. Beijing and Shanghai, the political and economic centers of China, represent two distinctive energy-use styles. Investigating the embodied energy use profiles and the relevant developmental and functional characteristics of these first-tier cities which locate at the apex of the new global city hierarchy could serve as a basis for the estimation and management of other medium and small cities.

Previous studies mainly focused on the traditional production perspective, considering only energy consumed directly by on-site industrial activities (Chen et al., 2016; Dhakal; Lorraine et al., 2012), thus ignoring the indirect energy use embodied in intermediate and final trade. Existing policies tend to target cities' local energy conservation through the end-of-pipe control on the supply side, but in order to intensify the energy conservation, it is also imperative to identify the driving forces of energy exploitation on the demand side and how the extracted primary energy is utilized by the economic system (Li et al., 2020c). Given this context, several recent studies have investigated the upstream energy inputs of urban economies based on the well-known concept of "embodied energy" (Mi et al., 2019; Odum, 1996; Wei et al., 2017). Moreover, the world economy is now characterized by entangled trade networks featuring long and complex supply chains that are deeply interlocked. This complex trade system brings the topic of cities' energy use in a broader scope. Specifically, large-scale manufacturing is not suitable in modern metropolises due to several factors (i.e., space constraints, high rent, and congested transport networks). Cities with insufficient energy resources can rely on external energy directly by importing energy as a type of commodity or indirectly by importing energy-intensive commodities (Chen et al., 2018; Wu and Chen, 2017). In terms of environmental costs, urban economies, especially large metropolises, are often inclined to import finished products to avoid the pollution associated with energy extraction and combustion processes at a local scale (Li et al., 2016b). However, such measures can lead to higher environmental costs at national and global scales, reducing pollution and other environmental impacts in cities but ultimately increasing them worldwide. Given that, the conventional siloed local perspective should give way to systematic thinking that understands the global direct and indirect energy transfer market as an integrated system. Furthermore, in the unprecedented interconnected global supply chain, not only are production and consumption geographically separated (Franzen and Mader, 2018; Liu et al., 2018), but production activities often cross at least one border, and typically many, before final assembly (Li et al., 2020b; World Trade Organization, 2019). This new reality gives rise to the unprecedented trade volume of intermediate products. A systemic assessment of domestic and foreign trade among large cities could significantly reshape our understanding of global energy use. Therefore, large cities' energy-use profiles should be evaluated within a globally integrated framework rather than being limited to a local scale. To quantify the energy embodied in trans-regional domestic and foreign trade, numerous studies applied the multi-region input-output (MRIO) model, which helped reveal the reallocation of energy or emissions flows from producers to consumers.

MRIO models have been widely applied at global (Ahmad and Wyckoff, 2003; Hertwich and Peters, 2009), national (Zhang et al., 2015b), and municipal scales (Zheng et al., 2018). Carbon flow among the four major municipalities (Beijing, Tianjin, Chongqing, and Shanghai) in China has attracted wide attention from scholars (Feng et al., 2014; Yao et al., 2013; Zhang et al., 2015a). However, MRIO analyses require massive data, which is sometimes unavailable, especially for urban economies. An updated method for regional ecological factor modeling is the multi-scale input-output model (MSIO) (Chen et al, 2013). It has a relatively low demand for data compared to MRIO modeling in terms of quantity, while the accuracy of results is largely preserved. Previous studies have mainly applied the MSIO method to resource flows within and outside economies, e.g., flows of water (Shao et al., 2017), carbon (Meng et al., 2018; Shao et al., 2016), and energy (Hao et al., 2018; Li et al., 2016a; Li et al., 2019). However, previous studies applying the MRIO or MSIO models have only considered single cities or urban agglomeration as their research objects, thereby failing to elucidate the distinct energy-use characteristics induced by different functions in various cities.

Beijing and Shanghai typify different urban functions—the former is a political center, and the latter is an economic center. As the capital of China, Beijing holds and requires crucial administrative resources. In terms of the evolutionary trend, it is a shrinking city with a policy of non-capital function extraction. In contrast, Shanghai is the national economic center and is the site of major global financial activity. It is regarded as an expanding city and is invested in developing a larger metropolitan region with its surrounding areas. These distinct city functions lead to distinct energy use patterns. As these two cities guide the future urbanization of several medium and small Chinese cities, a thorough study of their energy-use patterns is necessary to promote sustainable urbanization in China.

In this context, this study sought to elucidate the energy-use patterns of these two representative megacities from the perspective of embodied energy and to identify historical trends in Beijing and Shanghai's energy use. Therefore, this study applied MSIO model to compare the embodied energy use involved in final consumption and trade in Beijing and Shanghai. The paper is organized as follows: section 2 details the MSIO model, section 3 presents the study results from both sectorial and chronological perspectives, and section 4 offers policy suggestions.

2. Methodology and data sources

2.1 Case descriptions

As the capital of China, Beijing's total area was 16,410.54 km^2 and its total population was 21.54 million in 2018 (Beijing Statistical Bureau (BSB), 2019). As China's economic and cultural center, this city had the second-largest GDP in the country, below only Shanghai. Since the reform and opening up, the industrial structure of Beijing has been continuously upgraded, and tertiary industries have gradually overtaken primary and secondary industries in importance. In 2018, the output values of primary, secondary, and tertiary industries represented 0.40%, 18.60%, and 81.00% of the total industrial output, respectively (Beijing Statistical Bureau (BSB), 2019). Beijing's energy consumption is dominated by fossil fuels, and consumption increased from 63.59 Mt coal equivalent annually in 2010 to 71.33 Mt in 2017. As an energy-dependent city, Beijing's energy supply generally comes from other provinces. Beijing is a net-import city: exports were valued at $58.50 billion in 2017, whereas imports were valued at \$265.22 billion (Beijing Statistical Bureau (BSB), 2018). Therefore, it is essential to investigate the energy embodied in multi-scale imports and exports.

Like Beijing, Shanghai is one of China's primary economic centers, with its GDP ranking first in the country. The city had an area of 6,340.50 km^2 and a total population of 24.24 million in 2018. Dominated by tertiary industries, primary, secondary, and tertiary industries contributed 0.32%, 29.78%, and 69.90% of Shanghai's total industrial output value, respectively, in 2018 (Shanghai Municipal People's Government (SMPG), 2018; Shanghai Statistical Bureau (SSB), 2019). Shanghai's energy consumption is higher than that of Beijing. In 2017, the energy consumption in Shanghai was 118.59 Mt coal equivalent, an increase of 11.13% compared with that in 2010. As a net importer, Shanghai's exports were valued at \$193.68 billion whereas its imports were valued at \$282.44 billion in 2017 (Shanghai Statistical Bureau (SSB), 2018).

2.2 Multi-scale input-output analysis

Figure 1 presents a three-scale input-output diagram of urban energy use. The industrial inputs for the targeted city are sourced from local, domestic, and global systems. The products/services from these three domains possess various embodied energy intensities based on their distinct industrial patterns and technology development trends worldwide. Therefore, three energy flows originating from the local (E), domestic (EEId), and global (EEIf) scales are calculated to obtain the energy outputs from the local (DE), domestic (EEEd), and global (EEEf) scales.

To analyze the economic and the corresponding embodied energy flows within and across urban boundaries, relevant variables about embodied energy transfer in a three-scale input-output model of an urban economic system are presented in Table 1.

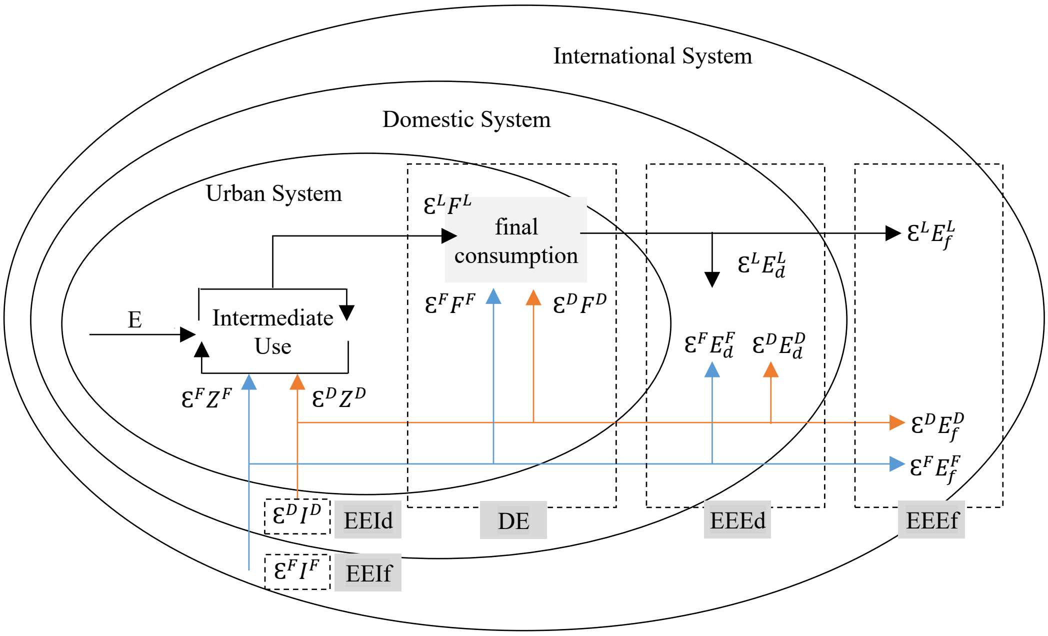


Figure 1. Three-scale diagram of embodied energy flow.

As depicted, z_{ij}^L, z_{ij}^D, and z_{ij}^F represent the intermediate inputs into Sector j derived from the local output, domestic imports, and foreign imports of Sector i, respectively; f_i^L, f_i^D, and f_i^F represent the local, domestic, and foreign final demands, respectively; $e_{d,j}^L$, $e_{d,j}^D$, and $e_{d,j}^F$ denote domestic exports to satisfy the demand of the domestic economy for local output, domestic imports, and foreign imports, respectively; $e_{f,j}^L$, $e_{f,j}^D$, and $e_{f,j}^F$ represent foreign exports to satisfy the demand of foreign economies via local output, domestic imports, and foreign imports, respectively; and e_j signifies the direct energy inputs into Sector j. Sector i and Sector j represent different sectors.

Based on the assumption that imported products are distributed among intermediate inputs and final uses following the same ratio as local products, the official competitive economic input-output tables, which do not differentiate between local and imported products, are transformed to non-competitive input-output tables (Shao et al., 2017).

Table 1 Three-scale input-output variables involved in urban economic systems

Input \ Output		Intermediate use			Final use		
		Sector 1	…	Sector n	Final demand	Domestic export	Foreign export
Local intermediate inputs	Sector 1	z_{11}^{L}	…	z_{1n}^{L}	f_{1}^{L}	$\mathrm{e}_{d,1}^{L}$	$\mathrm{e}_{f,1}^{L}$
	…	…	…	…	…	…	…
	Sector *n*	z_{n1}^{L}	…	z_{nn}^{L}	f_{n}^{L}	$\mathrm{e}_{d,n}^{L}$	$\mathrm{e}_{f,n}^{L}$
Domestic imported inputs	Sector 1	z_{11}^{D}	…	z_{1n}^{D}	f_{1}^{D}	$\mathrm{e}_{d,1}^{D}$	$\mathrm{e}_{f,1}^{D}$
	…	…	…	…	…	…	…
	Sector *n*	z_{n1}^{D}	…	z_{nn}^{D}	f_{n}^{D}	$\mathrm{e}_{d,n}^{D}$	$\mathrm{e}_{f,n}^{D}$
Foreign imported inputs	Sector 1	z_{11}^{F}	…	z_{1n}^{F}	f_{1}^{F}	$\mathrm{e}_{d,1}^{F}$	$\mathrm{e}_{f,1}^{F}$
	…	…	…	…	…	…	…
	Sector *n*	z_{n1}^{F}	…	z_{nn}^{F}	f_{n}^{F}	$\mathrm{e}_{d,n}^{F}$	$\mathrm{e}_{f,n}^{F}$
Direct energy inputs		e_{1}	…	e_{n}			

The first-order approximation of relationships between these variables can be presented as follows:

$$\mathrm{z}_{ij}^{L} = z_{ij}\left(\frac{x_i}{(x_i} + i_i^D + i_i^F\right), \quad (1)$$

$$\mathrm{z}_{ij}^{D} = z_{ij}\left(\frac{i_i^D}{(x_i} + i_i^D + i_i^F\right), \quad (2)$$

$$\mathrm{z}_{ij}^{F} = z_{ij}\left(\frac{i_i^F}{(x_i} + i_i^D + i_i^F\right); \quad (3)$$

$$f_j^L = f_j\left(\frac{x_i}{(x_i} + i_i^D + i_i^F\right), \quad (4)$$

$$f_j^D = f_j\left(\frac{i_i^D}{(x_i} + i_i^D + i_i^F\right), \quad (5)$$

$$f_j^F = f_j\left(\frac{i_i^F}{(x_i} + i_i^D + i_i^F\right). \tag{6}$$

The biophysical balance of the three-scale energy flows of Sector *i* within an urban system can be described as follows:

$$\varepsilon_j^L x_j = \sum_{i=1}^{n} \varepsilon_i^L z_{ij}^L + \sum_{i=1}^{n} \varepsilon_i^D z_{ij}^D + \sum_{i=1}^{n} \varepsilon_i^F z_{ij}^F + e_i, \tag{7}$$

where e_i represents direct energy inputs into Sector *i*; ε_j^L and ε_i^L are the local embodied energy intensities of Sectors *j* and *i,* respectively; ε_i^D and ε_i^F are the embodied intensities of domestic- and foreign-imported products/services; and x_j represents the total output. It is worth noting that ε_i^F is the averaged value of energy intensities for all the economies (with China excluded) in the globalized world, which is divided into *m* regions, each composed of *n* sectors. The biophysical balance equation for sector *i* in region *r* is as follows:

$$e_i^r + \sum_{s=1}^{m} \sum_{j=1}^{n} (\varepsilon_j^s z_{ji}^{sr}) = \varepsilon_i^r \left(\sum_{s=1}^{m} \sum_{j=1}^{n} z_{ij}^{rs} + \sum_{s=1}^{m} \sum_{k=1}^{l} f_{ik}^{rs}\right) \tag{8}$$

Where e_i^r denotes energy extracted by sector *i* in region *r*, z_{ji}^{sr} represents the monetary value of products from sector *j* in region *s* to sector *i* in region *r* in intermediate trade, f_{ik}^{rs} is the monetary value of products provided by sector *i* in region *r* for demand *k* in region *s*. Through the above-mentioned biophysical balance equation, ε_i^r that denotes the embodied energy intensity of products supplied by sector *i* in region *r* could be obtained as the basis of the accountings of ε_i^D and ε_i^F in the three-scale energy flow balance.

The corresponding matrix of the three-scale energy flows' biophysical balance (equation (7)) can thus be provided as follows:

$$\mathrm{E}^L \mathrm{X} = \mathrm{E}^L \mathrm{Z}^L + \mathrm{E}^D \mathrm{Z}^D + \mathrm{E}^F \mathrm{Z}^F + \mathrm{E}, \tag{9}$$

where $\mathcal{E}^L = [\varepsilon_j^L]_{1\times n}$, $X = [x_{ij}]_{n\times n}$, $Z^L = [z_{ij}^L]_{n\times n}$, $\mathcal{E}^D = [\varepsilon_j^D]_{1\times n}$, $Z^D = [z_{ij}^D]_{n\times n}$, $\mathcal{E}^F = [\varepsilon_j^F]_{1\times n}$, $Z^F = [z_{ij}^F]_{n\times n}$, and $E = [e_i]_{1\times n}$ e; and i, j ∈ (1,2,…,n), $x_{ij} = x_j$ (i = j), and $x_{ij} = 0$ (i ≠ j).

Thus, the embodied energy intensity can be expressed as matrix $\mathcal{E}^L$ as follows:

$$\mathcal{E}^L = (\mathcal{E}^D Z^D + \mathcal{E}^F Z^F + E)(X - Z^L)^{-1}. \quad (10)$$

According to Chen et al. (2013), the energy embodied in trade can be divided into nine categories based on the different input sources and output destinations shown in Table 2.

Table 2. Embodied energy flow according to three-scale input sources and three-scale output destinations

	Local consumption	Domestic exported consumption	Foreign exported consumption
Local production	LL	LD	LF
Domestic imported production	DL	DD	DF
Foreign imported production	FL	FD	FF

Therefore, the energy embodied in the local final use (DE_j), domestic imports ($EEId_j$), and foreign imports ($EEIf_j$) of Sector *j* can be calculated as follows:

$$DE_j = LL + DL + FL = \varepsilon_j^L f_j^L + \varepsilon_j^D f_j^D + \varepsilon_j^F f_j^F; \quad (11)$$

$$EEId_j = DL + DD + DF; \quad (12)$$

$$\mathrm{EEIf}_j = \mathrm{FL} + \mathrm{FD} + \mathrm{FF}. \quad (13)$$

The energy embodied in the imported products of Sector j, EEI_j, can be denoted as the summation of EEId_j and EEIf_j as follows:

$$\mathrm{EEI}_j = \mathrm{EEId}_j + \mathrm{EEIf}_j = \varepsilon_j^D \mathrm{i}_j^D + \varepsilon_j^F \mathrm{i}_j^F, \quad (14)$$

where i_j^D and i_j^F are the domestic and foreign imported economic flows, respectively.

The energy embodied in the domestic exports (EEEd_j) and foreign exports (EEEf_j) of Sector j can be calculated as follows:

$$\mathrm{EEEd}_j = \mathrm{LD} + \mathrm{DD} + \mathrm{FD} \quad (15)$$

$$\mathrm{EEEf}_j = \mathrm{LF} + \mathrm{DF} + \mathrm{FF}. \quad (16)$$

The embodied energy in the exports of Sector j, EEE_j, is expressed as the summation of EEEd_j and EEEf_j as follows:

$$\mathrm{EEE}_j = \mathrm{EEEd}_j + \mathrm{EEEf}_j = (\varepsilon_j^L \mathrm{e}_{d,j}^L + \varepsilon_j^D \mathrm{e}_{d,j}^D + \varepsilon_j^F \mathrm{e}_{d,j}^F) + (\varepsilon_j^L \mathrm{e}_{f,j}^L + \varepsilon_j^D \mathrm{e}_{f,j}^D + \varepsilon_j^F \mathrm{e}_{f,j}^F) \quad (17)$$

The net embodied energy in trade balance, EEB_j is shown as follows:

$$\mathrm{EEB} = \mathrm{LD} + \mathrm{LF} - \mathrm{DL} - \mathrm{FL}, \quad (18)$$

$$\mathrm{EEB}_j = \mathrm{EEE}_j - \mathrm{EEI}_j. \quad (19)$$

2.3 Data sources

This study aims to apply the MSIO model to quantitively examine the energy-use profiles of Beijing and Shanghai. Three types of datasets are necessary for the MSIO analysis, including direct energy exploitation datasets for the two representative economies, economic input-output data for Beijing and Shanghai, and embodied energy intensity datasets for Beijing's and Shanghai's nationally and internationally imported products. The direct energy exploitation datasets, including coal, oil, natural gas, hydrological, and nuclear power, were drawn from the *Beijing Statistical Yearbook* (Beijing Statistical Bureau (BSB), 2002, 2005, 2007, 2010, 2012) and *Shanghai Statistical Yearbook* (Shanghai Statistical Bureau (SSB), 2002, 2005, 2007, 2010, 2012). The official economic input-output tables for the two representative economies were obtained from the Beijing Statistical Bureau and Shanghai Statistical Bureau. These tables divide the two cities into 42 sectors (i.e., one agricultural, four mining, 17 general industrial, two domestic production and supply departments, one water production and supply department, one transportation, two construction and real estate, and 14 other service sectors). In the multi-scale modeling process, these competitive input-output tables are transformed into non-competitive input-output tables (Shao et al., 2017). The detailed mapping criterion between energy extraction data and MSIO tables are illustrated in Appendix Table A4. The Eora Global MRIO database was used to calculate the average embodied intensities for all sectors on the domestic and international scales. The intensities for each sector represent the global weighted average excluding China. To match the 42 input and output sectors in Beijing and Shanghai, the 26 sector-based Eora intensity data were extrapolated to fit the 42 sector-based Beijing/Shanghai input-output data (see Appendix Table A3).

3. Results

3.1 Total energy use profile in 2012

3.1.1 Energy embodied in the aggregated final use

Figure 2 shows that the embodied energy use in Shanghai was 4.49E +18 J, which exceeded the embodied energy use in Beijing (3.63E +18 J). Aggregated final energy use can be divided among household consumption (i.e., rural household consumption and urban household consumption), governmental consumption, and total capital formation (i.e., fixed capital formation and inventory change). Fixed capital formation is the top final user in these two cities, contributing approximately half of the total embodied energy use, followed by urban household consumption, which represents more than a quarter of the total.

Specifically, energy use embodied in fixed capital formation in Beijing and Shanghai, which contributes to ongoing city growth, accounts for 46% and 43% of the total, respectively. The huge part of energy use from fixed capital formation indicates fast-growing urbanization in these two cities, which shows something about how much of the new value-added to these economies. For example, in the urban planning outline, urban renewal and inventory optimization are always proposed with priority in Shanghai and Beijing. In Shanghai's Urban Master Planning Outline, it is proposed to make full use of underground space and actively develop low-altitude sky areas, and to optimize the structure of land use and improve land use performance as well. In Beijing's Urban Master Planning Outline, optimizing the land allocation and improving land use efficiency to upgrade the modern service industry is highlighted. Apart from the policies on increasing land use efficiency, these two cities also focus on new infrastructure construction, as detailed in Action Plan of Shanghai Municipality on Promoting the Construction of New Infrastructure (2020-2022) and Action Plan for Accelerating the Construction of New Infrastructure in Beijing (2020-2022).

Shanghai's embodied energy involved in urban household consumption (1.65E +18 J) is higher than that of Beijing (1.03E +18 J), which could be attributable to Shanghai's higher urbanization rate and resident income compared with those of Beijing. Further, the gap between energy use embodied in urban and rural consumption in Shanghai is large, reflecting the unbalanced urban-rural development within Shanghai. Notably, the proportion of energy use embodied in Beijing's governmental consumption (6.07E +17 J) is approximately 17% of the total embodied energy use. This percentage is considerably higher than that in Shanghai, where it is 10% of the total.

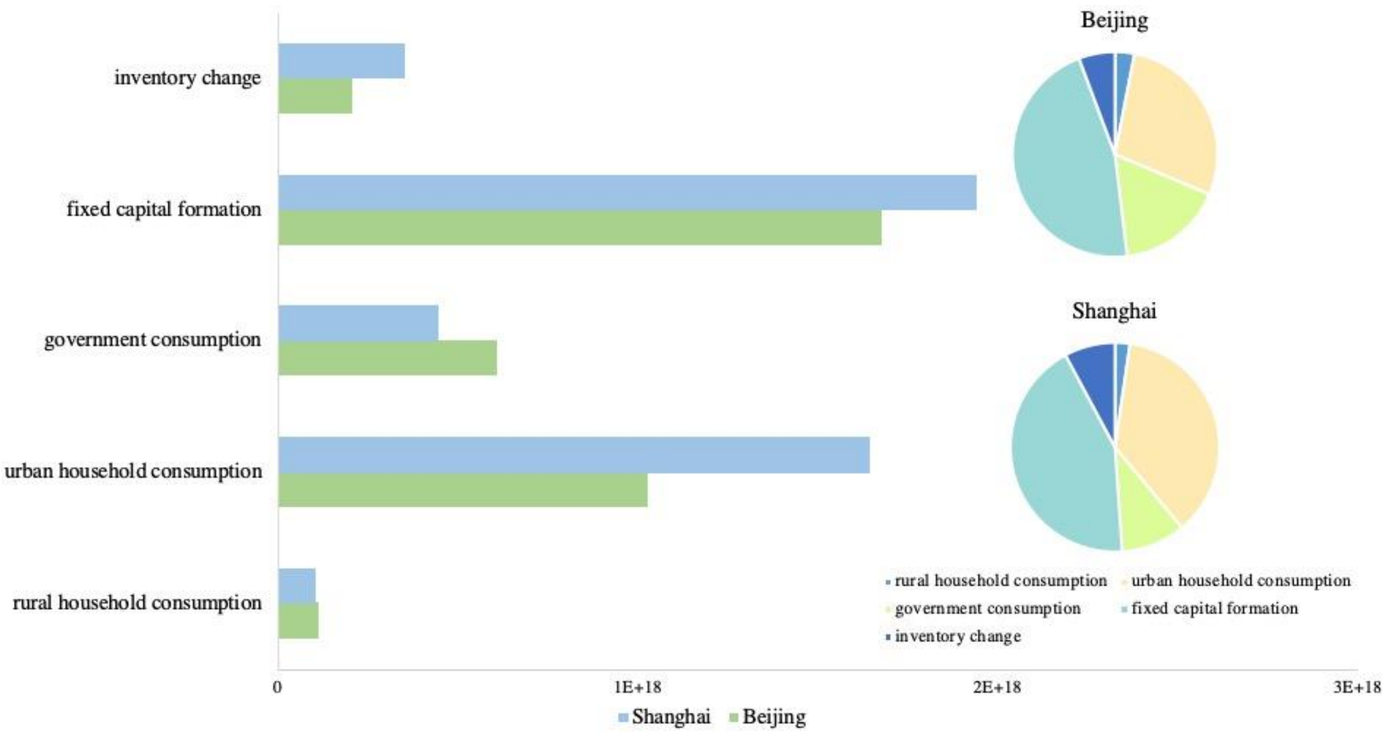
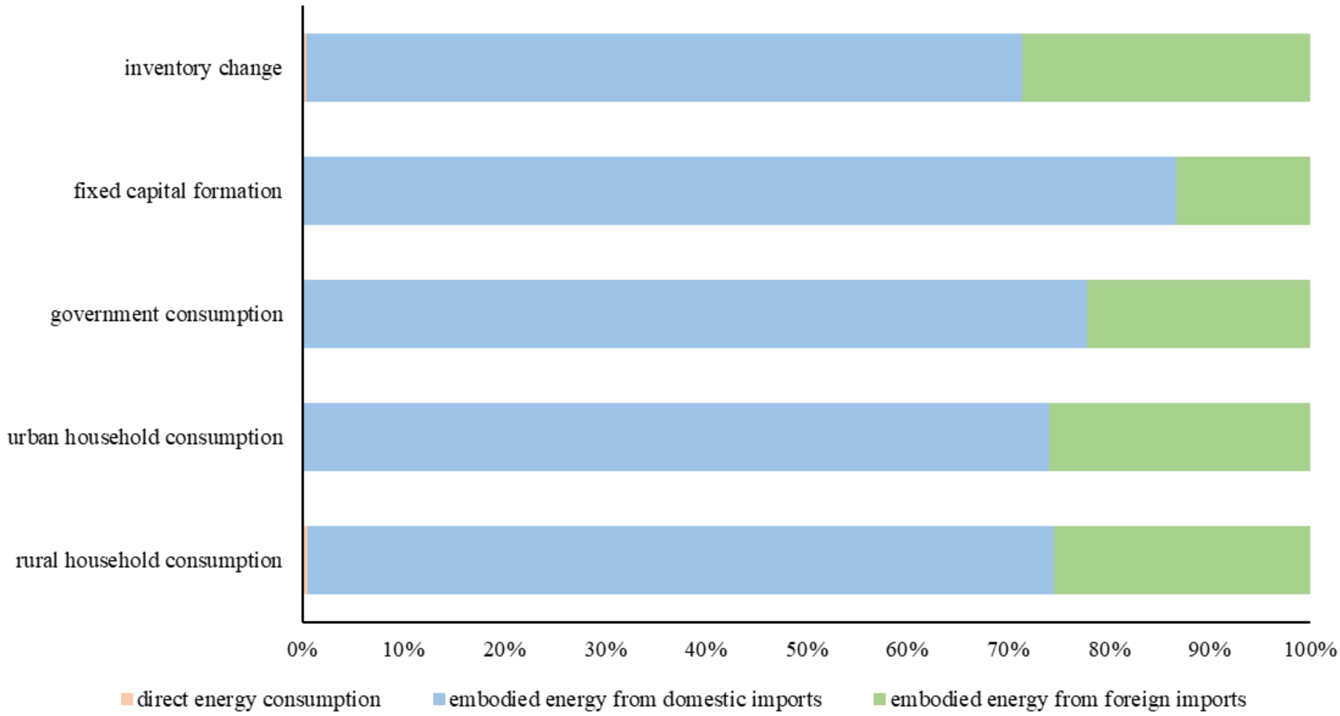
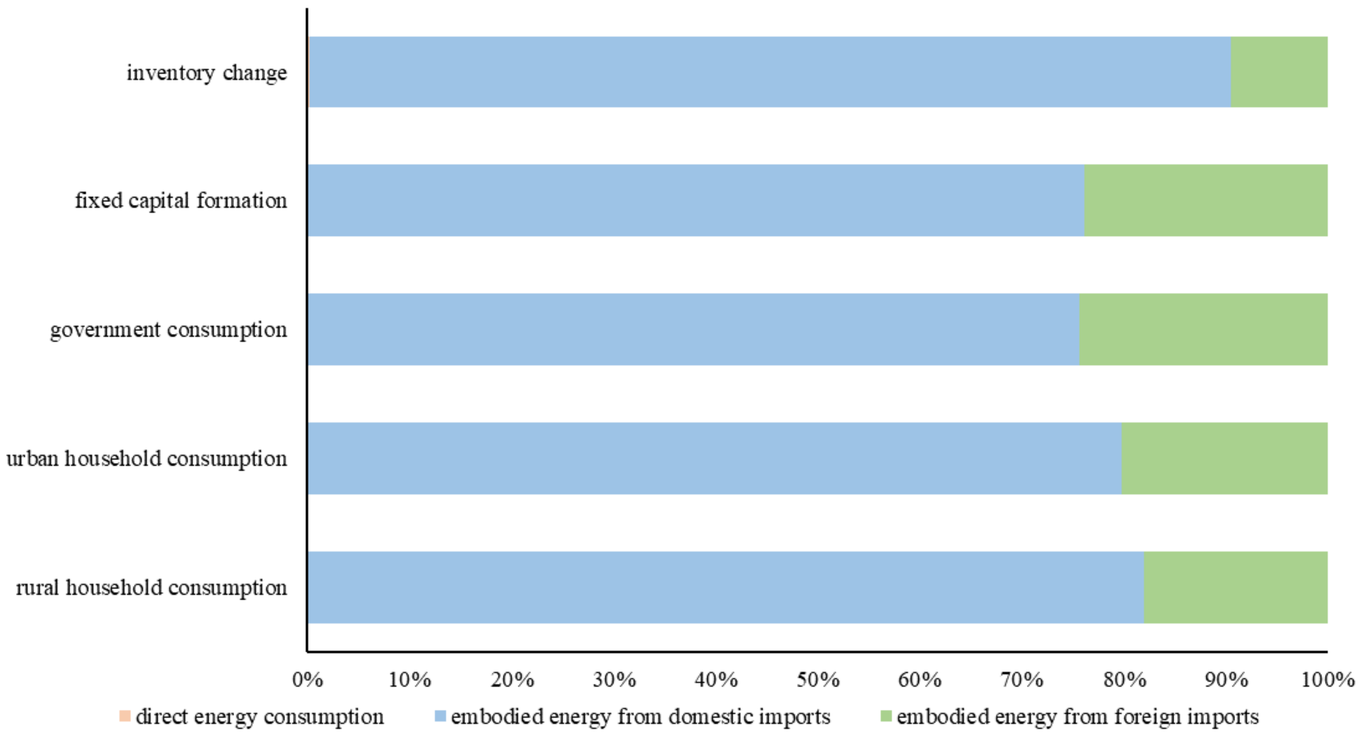


Figure 2. Proportion of aggregated final energy use embodied in five sectors in 2012 (units: J).

With their conventional heterotrophic systems, Beijing and Shanghai rely on domestic and foreign imports of various resources to maintain their daily operations. Our results imply that nearly all of these cities' embodied energy consumption stems from non-local sources. Figure 3 demonstrates that nearly four-fifths of the embodied energy use in Beijing and Shanghai is attributable to domestically imported products/services, with the remainder originating from foreign economies. However, direct energy consumption in the two cities is negligible. In general, Shanghai relies heavily on imports, particularly the energy use embodied in capital products and governmental consumption. The energy embodied in capital imported from domestic and foreign sources was 1.48E +18 J and 4.64E +17 J, respectively, in Shanghai. By contrast, those of Beijing were 1.45E +18 J and 2.24E +17 J. The embodied energy from Shanghai's foreign imports of capital products is nearly twice that of Beijing. Regarding governmental consumption, Beijing's embodied energy attributable to domestic and foreign imports is 4.72E +17 J and 1.35E +17 J, respectively, whereas that of Shanghai is 3.38E +17 J and 1.09E +17 J.



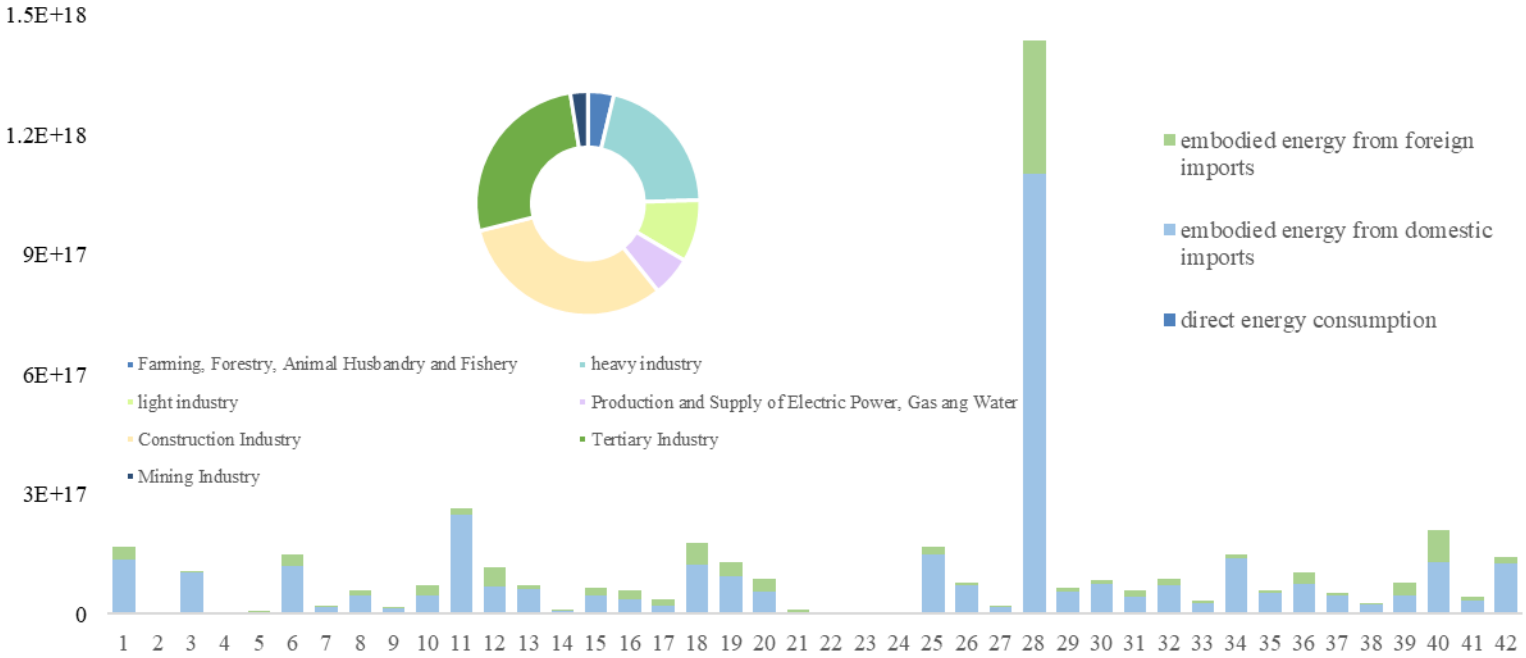
(a) Beijing



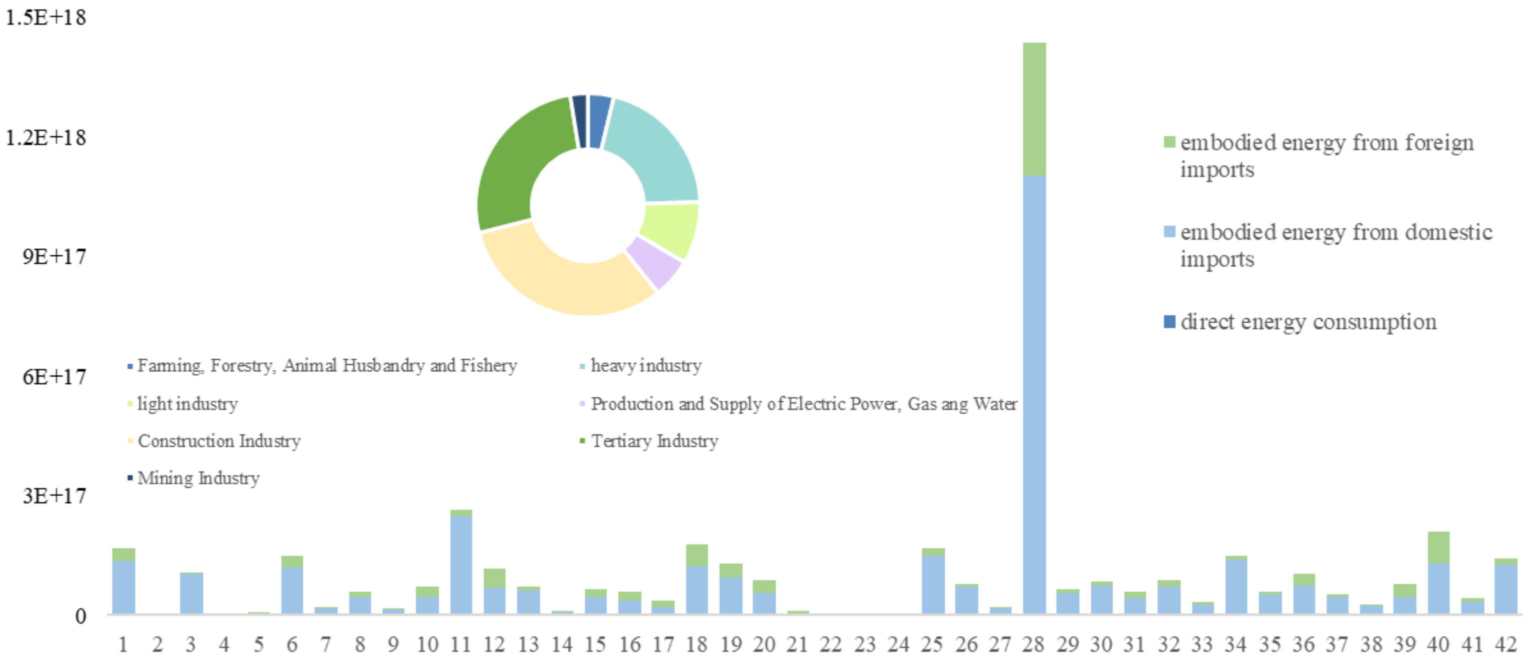
(b) Shanghai

Figure 3. Sources of embodied energy consumed in five divisions of the aggregated final energy use of Beijing and Shanghai in 2012.

3.1.2 Sectoral embodied energy use



(a) Beijing



(b) Shanghai

Figure 4. Embodied energy use in 42 sectors of Beijing and Shanghai's economies in 2012.

To identify specific drivers behind energy-use trends in Beijing and Shanghai, this study also examined the sectoral structure of final energy use and summarized the results according to 42 sectors. The relevant sectors are listed in Table A1.

As presented in Figure 4(a), the five sectors with the highest embodied energy use in Beijing are construction; health care and social services; petroleum processing, coking, and nuclear fuel production; public administration, social security, and social organizations; and real estate. In Shanghai, the top five sectors are construction; petroleum processing, coking, and nuclear fuel production; health care and social services; transportation equipment manufacturing; and farming, forestry, animal husbandry, and fishery (as shown in Figure 4(b)). Embodied energy use in the construction sector significantly exceeds that of other sectors. Moreover, Beijing and Shanghai share similarly structured sectoral embodied-energy use, with construction and tertiary industries consuming the largest portions. In Beijing, the embodied energy use in construction and tertiary industries is 1.35E +18 J (37% of the total) and 1.11E +18 J (31% of the total), respectively. However, those in Shanghai are 1.43E +18 J (32% of the total) and 1.19E +18 J (26% of the total), respectively.

On one hand, the construction industry has greater energy use than any other industry owing to the rapid growth of the real estate industry in these cities. Moreover, this trend has been accelerated by urban expansion. However, the majority of the building materials are produced and processed in the provinces outside the boundaries of the two cities, which creates an energy-extraction burden in those areas. Hence, the urban expansion of Beijing and Shanghai comes at the cost of environmental degradation in other provinces.

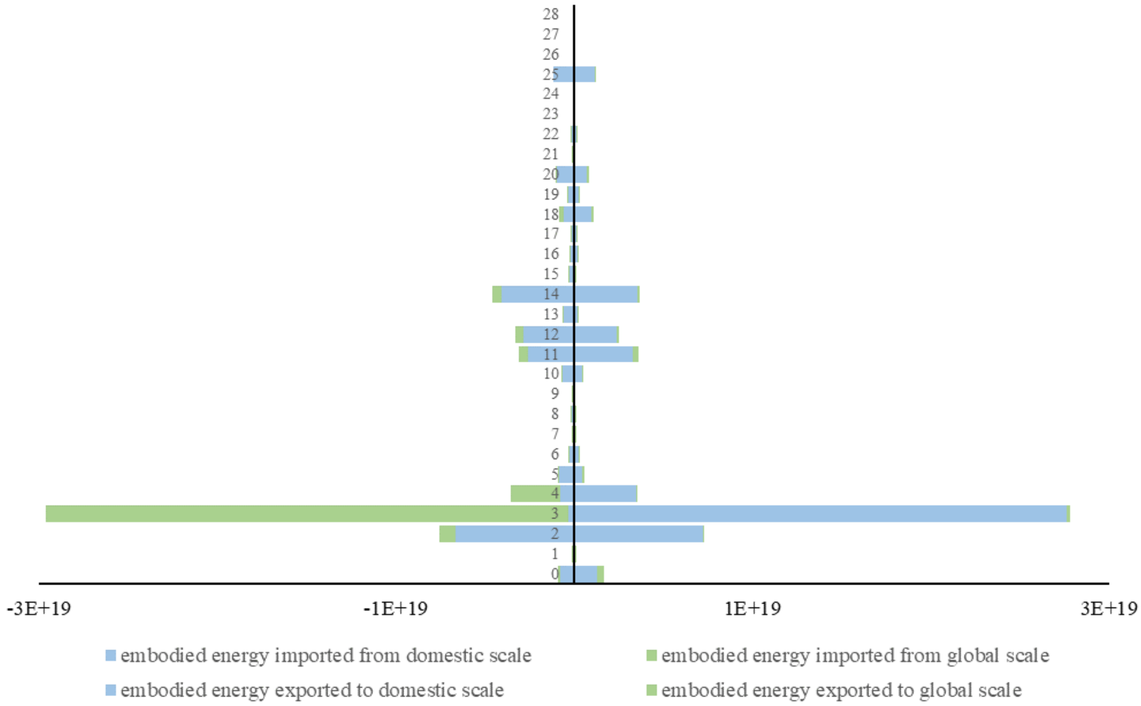
3.1.3 Energy embodied in trade

Figure 5(a) and Figure 5(b) depict the overall energy use embodied in the domestic and foreign trade of Beijing and Shanghai. The previously described disparities indicate that energy consumption in these global cities depends more significantly on trade than on local resource exploitation. Therefore, detailed energy profiles, embodied imported and exported energy allocations, and domestic and foreign supply chains are discussed comprehensively below.

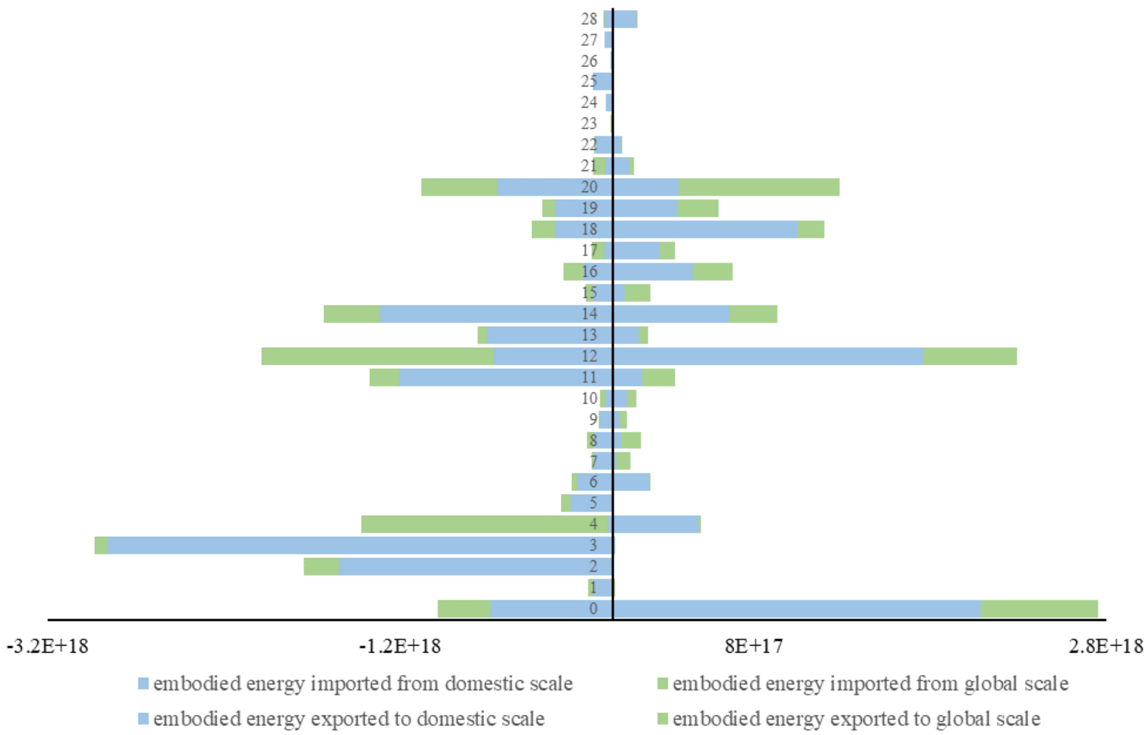
Both Beijing and Shanghai are net importers and their net embodied energy imports were 3.48E +18 J and 6.24E +18 J. These figures represent 1,142 and 1,536 times, respectively, the amount of energy directly exploited. Despite the clear import-dominated pattern implied by these figures, the situation in Beijing varies under specific conditions at specific scales. On the domestic scale, Beijing is a net energy exporter with a surplus of 3.01E +19 J; when the energy inflow is considered discovered globally, however, its net imports are approximately 3.36E +19 J. In contrast, Shanghai could be described as a “pure” net importer because of the flux of embodied energy on the two scales, in which domestic trade contributes up to 89.26% of Shanghai’s the aggregated consumption (i.e., 8.52E +18 J). Given its sectoral structure, the abnormal surplus in Beijing could be attributable to the petroleum and gas industry because of the overestimated values from company statistics, as exports of this industry’s productions account for 90.88% of Beijing’s net domestic exports (1.52E +18 J). In tracing the total embodied energy use along the entire supply chain, Beijing and Shanghai can both be categorized as substantial consumers, though the energy embodied in Shanghai’s commercial activities is significantly greater than that in Beijing. Furthermore, the industrial energy-use patterns of the two cities are largely similar. The secondary industries in the two cities are net importers of energy, but services and commodities are exported by tertiary industries throughout global supply chains. However, the energy embodied in tertiary industries is equivalent to merely 22.22% of the net energy imports in the secondary industries in Beijing due to the relatively low energy intensity of tertiary industries. The corresponding proportion for Shanghai is 38.40%, thereby indicating the comparative advantage of global economic participation and the city's improving position in international trade.

Shanghai plays a significant role in trade associated with innovation and technology. In Shanghai, the proportions of energy embodied in international trade in the service sector and communication equipment, computer, and other electronic equipment manufacturing sectors were 17.31% and 23.80%, respectively, in 2012. In the latter sector, the embodied energy involved in exports is the largest proportion, 13.36% higher than the corresponding proportion for Beijing and representing 4.85 times more energy (i.e., 9.15E +17 J and 1.89E +17 J). Further, products of the petroleum and natural gas extraction sector imported into Beijing contain large amounts of embodied energy on the global scale (2.93E +19 J), far more than that in Shanghai (7.32E +17 J). In addition, heavy industries in Beijing, such as the metal-products manufacturing and the chemical industries, closely interact with foreign and domestic economies. The gross embodied energy of these industries in domestic trade is 5.17E +18 J and 7.63E +18 J, while the values embodied in foreign trade are 6.34E +17 J and 6.06E +17 J. According to its industrial structure, Beijing exports 7.12E +17 J of 8.94E +17 J embodied energy on the domestic scale (79.64%), whereas Shanghai exports 1.84E +18 J of 2.71E +18 J (67.87%). These figures suggest that Beijing's heavy industry is domestically oriented but still highly internationally reliant embodied-energy distribution, in which Shanghai has a relatively import-oriented and sustainable modern economy.

In general, the energy embodied in domestic trade (inflows and outflows) was greater than that in foreign trade (imports and exports). Exceptions exist in a few sectors: metal products manufacturing, mining and processing of metal ores, communication equipment manufacturing, computer and other electronic equipment manufacturing (in Shanghai), and petroleum and natural gas extraction (in Beijing). The net differences between the energy embodied at the domestic and global scales in these sectors are 8.90E +17 J (metal products manufacturing), 6.20E +17 J (mining and processing of metal ores), 3.17E +17 J (communication equipment, computer, and other electronic equipment (in Shanghai)), and 1.51E +18 J (petroleum and natural gas extraction (in Beijing)). Consequently, these energy-intensive industries play a significant role in determining the cities' overall energy-use profiles, indicating the increasing dependence on foreign energy and resources for scaled entrepôt stations in foreign trade. Moreover, the positive balance toward foreign trade in the scrap and waste industry is relatively trivial compared with the other industries in Beijing and Shanghai but is remarkable within the context of this more minor industry, in which the embodied energy transfer in this sector is 8.24E +14 J (in Beijing) and 5.50E +15 J (in Shanghai). This trade balance may reflect some critical issues concerning imported waste.



(a) Beijing



(b) Shanghai

Figure 5. Embodied energy inflow and outflow of 42 sectors (sectors 29–42 (service industry) are encoded as (0) of Beijing and Shanghai's economy in 2012.

3.2 Evolution of energy use patterns

Energy use patterns change dynamically with a city's development. Therefore, this study explored historical trends in Beijing and Shanghai's energy use to shape policy proposals to improve future energy management.

3.2.1 Temporal evolution of energy embodied in final use

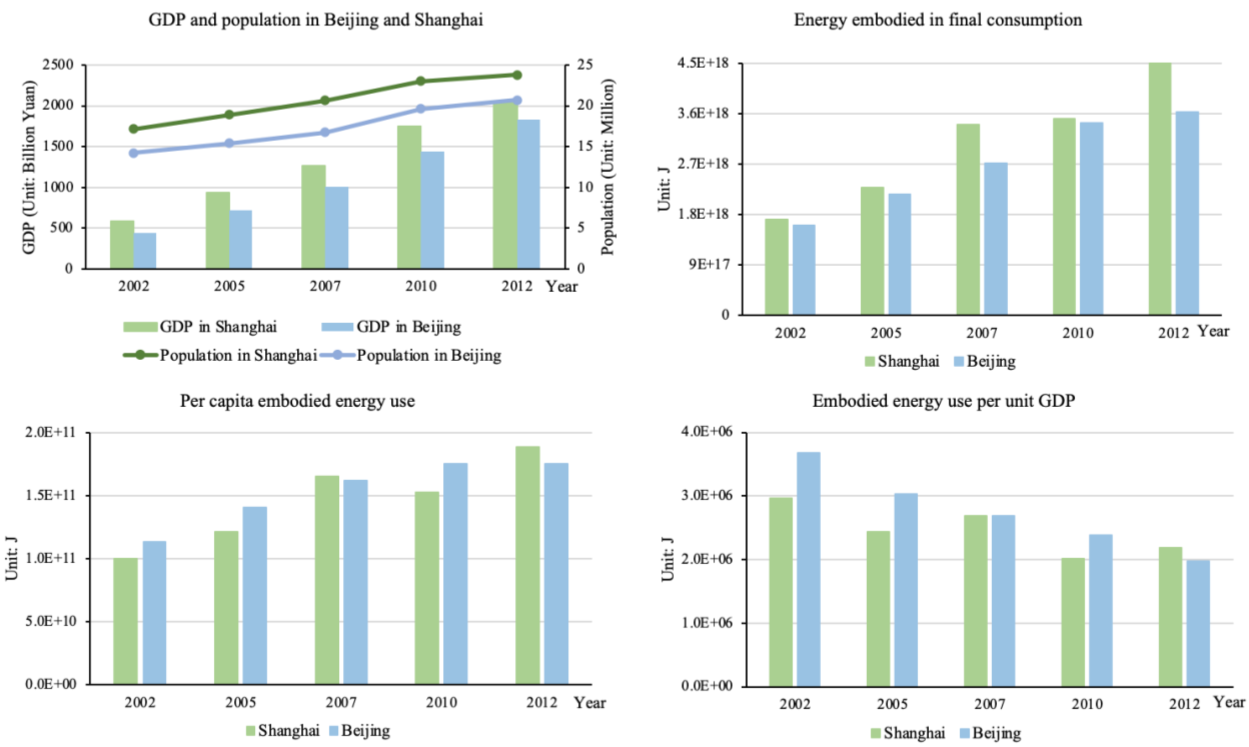


Figure 6. Temporal evolution of the total energy use and its relationship between social characteristics from 2002 to 2012 in Beijing and Shanghai.

The growing gap between the embodied energy in final use of Beijing and Shanghai reflects the distinct development trends of the two cities. In 2012, the total energy embodied in final use in Shanghai was 4.49E +18 J, 2.62 times the 1.72E +18 J embodied energy in 2002. In contrast, Beijing's total energy embodied in final use increased from 1.62E +18 J to 3.63E +18 J during the same period, growing by 1.24 times (as shown in Figure 6). These consistently increasing trends can be attributed to large-scale human migration and industrial expansion. The rapid growth of manufacturing and real estate in recent decades has attracted many immigrants to the two cities, thereby nearly doubling the final energy use.

While the energy embodied in final use in Shanghai is increasing at a substantial rate, the growth rate in Beijing is considerably lower and has even slowed over time. A decline in Beijing's growth rate was observed from 2010 to 2012, during which the rate was only approximately 5.50%, lower than the 26.80% rate from 2007 to 2010.

Notably, the evolution of per capita energy use in these two cities steadily increased from 2002 to 2012, except for a transitory decline in 2010 in Shanghai. It proves that with the improvement of people's living standards, the demand for energy-intensive products changes from meeting the basic standard of living to a higher standard. Therefore, for large cities, how to balance the problem between controlling the energy consumption and ensuring economic development with the rising living standard of residents has become a key issue in the future. In addition, attention should be paid to energy use equality among different income groups. A previous study has found international energy consumption far from equitable and varying to extreme degrees across countries and income groups. When many people suffer from energy deprivation, quite a few are consuming far too much, with no consumption category free from that. Therefore, different per capita energy consumption standards should be set for different consumer groups for equality (Oswald et al., 2020).

On the contrary, the embodied energy use per unit GDP generally decreased in those ten years, especially stably descended in Shanghai, which indicates the global technological progress and developing energy use efficiency. This trend also implies the decoupling between GDP and energy consumption in Beijing and Shanghai from a consumption-based perspective, due to their falling dependence on inappropriate energy consumption to support economic growth and increasing energy use efficiency.

3.2.2 Multi-scale sources of the energy embodied in final use

To explore the relationships with domestic and foreign regions induced by the distinct city planning schemes of Beijing and Shanghai, the following section elaborates on shifts in embodied energy dependence on the domestic and global scales.

Figure 7 represents the multi-scale sources of energy use embodied in Beijing and Shanghai's final use, respectively. From inside to outside, the concentric circles chronologically illustrate multi-scale sources of energy embodied in the final use of the two cities. The pink, blue, and green circles represent the local, domestic, and global scales, respectively. As an international metropolis, Shanghai relied heavily on energy imported from foreign regions in the early years of the study period, specifically from 2002 (7.23%) to 2005 (13.15%). In 2005, the embodied energy from global sources (13.15%) even exceeded that from domestic sources (9.73%). Thereafter, Shanghai's dependence on domestic-scale embodied energy notably increased, representing

16.38%, 42.69%, and 17.02% of the total embodied energy in 2007, 2010, and 2012, respectively. This phenomenon is inextricably linked to Shanghai's growth due to domestic immigration. Over the past decade, Shanghai has expanded considerably owing to the construction of several traffic trunk lines, particularly in 2010, when the World Expo attracted many tourists. The ever-increasing investment in real estate and urban renewal relies on labor resources and materials from other provinces, and the resulting population inflow fosters resource integration and integrative development. After a 2009 policy revision to increase efforts to attract multinational companies' headquarters, the global-scale energy embodied in the final use has increased in Beijing (i.e., 7.19% in 2010, which is thrice that in 2007).

Figure 7. Multi-scale sources of energy embodied in final use (The left circle represents Beijing and the right, Shanghai).

3.2.3 Distinct energy use structures induced by different city functions

The structure of final-demand energy use reflects the focus of urban management and the direction of urban planning. To make relevant policy recommendations, some distinct characteristics of the final-demand energy-use structure of the two cities are shown in Figure 8. As the political and international communications center of China, Beijing serves the operation of the central government. Accordingly, government energy consumption in Beijing (2.06E +18 J) is higher than that in Shanghai (1.3E +18 J). Given the highly specialized functional orientation of Beijing, the growth of government consumption substantially outweighs increases in other categories. In 2002, 2005, 2007, 2010, and 2012, governmental consumption reached 1.92E +17, 2.83E +17, 3.92E +17, 5.83E +17, and 6.07E +17 J, respectively. Thus, the final demand of governmental consumption has more than tripled over 10 years, followed by urban consumption, which increased only 2.70 times.

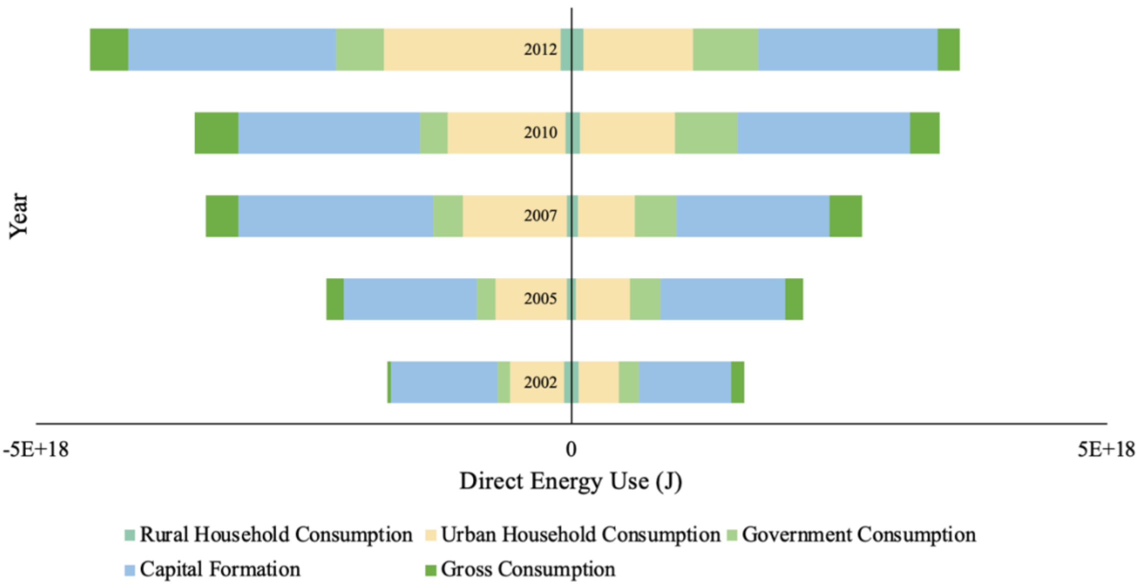


Figure 8. Distinct energy-use structures induced by five different city functions in Beijing and Shanghai.

4. Conclusion and policy implications

4.1 Conclusions

This study applied a three-scale input-output model to depict the different energy-use profiles of two representative large cities in China. We constructed an integrated multi-scale framework using the input-output model to identify embodied energy use at the local, national, and global scales. The empirical results of this study can provide additional insights that are not obtainable through conventional input-output analysis. These results could facilitate a comprehensive understanding of different energy use profiles driven by distinct development plans and urban functions.

In comparing the embodied energy-use profiles of Beijing and Shanghai, this study concludes that the two cities have succeeded in transitioning to tertiary industry-oriented economies and have functioned well as China's political center and financial center, respectively. Moreover, the energy use embodied in urban consumption reflects the high urbanization rates in Beijing and Shanghai, while regionally unbalanced development remains because of the gap between the energy use involved in urban and rural consumption. Regarding sectoral embodied energy use, the construction industry vastly exceeds other sectors and represents a significant proportion of total energy use. The rapid growth of the real estate industry in Beijing and Shanghai in recent years is seen in our results and reflects the urban expansion of the two metropolises.

However, our results largely suggest that Beijing and Shanghai have developed by relying on resources imported from other Chinese provinces or other countries. We found that the net embodied energy involved in Beijing and Shanghai's energy imports are 3.48E +18 J and 6.24E +18 J, respectively, which are 1,142 and 1,536 times that of the energy directly exploited, respectively. This result implies that nearly all the embodied energy use in Beijing and Shanghai stems from domestic and foreign imports. Shanghai is more reliant on imports than Beijing, particularly on a global scale. The location of the two cities may affect the results, because Shanghai is located in the

Yangtze River Delta, a global transport hub, and Beijing is located in a somewhat more isolated region of northern China. Our result also indicates that the development of Beijing and Shanghai has occurred at a significant energy cost to other areas and may be responsible for the environmental degradation of other provinces as well.

In terms of industrial structure, Beijing embraces a highly interregional network of heavy industry with local restrictions on energy-intensive enterprises. This implies that Beijing must address the environmental pressures extended to other regions and seek to reduce the embodied energy use inherent in fossil-fuel utilization. In contrast, Shanghai has begun focusing on pristine energy commodities, through an emphasis on innovative, green, and high-value-added economic development.

Our results also reflect the temporal evolution of energy use in the two megacities. From 2002 to 2012, total energy use in Shanghai increased from 1.72E +18 J to 4.49E +18 J, while that in Beijing only increased from 1.62E +18 J to 3.63E +18 J. The discrepancy indicates the different development patterns of the two cities, in which Beijing is experiencing urban shrinkage while Shanghai is experiencing urban expansion.

Therefore, we suggest that future energy policies should be based on two principles. Firsts, policies should focus on regional synergy and supply chain optimization. Given that Beijing and Shanghai are dependent on imports, energy abatement should focus on both local consumptions and upstream global and national supply chains. Second, energy policies should reflect the development patterns and functions of individual cities. That is, Beijing should function as China’s political center, considerably emphasize energy-use mitigation on the local and national scales, and reduce governmental consumption and non-governmental capacity. In contrast, Shanghai should work to manage energy use on the local, domestic, and global scales due to its status as a global financial center and seek sustainable approaches for additional urban expansion. Future studies should discuss the impact of evolving development patterns on energy use in megacities and evaluate the efficacy and efficiency of policies related to energy abatement on the local, national, and global scales.

4.2 Policy implications

Our results present the basic energy-use patterns of Beijing and Shanghai through an MSIO model, highlighting the significant interactions of large cities with national and global systems. On one hand, as China's two most representative first-tier cities, the energy-use patterns of Beijing and Shanghai show several similar features. On the other hand, their diversified development models and strategies have fostered distinct regional-international connections and evolutionary trends. Facing the unprecedented urbanization process, the cases of Beijing and Shanghai, two leading cities with their own characteristics, are of great significance to other small and medium-sized cities. In this context, we offer relevant policy implications and suggestions based on our results that reflect the similarities and differences of energy-use patterns in Beijing and Shanghai.

(1) Common policy implications

Our results confirm that both Beijing and Shanghai share common metropolis-dominated consumer-oriented energy-use characteristics. Locating at the apex of the new global hierarchy, Beijing and Shanghai show obvious heterotrophic characteristics. As evidenced by the results that more than 95% of the energy consumed by them is originally exploited in regions outside their city boundaries (in different geographical locations). Both cities are net exporters in the service industry and net importers in the manufacturing industry. The tertiary sector dominates the total output of Beijing and Shanghai. Such trading structures further prove the consumer roles of the two cities within the global energy supply chain. This phenomenon may lead to a considerable gap between the direct and embodied energy use in the two megacities, thereby shifting the burdens and pollution issues inherent in energy extraction to downstream agents.

However, reducing on-site direct energy consumption is generally the sole focus of existed policies. These previous policies neglect energy extraction press and environmental pollution shifts accompanied by the transfer of embodied energy. To be concrete, the newly released 13th five-year plans on energy conservation and climate change response, the energy consumption and carbon dioxide emissions per GDP in Beijing and Shanghai are required to be reduced by 17% and 20.5% respectively by 2020. However, the progress thus far made in local energy conservation can be partially attributed to the closure and relocation of factories in the megacities. For example, in 2014, over 50 enterprises producing steel, heavy machinery, and chemicals in Beijing were closed or relocated to Hebei Province. Thus, these policies work in the short term, but they contribute to energy exploitation and environmental pressures in nearby regions. This "local decrease but overall increase" phenomenon may mitigate the efforts contributed by the local governments of Beijing and Shanghai. In the globalized world, economies are increasingly entangled through international trade and complex inter-sectoral linkages. As a result, local energy use not only hinges on local attitudes and practices but is also influenced by international economic, political, and social dynamics (WTO, 2019). Therefore, issues in megacities' energy use should be investigated on a global scale and should consider the interactive effects of supply chains. For instance, the government can introduce strategies that implement regional integration to strengthen the synergistic development model for the Beijing–Tianjin–Hebei region and the Yangtze River Delta Region. Consideration of these integrated economic circles will contribute significantly to the achievement of sustainable development goals (SDGs) and collaborative energy management. Further, Beijing and Shanghai should share advanced energy technology with surrounding small and medium-sized cities to improve overall energy efficiency and conservation. Further, the two megacities' governments can implement policies that would make consumers in Beijing and Shanghai pay for the environmental externalities associated with their products, thereby reducing upstream embodied-energy consumption.

China aims to peak carbon dioxide emissions by 2030 and achieves carbon neutrality by 2060, apart from the energy use profile, the discussions on Beijing and Shanghai's carbon emissions can also offer crucial policy implications for other Chinese cities. Previous studies have discussed carbon emission reduction responsibility worldwide. The final consumers should be responsible for the emissions related to their consuming products. But for the disparity in technology, the producers should also undertake some extra responsibility caused by less developed technology, which shows more fairness in the allocation of emission reduction responsibility (Zhu et al., 2018).

(2) Differentiated policy implications

The two megacities' energy-use disparities are mainly due to their differing final consumption, foreign reliance, and expansion modes. First, the energy use embodied in Beijing's governmental consumption has grown rapidly in recent years and far exceeds that of Shanghai. In this context, finding pathways for reducing energy use embodied in governmental activities is particularly crucial for Beijing. To mitigate the energy use embodied in Beijing's governmental consumption, more energy-efficient offices and agencies are necessary. For example, establishing an online government portal can contribute significantly to reducing massive energy use embodied in office equipment costs. Unlike Beijing's large government-dominated final energy use, the rapid expansion of infrastructure and residential buildings in Shanghai has fueled the growth of energy use embodied in its fixed capital formation.

Furthermore, the energy consumed by urban households in Shanghai deserves more attention. According to our accounting results, there is not much difference between embodied energy use by rural households in these two cities, whereas the total embodied energy use by Shanghai's urban households far exceeds that of Beijing, reaching the level of nearly twice that of Beijing. That proves the highly close relation of embodied energy use and urbanization process in Shanghai. As China continues to urbanize, a considerable amount of direct and indirect energy is needed to expand existing cities and convert energy consumption by rural residents to urban residents. To better guide residents to conserve energy, relevant government messaging that encourages personal investment in sustainability should be implemented, e.g., emphasizing the benefits to individuals and heightening residents' sense of accomplishment when choosing sustainable practices. Meanwhile, policymakers should also pay enough attention to the problem of environmental inequality while eliminating income inequality. The energy use is unequally distributed among urban and rural households due to the differences in the scale and patterns of consumption (Wiedenhofer et al., 2017). The energy-intensive consumption lifestyle of the urban middle class and rich households induces excessive energy use, while the rural and urban poor, which takes a larger percentage of the population, might not access energy for their basic daily consumption. Therefore, the municipal government, especially Shanghai, can set the differentiated energy conservation goals targeted to each income group, to alleviate the energy consumption inequality and achieve overall energy abatement more efficiently.

Second, in terms of the two megacities' different levels of energy external dependence, targeted trade strategies should be crafted that fully consider megacities' interactions with national and global economies. Our results confirm that Shanghai depends on embodied energy imports from foreign regions more heavily than does Beijing, and the gap is widening. Thus, to change present energy-use behavior and reach energy conservation goals in China's global financial center, trade-dominated policies are suggested. On the other hand, the constantly growing energy embodied in Beijing's inflows and outflows reveals its significant headquarter effect. As Beijing has housed a large quantity of corporate headquarters, it plays a crucial role in transferring and redistributing the embodied energy to satisfy the demand of other regions where the sub-companies are located (Li et al., 2020a). Therefore, the headquarter effect can be leveraged when governments drafting their trade policies to integrate energy use across entire supply chains and optimize supply-chain management. The headquarters in Beijing are suggested to make full use of the advantages in geographical aggregation to exchange information and collaboratively investigate high energy efficiency technologies along the whole supply chain. They can also make sectoral regulations or create incentives for downstream subsidiaries to spur energy conservation. Besides, subsidies for products using clean energy and tariff adjustments for energy-intensive products could be considered.

Third, the results also suggest distinct energy use expansion trends in the two megacities. The different urban functions and development strategies of Beijing and Shanghai have led to their differing dynamic development models—Beijing has excluded non-governmental functions while Shanghai is expanding with the growth of local commercial resources. In the Ninth Meeting of the Central Leading Group on Finance and Economics, Chinese President Xi Jinping proposed that as the capital of a large country with over 1.30 billion people, Beijing cannot and does not have sufficient capacity to take on too many non-governmental functions. In 2017, the central government established the Xiong'an New Area to absorb the non-governmental functions of Beijing. As a result, the number of factories and residents moving from Beijing to Hebei will continue to grow. In contrast, Shanghai, with the expansion of its urban development planning and the construction of traffic trunk lines, is continuously expanding and is experiencing increasing international trade, active capital inflows and outflows, and large-scale immigration. Therefore, cooperative measures within their urban agglomerations are necessary to mitigate Beijing and Shanghai's energy use. Beijing should leverage its standing to promote the economic development of Hebei and assist in emissions reduction through technology and talent sharing. The economies of Shanghai's neighbors (Zhejiang, Jiangsu) are both at the forefront nationwide, and the Yangtze River Delta region is characterized by relatively balanced development. Therefore, the government can consider Shanghai, Jiangsu, and Zhejiang as a whole and put forward a uniform policy framework for the entire region.

Acknowledgments

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References:

Ahmad, N., Wyckoff, A., 2003. Carbon Dioxide Emissions Embodied in International Trade of Goods.

Beijing Statistical Bureau (BSB), 2002, 2005, 2007, 2010, 2012. Beijing Statistical Year Book. China Statistical Publishing House, Beijing.

Beijing Statistical Bureau (BSB), 2018. Beijing Statistical Year Book. China Statistical Publishing House, Beijing.

Beijing Statistical Bureau (BSB), 2019. Beijing National Economic and Social Development Statistical Bulletin in 2018.

Boyang, G., Weidong, L., Dunford, M., 2014. State land policy, land markets and geographies of manufacturing: The case of Beijing, China. Land Use Policy 36, 1-12.

Chen, B., Li, J.S., Wu, X.F., Han, M.Y., Zeng, L., Li, Z., Chen, G.Q., 2018. Global energy flows embodied in international trade: A combination of environmentally extended input-output analysis and complex network analysis. Applied Energy 210, 98-107.

Chen, G., Wiedmann, T., Wang, Y., Hadjikakou, M., 2016. Transnational city carbon footprint networks - Exploring carbon links between Australian and Chinese cities. Applied Energy 184, 1082-1092.

Chen, G.Q., Chen, H., Chen, Z.M., Zhang, B., Shao, L., Guo, S., Zhou, S.Y., Jiang, M.M., 2011. Low-carbon building assessment and multi-scale input-output analysis. Communications in Nonlinear Science and Numerical Simulation 16, 583-595.

Chen, G.Q., Guo, S., Shao, L., Li, J.S., Chen, Z.-M., 2013. Three-scale input–output modeling for urban economy: Carbon emission by Beijing 2007. Communications in Nonlinear Science and Numerical Simulation 18, 2493-2506.

Dhakal, S., Urban energy use and carbon emissions from cities in China and policy implications. Energy Policy 37, 4208-4219.

Fang, D., Chen, B., 2018. Linkage analysis for water-carbon nexus in China. Applied Energy 225, 682-695.

Feng, K., Hubacek, K., Sun, L., Liu, Z., 2014. Consumption-based CO2 accounting of China's megacities: The case of Beijing, Tianjin, Shanghai and Chongqing. Ecological Indicators 47, 26-31.

Franzen, A., Mader, S., 2018. Consumption-based versus production-based accounting of CO2 emissions: Is there evidence for carbon leakage? Environmental Science & Policy 84, 34-40.

Guo, S., Zheng, S., Hu, Y., Hong, J., Wu, X., Tang, M., 2019. Embodied energy use in the global construction industry. Applied Energy 256, 113838.

Hao, Y., Zhang, M., Zhang, Y., Fu, C., Lu, Z., 2018. Multi-scale analysis of the energy metabolic processes in the Beijing-Tianjin-Hebei (Jing-Jin-Ji) urban agglomeration. Ecological Modelling 369, 66-76.

Hertwich, E.G., Peters, G.P., 2009. Carbon Footprint of Nations: A Global, Trade-Linked Analysis. Environmental Science & Technology 43, 6414-6420.

Li, J.S., Xia, X.H., Chen, G.Q., Alsaedi, A., Hayat, T., 2016a. Optimal embodied energy abatement strategy for Beijing economy: Based on a three-scale input-output analysis.

Renewable and Sustainable Energy Reviews 53, 1602-1610.

Li, J.S., Xia, X.H., Chen, G.Q., Alsaedi, A., Hayat, T., 2016b. Optimal embodied energy abatement strategy for Beijing economy: Based on a three-scale input-output analysis. Renewable & Sustainable Energy Reviews 53, 1602-1610.

Li, Y., Chen, B., Chen, G., Meng, J., Hayat, T., 2020a. An embodied energy perspective of urban economy: A three-scale analysis for Beijing 2002–2012 with headquarter effect. Science of The Total Environment 732, 139097.

Li, Y., Chen, B., Li, C., Li, Z., Chen, G., 2020b. Energy perspective of Sino-US trade imbalance in global supply chains. Energy Economics 92, 104959.

Li, Y.L., Chen, B., Chen, G.Q., 2020c. Carbon network embodied in international trade: Global structural evolution and its policy implications. Energy Policy 139, 111316.

Li, Y.L., Han, M.Y., Liu, S.Y., Chen, G.Q., 2019. Energy consumption and greenhouse gas emissions by buildings: A multi-scale perspective. Building and Environment 151, 240-250.

Liu, L., Huang, G., Baetz, B., Zhang, K., 2018. Environmentally-extended input-output simulation for analyzing production-based and consumption-based industrial greenhouse gas mitigation policies. Applied Energy 232, 69-78.

Lorraine, S., Christopher, K., Edward, L., 2012. Greenhouse Gas Emissions from Chinese Cities. Journal of Industrial Ecology.

Meng, F., Liu, G., Hu, Y., Su, M., Yang, Z., 2018. Urban carbon flow and structure analysis in a multi-scales economy. Energy Policy 121, 553-564.

Mi, Z., Zheng, J., Meng, J., Zheng, H., Li, X., Coffman, D.M., Woltjer, J., Wang, S., Guan, D., 2019. Carbon emissions of cities from a consumption-based perspective. Applied Energy 235, 509-518.

Odum, H.T., 1996. Environmental accounting: Emergy and environmental decision making. John Wiley, New York.

Oswald, Y., Owen, A., Steinberger, J.K., 2020. Large inequality in international and intranational energy footprints between income groups and across consumption categories. Nature Energy 5, 231-239.

Rao, N.D., Min, J., Mastrucci, A., 2019. Energy requirements for decent living in India, Brazil and South Africa. Nature Energy 4, 1025-1032.

Seto, K., Dhakal, S., Bigio, A., Blanco, H., Delgado Ramos, G.C., Dewar, D., Huang, L., Inaba, A., 2014. Climate Change 2014: Mitigation of Climate Change, Cambridge and New York.

Shanghai Municipal People's Government (SMPG), 2018.

Shanghai Statistical Bureau (SSB), 2002, 2005, 2007, 2010, 2012. Shanghai Statistical Year Book. Shanghai Statistical Publishing House, Shanghai.

Shanghai Statistical Bureau (SSB), 2018. Shanghai Statistical Year Book. Shanghai Statistical Publishing House, Shanghai.

Shanghai Statistical Bureau (SSB), 2019. Shanghai National Economic and Social Development Statistical Bulletin in 2018.

Shao, L., Guan, D., Wu, Z., Wang, P., Chen, G.Q., 2017. Multi-scale input-output analysis of consumption-based water resources: Method and application. J. Clean. Prod. 164, 338-346.

Shao, L., Guan, D., Zhang, N., Shan, Y., Chen, G.Q., 2016. Carbon emissions from fossil fuel consumption of Beijing in 2012. Environmental Research Letters 11.

Wang, Z., Li, C., Liu, Q., Niu, B., Peng, S., Deng, L., Kang, P., Zhang, X., 2019. Pollution haven hypothesis of domestic trade in China: A perspective of SO2 emissions. Science of The Total Environment 663, 198-205.

Wei, Z., Jie, Z., Feng, W., Hongqiang, J., Jinnan, W., Lin, J., 2017. Spacial

Agglomeration of Industrial Air Pollutant Emission in Beijing-Tianjin-Hebei Region. Urban development Studies 24, 81-87.

Wiedenhofer, D., Guan, D., Liu, Z., Meng, J., Zhang, N., Wei, Y.-M., 2017. Unequal household carbon footprints in China. Nature Climate Change 7, 75-80.

World Trade Organization, 2019. Global Value Chain Development Report 2019.

WTO, 2019. Glocal value chain development report 2019: Technical innovation, supply chain trade, and workers in a globalized world. World Trade Organization.

Wu, X.F., Chen, G.Q., 2017. Global primary energy use associated with production, consumption and international trade. Energy Policy 111, 85-94.

Yao, L., Liu, J., Wang, R., Yin, K., 2013. Carbon footprint accounting of regional household consumption in China through multi-regional input-output model. Huanjing Kexue Xuebao/Acta Scientiae Circumstantiae 33, 2050-2058.

Yu, D., Yanxu, L., Bojie, F., 2019. Urban growth simulation guided by ecological constraints in Beijing city: Methods and implications for spatial planning. Journal of Environmental Management 243, 402-410.

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

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

Zheng, H., Wang, X., Li, M., Zhang, Y., Fan, Y., 2018. Interregional trade among regions of urban energy metabolism: A case study between Beijing-Tianjin-Hebei and others in China. Resources Conservation and Recycling 132, 339-351.

Zhu, Y., Shi, Y., Wu, J., Wu, L., Xiong, W., 2018. Exploring the Characteristics of CO2

Emissions Embodied in International Trade and the Fair Share of Responsibility. Ecological Economics 146, 574-587.

Appendix

Table A1. 42 industrial sectors of the Beijing and Shanghai economies in 2012

Sector code	Sector content
1	Farming, forestry, animal husbandry and fishery
2	Mining and washing of coal
3	Petroleum and natural gas extraction
4	Mining and processing of metal ores
5	Mining and processing of nonmetal ores and other ores
6	Foods and tobacco manufacturing
7	Textile manufacturing
8	Textile wearing apparel, footwear, caps, leather, fur, feather(down) and its products manufacturing
9	Timbers processing and furniture manufacturing
10	Papermaking, printing and manufacture of articles for culture, education and sports activities
11	Petroleum processing, coking, processing of nuclear fuel production
12	Chemical industry
13	Nonmetallic mineral products manufacturing
14	Smelting and rolling of metals
15	Metal products manufacturing
16	General purpose machinery manufacturing
17	Special purpose machinery manufacturing
18	Transport equipment manufacturing
19	Electrical machinery and equipment manufacturing
20	Communication equipment, computer and other electronic equipment manufacturing
21	Measuring instrument and meter manufacturing
22	Other manufacturing
23	Scrap and waste

24	Repair of fabricated metal products, machinery and equipment
25	Production and supply of electric power and heat power
26	Production and distribution of gas
27	Production and distribution of water
28	Construction
29	Wholesale and retail trades
30	Transportation, storage, posts and telecommunications
31	Hotels and catering services
32	Information transmission, software and information technology services
33	Finance
34	Real estate trade
35	Tenancy and commercial services
36	Scientific research and development, technical services
37	Water, environment and municipal engineering conservancy
38	Resident services, repair and other services
39	Education
40	Health care and social services
41	Culture, art, sports and recreation
42	Public administration, social security and social organizations

Table A2. Sector classification in Eora 26

Sector code	Sector content
1	Agriculture
2	Fishing
3	Mining and Quarrying
4	Food & Beverages
5	Textiles and Wearing Apparel
6	Wood and Paper
7	Petroleum, Chemical and Non-Metallic Mineral Products
8	Metal Products
9	Electrical and Machinery
10	Transport Equipment
11	Other Manufacturing
12	Recycling
13	Electricity, Gas and Water
14	Construction
15	Maintenance and Repair
16	Wholesale Trade
17	Retail Trade
18	Hotels and Restraurants
19	Transport
20	Post and Telecommunications
21	Finacial Intermediation and Business Activities
22	Public Administration
23	Education, Health and Other Services
24	Private Households
25	Others
26	Re-export & Re-import

Table A3. Eora 26 connected to 42 industrial sectors

Sector code	Sector content (42 sectors)	Connected eora sector
1	Farming, forestry, animal husbandry and fishery	Agriculture, fishing
2	Mining and washing of coal	Mining and quarrying
3	Petroleum and natural gas extraction	Mining and quarrying
4	Mining and processing of metal ores	Mining and quarrying
5	Mining and processing of nonmetal ores and other ores	Mining and quarrying
6	Foods and tobacco manufacturing	Food & beverages
7	Textile manufacturing	Textiles and wearing apparel
8	Textile wearing apparel, footwear, caps, leather, fur, feather(down) and its products manufacturing	Textiles and wearing apparel
9	Timbers processing and furniture manufacturing	Wood and paper
10	Papermaking, printing and manufacture of articles for culture, education and sports activities	Wood and paper

11	Petroleum processing, coking, processing of nuclear fuel production	Petroleum, chemical and non-metallic mineral products
12	Chemical industry	Petroleum, chemical and non-metallic mineral products
13	Nonmetallic mineral products manufacturing	Petroleum, chemical and non-metallic mineral products
14	Smelting and rolling of metals	Metal products
15	Metal products manufacturing	Metal products
16	General purpose machinery manufacturing	Electrical and machinery
17	Special purpose machinery manufacturing	Electrical and machinery
18	Transport equipment manufacturing	Transport equipment
19	Electrical machinery and equipment manufacturing	Electrical and machinery
20	Communication equipment, computer and other electronic equipment manufacturing	Electrical and machinery
21	Measuring instrument and meter manufacturing	Electrical and machinery
22	Other manufacturing	Other manufacturing
23	Scrap and waste	Recycling

24	Repair of fabricated metal products, machinery and equipment	Maintenance and repair
25	Production and supply of electric power and heat power	Electricity, gas and water
26	Production and distribution of gas	Electricity, gas and water
27	Production and distribution of water	Electricity, gas and water
28	Construction	Construction
29	Wholesale and retail trades	Wholesale trade, retail trade
30	Transportation, storage, posts and telecommunications	Transport, post and telecommunications
31	Hotels and catering services	Hotels and restaurants
32	Information transmission, software and information technology services	Post and telecommunications
33	Finance	Financial intermediation and business activities
34	Real estate trade	Financial intermediation and business activities
35	Tenancy and commercial services	Financial intermediation and business activities
36	Scientific research and development, technical services	Financial intermediation and business activities
37	Water, environment and municipal engineering conservancy	Public administration
38	Resident services, repair and other services	Private households
39	Education	Education, health and other services

40	Health care and social services	Education, health and other services
41	Culture, art, sports and recreation	Education, health and other services
42	Public administration, social security and social organizations	Public administration

Table A4. Mapping IEA energy exploitation data to the MRIO table sectors

IEA production data category	Global MRIO sector
Crude oil	Mining and quarrying (Sector 4)
Coal	Mining and quarrying (Sector 4)
Natural gas	Mining and quarrying (Sector 4)
Biomass	Crop and animal production, hunting and related service activities (Sector 1)
Hydro	Electricity, gas, steam and air conditioning supply (24)
Nuclear energy	Mining and quarrying (Sector 4)
Other renewables	Electricity, gas, steam and air conditioning supply (24)