

# Exports-driven primary energy requirements and the structural paths of Chinese regions

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**Abstract** As the major primary energy importer in the world, China has engaged in considerable efforts to ensure energy security. However, little attention has been paid to China's embodied primary energy exports. Separating the international export from regional final demand, this paper focuses on quantifying provincial primary energy requirement arising from China's exports, and tracing its concrete interprovincial supply chains using multi-regional input-output analysis and structural path analysis. Results show that China's embodied primary energy uses in exports (EEE) reached 633.01 Mtce in 2012, compared to 565.15 Mtce in 2007. Four fifths of the EEE were supplied through interprovincial trade. Eastern coastal provinces accounted for nearly 70% of the national total EEE, while their primary energy supply mainly sourced from the central and western provinces. Most interprovincial supply chain paths of embodied primary energy exports were traced to the coal mining sectors of Shanxi, Inner Mongolia and Shaanxi. Critical receiving sectors in the final export provinces were Chemical industry, Metallurgy, Electronic equipment, Textile and other manufacturing sectors. Important transmission sectors were Electricity and hot water production and supply and Petroleum refining, coking, etc. In view of the specific role of exports in primary energy requirements, provincial energy uses are largely dependent on its domestic trade position and degrees of industrial participation in the global economy. Managing critical industrial sectors and supply chain paths associated with the international exports provide new insights to ensure China's energy security and to formulate targeted energy policies.

**Keywords** embodied energy, multi-regional input-output analysis, structural path analysis, interregional supply chains, China's exports

## 1 Introduction

Energy security and energy-related environmental issues are closely linked to sustainable development. As the world's largest energy consumer, China's energy demand has been the focus of the world's attention. To ensure a steady primary energy supply, China's imports of crude oil, natural gas and raw coal were 599.24, 125.82, and 193.52 Mtce in 2017, respectively (NBSC, 2019). As a major energy importer, China is under enormous pressure in international energy market. However, what is always overlooked is that abundant commodities 'Made in China' are supplied to international market every year, which has induced a tremendous amount of domestic energy use in the production chain of those commodities. Hence, when evaluating the overall impacts of export trade, both economic benefits and related impacts on resources and the environment (e.g., Weber et al., 2008; Jiang et al., 2015; Tang et al., 2016; Zhao et al., 2016; Nawab et al., 2019) from the primary energy requirements should be taken into account. For China, due to the urgent need of developing a sustainable trade structure and guaranteeing energy security, it is of particular importance to carry out such an evaluation.

Conventional energy analysis focuses on the energy use that occurs during the on-site production process of commodities. Off-site information, however, finds no reflection in the related accounting framework. The pursuit of maximum economic efficiency has promoted a high-efficient production mode, highlighting intricate regional

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specialization. With a global supply chain taking shape, frequent international trade has become a channel for not only the swap of commodities but also the transboundary flows of energy use between different regions of the world. Just as noted by Nordhaus (2009), the world economy has grown into an integrated world market, in which much traditional thinking on energy security is misguided. From an integrated perspective, primary energy resources come into the economy after being exploited. The economic utility of the energy use keeps circulating in the economic system via interregional trade in the form of embodied primary energy and is finally sinking into the society as final demand (Herendeen, 1973; Wu et al., 2018). In an overview of the coal use by Wu and Chen (2018), the off-site coal use is revealed to be in magnitude around half of the on-site use for the United States, and 1.4 times for Japan. As a result, a better understanding of the energy profile of a country or a region necessitates a comprehensive accounting for the total energy use related to the consumption of goods and services. In this regard, the concept of embodied primary energy, which serves a valid tool to account for the total (both on- and off-site) energy resource required to produce goods or services, is resorted in this study (Zhang et al., 2013).

Originated from systems ecology, embodied primary energy accounting aims to assess all the primary energy resources required in the entire production chain of goods or services (Zhang et al., 2017). Those resources are regarded as ‘embodied’ in the goods or services and flowing along with them via trade activities in the economic system. Recently, extensive studies have adopted the idea of embodied primary energy and proved it as an important method for energy analyses at macroeconomic scale for global, national and regional economies (Chen and Wu, 2017) and at microeconomic scale of individual production and consumption activities (Su and Zhang, 2016). To account for energy use embodied in products and services, the mainstream methods adopt the input-output model to suit different scales of data (e.g., Peters, 2008; Kanemoto et al., 2012; Chen et al., 2019; Wu et al., 2019a and 2019b). As one of the most commonly-used methods, the input-output analysis quantifies how energy use is assigned to final demand by incorporating primary energy inputs into the socioeconomic context, which has been widely used to reveal the resource and environmental issues in certain economic activities (e.g., Wiedmann, 2009; Peters et al., 2011; Hawkins et al., 2015; Chen et al., 2018; Xu et al., 2018; Tian et al., 2019). Particularly, with the help of the input-output analysis, some scholars have observed the impact of international exports on China’s energy use and related environmental emissions (e.g., Guo et al., 2012; Meng et al., 2013; Jiang et al., 2015; Tang et al., 2015 and 2016; Zhang et al., 2017 and 2018b; Zhang et al., 2019). Furthermore, when the input-output analysis is applied to an economy with

multiple regions, it relies on the multi-regional input-output (MRIO) model. The MRIO models enable the spatial linkages and inter-dependencies to be identified among different regions and have been widely adopted to explore the impact and effect of domestic trade on regional energy uses (e.g., Chen et al., 2017; Sun et al., 2017; Gao et al., 2018; Liu et al., 2018a; Zhao et al., 2018; Tang et al., 2019). For instance, Zhang et al. (2016) reported that the total exports-driven embodied primary energy transfers among China’s eight regions increased from 86.19 Mtce in 2002 to 418.63 Mtce in 2007. Although large amounts of embodied primary energy exports are revealed in previous studies, the supply chains of domestic production to meet China’s export demands remain to be systematically revealed, which has been increasingly prominent with the export boom. Thus, it is necessary to investigate interprovincial embodied primary energy transfer driven by the export trade from a systems perspective.

To track how embodied primary energy flows between producers and consumers, the structural path analysis (SPA) provides an approach to uncover where the resources are from and how they go into different economic sectors of various regions (Zhao et al., 2019). This method emphasizes the process of embodied energy flow from extraction to final demand and reveals the energy supply chain under economic linkages (Skelton et al., 2011; Oshita, 2012; Yuko, 2012; Llop and Ponce-Alifonso, 2015; Lenzen, 2016). In view of the importance and merit of the SPA, increasing studies have used this method to analyze the flows of energy, CO<sub>2</sub> emissions, water and other ecological elements through industrial networks, and then identify important paths along Chinese supply chains (e.g. Meng et al., 2015; Wang et al., 2017; Yang et al., 2018; Zhang et al., 2017, 2018a; Feng et al., 2019; Su et al., 2019). Especially, Hong et al. (2016) revealed energy drivers in typical regions to quantify impact transmission in the entire supply chain. Shao et al. (2018) used the SPA approach to address regional CO<sub>2</sub> imbalances and outsourcing issues in China. Zhao et al. (2018) identified critical interprovincial supply chains of virtual water uses combining with the SPA. However, there is no study focusing on energy interactions among industrial sectors of different regions so as to explore the export-related paths of embodied primary energy use along the supply chains.

To fill this gap, this study aims to explore China’s exports-driven primary energy requirements and trace the interprovincial supply chains of embodied primary energy transfer by performing the MRIO and the SPA methods. We quantify the embodied primary energy uses in international exports associated with 31 provincial regions and related sectors, and investigate the interprovincial transfer processes associated with exports. Critical industrial sectors and supply chain paths are then identified. Corresponding policy implications for supply chain

management of exports-driven primary energy requirements are discussed.

## 2 Methodology and data sources

### 2.1 MRIO analysis and SPA methods

The latest MRIO table for China in 2012 is compiled jointly by Chinese Academy of Science and National Bureau of Statistics of China (Liu et al., 2018b), which is a non-competitive MRIO table with 31 provincial regions of Chinese mainland and 42 sectors covered. According to the structure of the MRIO table, the items of international imports have been excluded. Thus, the MRIO model can be built based on the domestic economic linkages and interregional trade network. Detailed regional and sectoral information are listed in Tables S1 and S2 in the Electronic Supplementary Materials.

The whole economic balance for the MRIO table can be expressed as,

$$X = AX + Y, \quad (1)$$

where  $X$  is the total output;  $A$  is the technology coefficients matrix describing the relationship between all sectors of the economy; and  $Y$  is the final demand.

To link primary energy inputs to the MRIO model, the embodied primary energy use induced by final demand ( $EEU$ ) can be formulated as,

$$EEU = w \times Y = w^d \times L \times Y, \quad (2)$$

where  $w$  and  $w^d$  represents the embodied primary energy intensity and direct energy coefficient (i.e., the total and direct energy use induced by per unit of value of industrial output), respectively; and  $L$  is the domestic Leontief inverse matrix, whose element  $L_{ij}$  tracks the overall direct and indirect input along the supply chain from Sector  $i$  for generating unit output in Sector  $j$ .  $L = (I - A)^{-1}$ , and  $I$  is the identity matrix.

As to the international exports as a specific final demand category, represented by  $Y_e$ , the embodied primary energy use in international exports ( $EEE$ ) can be calculated as,

$$EEE = w \times Y_e. \quad (3)$$

With regard to the 31 provincial regions, the exports-driven primary energy use embodied in interprovincial outflows ( $EEIO$ ) of Region 1 can be expressed as follows (Zhang et al., 2015 and 2016),

$$EEIO_1 = w_1^d (I - A)^{-1} \times e_s = \sum_{s=2}^{31} EEIT_{1s}, \quad (4)$$

where  $w_1^d$  only covers the direct primary energy coefficient from Region 1;  $e_s$  is the  $31 \times 1$  column vector representing the exports of Region  $s$  ( $s \neq 1$ ); and  $EEIT_{1s}$  is the transfer of

embodied primary energy from Region 1 to Region  $s$ .

The exports-driven primary energy use embodied in interprovincial inflows ( $EEII$ ) of Region 1 can be expressed as follows,

$$EEII_1 = \sum_{s=2}^{31} EEIT_{s1}, \quad (5)$$

where  $EEIT_{s1}$  is the transfer of embodied primary energy flows from Region  $s$  to Region 1.

The net embodied primary energy transfer in interprovincial trade balance ( $EEIB = EEIO - EEII$ ) can be further calculated. The regions with positive  $EEIB$  are interprovincial net exporters of embodied primary energy, while the regions with negative  $EEIB$  are identified as interprovincial net importers. Meanwhile, the  $EDEI$  of a region indicates the local direct primary energy input to meet the intra-provincial and interprovincial demands for international exports, excluding its exports-induced  $EEII$ . In other words, regional  $EEIB$  is also the difference between regional  $EDEI$  and  $EEE$ .

To perform the SPA for embodied primary energy use, the Leontief inverse can be expanded using the Taylor series approximation as,

$$L = (I - A)^{-1} = I + A + A^2 + A^3 + \dots + A^t. \quad (6)$$

On the right-hand side of Eq. (6), each element in the expansion denotes a different production layer (PL) or tier. A production layer (PL) is defined as each term in the power series expansion (Meng et al., 2015; Zhang et al., 2018a). Each additional layer ( $PL^{t+1}$ ) represents the production of intermediate products in  $(t + 1)$ th production tier used as inputs into the  $t$ th production tier.

The primary energy use embodied in international exports can be expressed as,

$$w^d \times (I - A)^{-1} \times Y_e = w^d I Y_e + w^d A Y_e + w^d A^2 Y_e + \dots + w^d A^t Y_e. \quad (7)$$

### 2.2 Data sources

The extraction of primary energy resources includes raw coal, crude oil, natural gas, hydropower, nuclear power, wind power and other renewable energy sources. The inputs of fossil fuels into regional economy are available from China Energy Statistical Yearbook 2014 (NBSC, 2015). Other primary energy inputs are estimated based on electricity production and corresponding electricity generation efficiencies, referring to Zhang et al. (2013 and 2015). Regional electricity generation data are collected from China Electric Power Yearbook (CEPY, 2013). Extensive illustrations for the accounting of primary energy inputs can be referred to Zhang et al. (2013, 2015, and 2016).

### 3 Results

#### 3.1 Exports-induced primary energy requirements in Chinese regions

The total embodied primary energy use in international exports (*EEE*) was 633.01 Mtce in 2012. Coal contributed a dominant share of 80.2% (507.44 Mtce). Oil and gas and other primary energy accounted for 14.8% and 5.1% of the national *EEE*, respectively. Figure 1(a) shows the regional energy requirements driven by exports as classified by energy types. The eastern area contributed the largest fraction of 75.5% (477.77 Mtce) to the national total *EEE*, followed by the western area (10.6%, 67.03 Mtce), the central area (9.2%, 57.96 Mtce), and the north-eastern area (4.8%, 30.25 Mtce). At the regional level, the eastern provinces generally had higher *EEE*, compared to the western and central regions. The top five provinces with the largest *EEE* were all located in the eastern area: Jiangsu had the largest *EEE* volume of 122.07 Mtce, followed by Guangdong of 98.85 Mtce, Zhejiang of 89.28 Mtce, Shanghai of 69.43 Mtce, and Shandong of 42.60 Mtce.

Figure 1(b) displays the *EEE* composition by sector. All of the 42 industrial sectors are merged into eight broad categories, i.e., agriculture, mining, heavy industry, light industry, power, gas and water, construction, transportation and services, as listed in Table S2. Heavy industry occupied a dominant position in all provincial regions (except for Tibet), accounting for 40%–80% of their *EEEs* (such as 76.9% in Liaoning, 75.0% in Jiangsu, 71.4% in Shandong, and 60.3% in Guangdong). Light industry contributed 10%–40% of the regional *EEEs* (e.g., 33.7% in Fujian, and 31.5% in Zhejiang). Transport held a large share for the exports of embodied primary energy in Inner Mongolia, Shanxi, Shanghai and Tianjin, reaching 36.0%, 21.3%, 15.5% and 10.1%, respectively. Services made a prominent contribution to the *EEEs* in some eastern coastal regions, due to the advanced commerce and technology levels in the regions. The exported products were mainly electronic and electrical equipment, clothing, chemical products and services.

Owing to a vast territory, differences can be witnessed in resource endowments among provincial regions. China's energy resources are mainly distributed in the central and western regions, where Inner Mongolia, Shanxi and Shaanxi are main suppliers of coal. By contrast, developed eastern regions have larger export demands, but are less self-sufficient in energy resources. The distribution of provincial *EEE* from a consumption perspective is quite different from that of the *EDEI* from a production perspective (see Tables S3 and S4). As to the *EDEI*, the north-eastern, eastern, central, and western areas were responsible for 6.2% (39.55 Mtce), 14.3% (90.51 Mtce), 26.6% (168.56 Mtce) and 52.8% (334.39 Mtce) of the total, respectively. The *EEEs* in some central and western

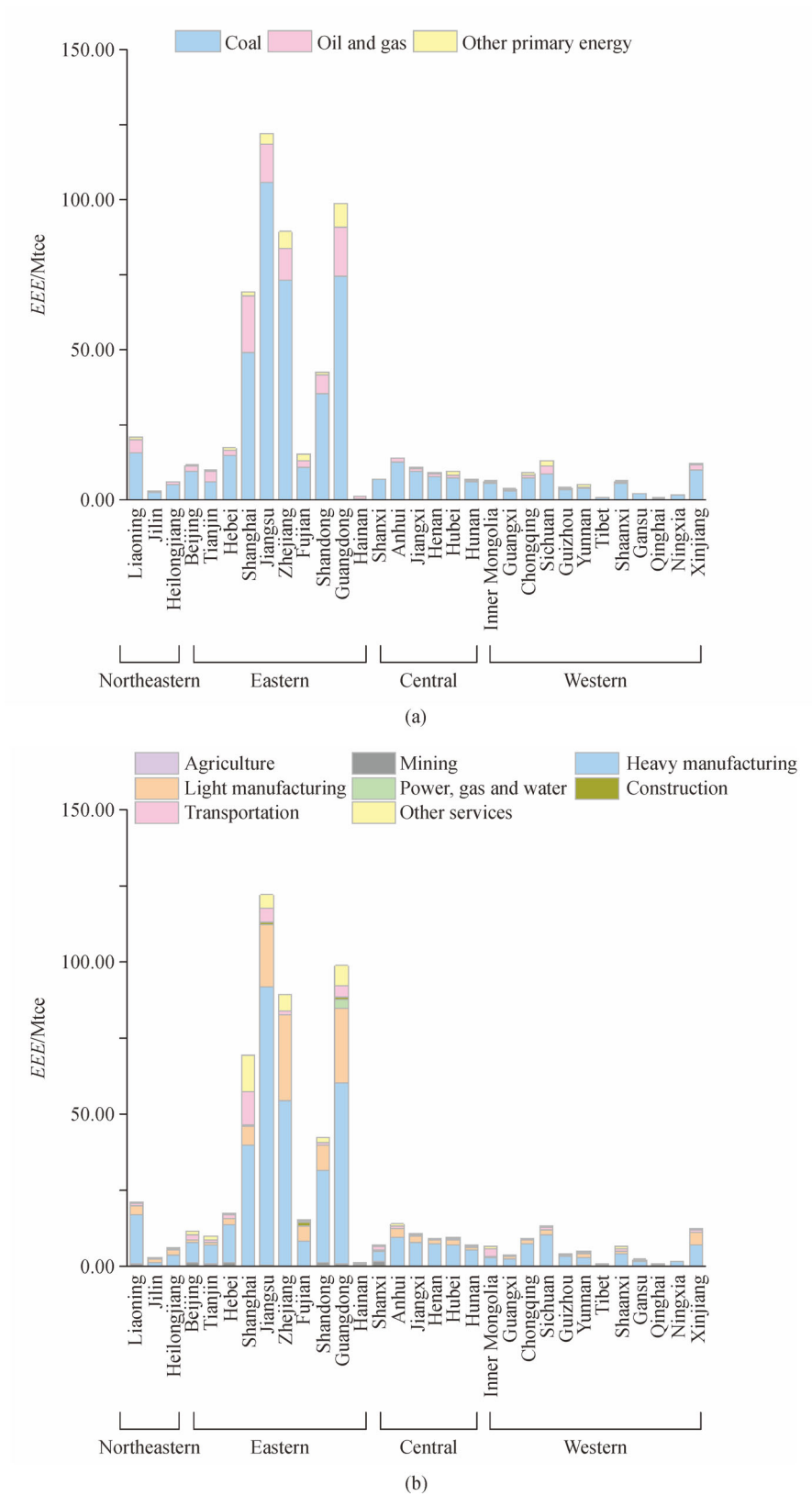
regions were much lower than their *EDEIs*, and the *EEEs* of Inner Mongolia, Shanxi, and Shaanxi were equal to only 4.8%, 5.7%, and 7.9% of their *EDEIs*, respectively. Inner Mongolia contributed the largest share of 21.7% to the national total *EDEI*, but its *EEE* accounted for only 1.0%. Similarly, the shares of Shanxi (19.7% for *EDEI*) and Shaanxi (13.0% for *EDEI*) in the national total *EEE* were only 1.1% and 1.0%, respectively. In comparison, the *EEEs* in most eastern regions were much higher than their *EDEIs*. The *EEEs* in Shanghai, Jiangsu, and Zhejiang were 247.92, 19.52 and 17.70 times of their *EDEIs*, respectively.

#### 3.2 Interprovincial transfers of embodied primary energy across China

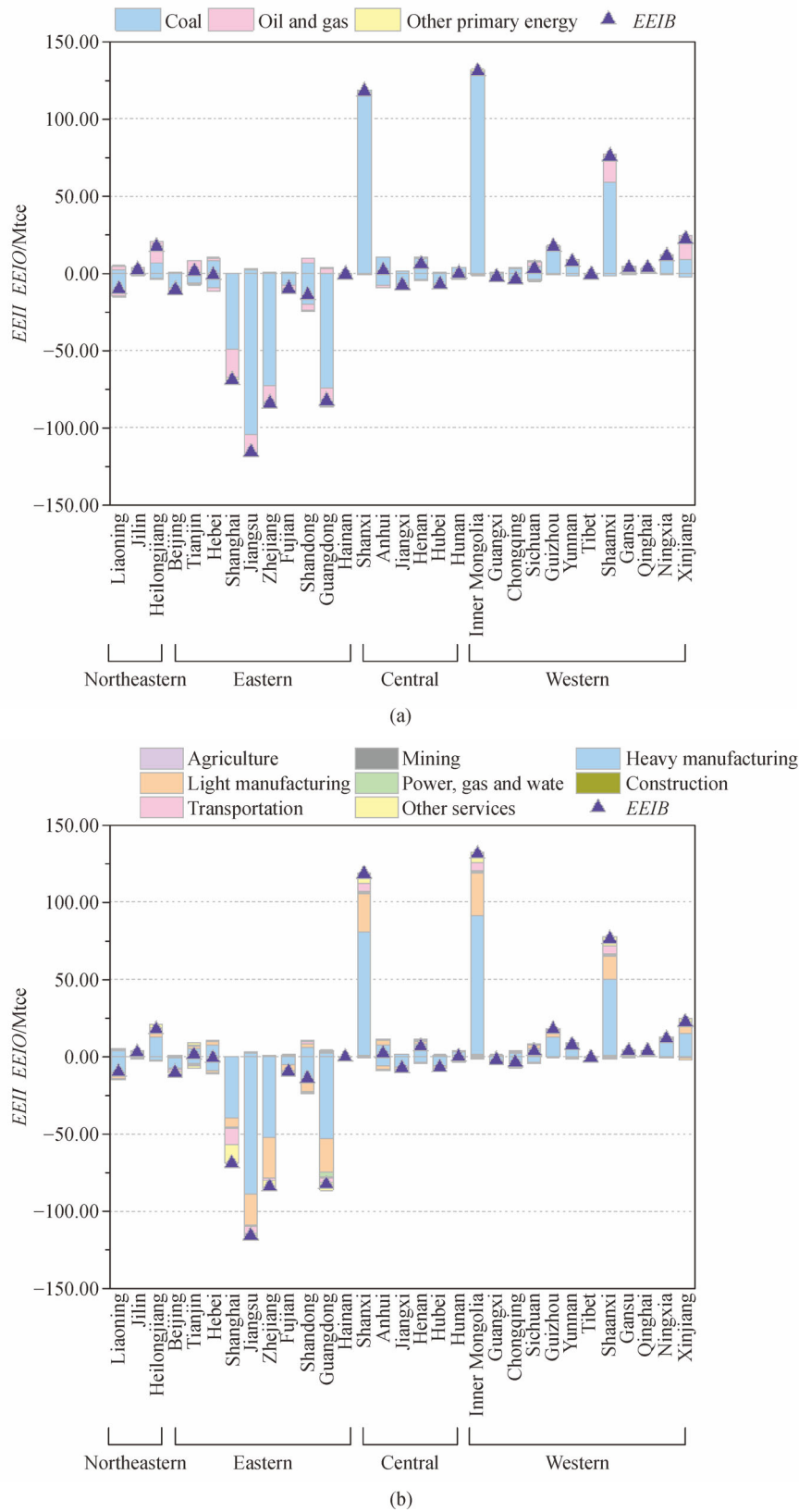
The total interprovincial transfer of embodied primary energy induced by international exports (*EEIT*) was 509.43 Mtce in 2012. Figure 2 presents the regional distribution of such interprovincial transfer. Coal was the dominant type in the interprovincial trade of embodied primary energy (see Fig. 2(a)). As to the *EEIT*, Jiangsu had the largest share of 23.3% of the national total, followed by Guangdong (17.0%), Zhejiang (16.7%), Shanghai (13.6%), and Shandong (4.8%). The aforementioned five regions, which are all located in the eastern area, contributed altogether to 75.4% of the national total. For the *EEIO*, the largest interprovincial exporter was Inner Mongolia, accounting for 25.9% of the total, followed by Shanxi (23.3%), Shaanxi (15.3%), Xinjiang (4.8%) and Heilongjiang (4.1%). The aforementioned five regions together contributed 73.4% to the national total. As to the *EEIB*, Inner Mongolia was the largest interprovincial net exporter, with the net trade volume amounting to 130.60 Mtce, followed by Shanxi (117.81 Mtce), Shaanxi (75.82 Mtce) and Xinjiang (22.13 Mtce). By contrast, Jiangsu was the leading region with the largest net inflow of 115.82 Mtce. The next three interprovincial net importers were Zhejiang (84.23 Mtce), Guangdong (82.55 Mtce) and Shanghai (69.15 Mtce).

From a sectoral perspective, manufacturing goods, especially the goods from heavy industry, were the major contributors. Shanxi, Inner Mongolia and Shaanxi were the major interprovincial net exporters of manufacturing goods, while Jiangsu, Zhejiang, Shanghai and Guangdong were the top four net importers, as shown in Fig. 2(b). The products exchanged between the sectors were mainly energy-intensive products, such as metal and nonmetal products, chemical products and electricity. Detailed data are listed in Tables S5 and S6.

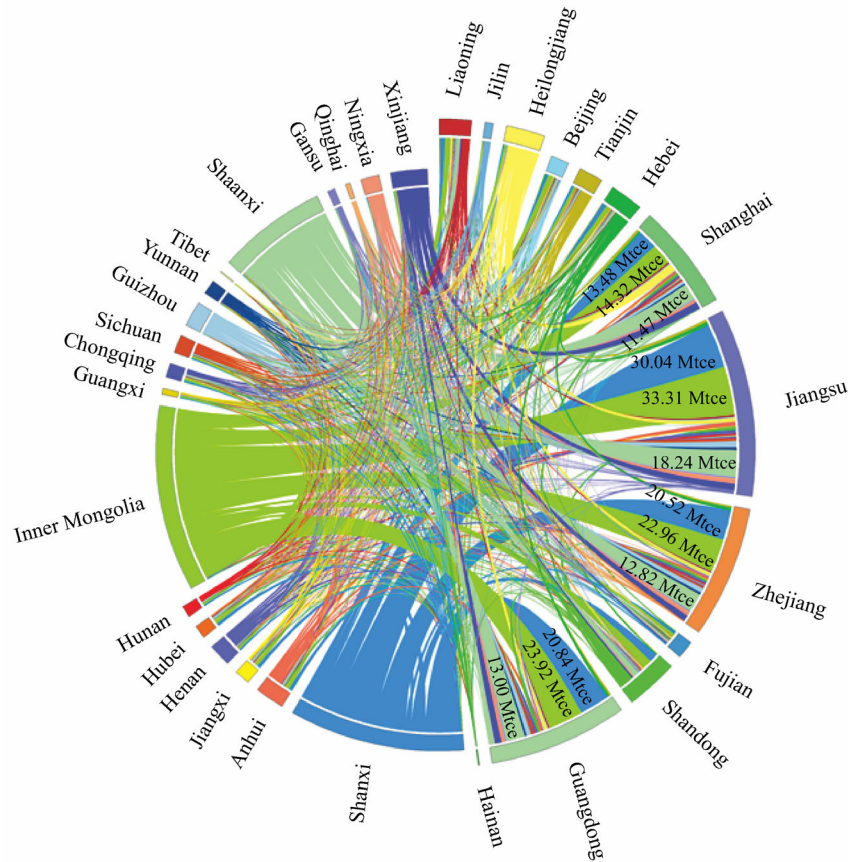
Figure 3 further displays the interprovincial trading flows of embodied primary energy driven by international export among the 31 provincial regions. The dominant fluxes of embodied primary energy were the outflows from Inner Mongolia (33.31 Mtce) and Shanxi (30.04 Mtce) to Jiangsu. Inner Mongolia exported substantial embodied



**Fig. 1** Regional distribution of the embodied primary energy uses in exports: (a) *EEE* composition by primary energy type; (b) *EEE* composition by aggregated sector.



**Fig. 2** Embodied primary energy uses in interprovincial outflows and inflows induced by exports in terms of (a) energy type and (b) aggregated sector.



**Fig. 3** Exports-driven interprovincial transfers of embodied primary energy. Note: The circle has four different radii to distinguish the four areas. The color of the connecting line is consistent with the interprovincial exporter of embodied primary energy; the width of the connecting line indicates the amount of trading flows.

primary energy to Guangdong, Zhejiang and Shanghai, at 23.92, 22.96, and 14.32 Mtce, respectively. The trading flows from Shanxi to Guangdong/Zhejiang and from Shaanxi to Jiangsu/Guangdong were important pairs in domestic transfer network of embodied primary energy.

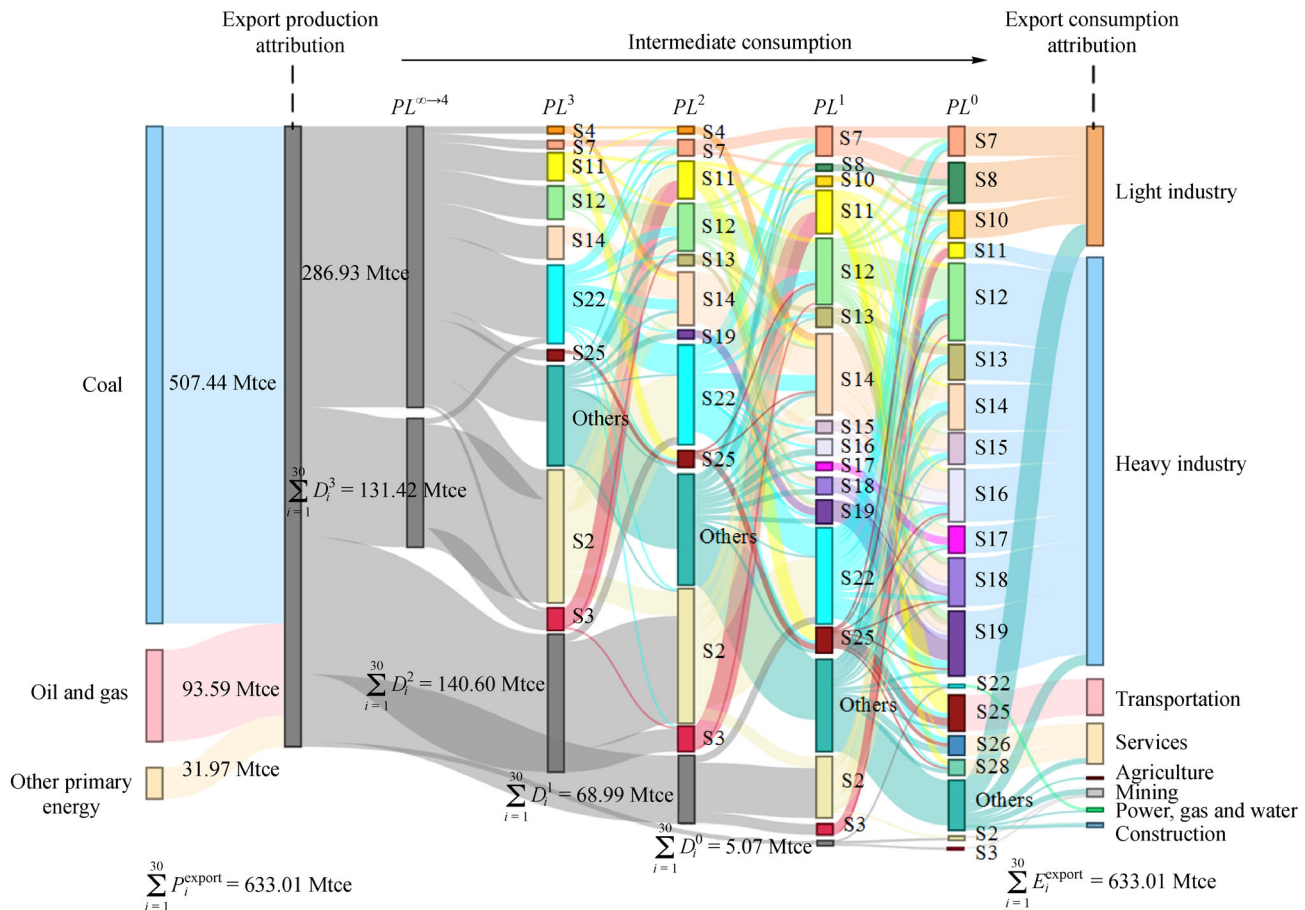
### 3.3 Supply chain paths of embodied primary energy exports

To explore concrete supply chain paths, the energy resources should be tracked from exploitation to final export, which can reveal the entire paths of embodied primary energy use. Generally, the SPA method could generate innumerable paths with the extension of production tier, which means big challenges faced by researchers in calculating and revealing concrete supply chain paths, owing to the limited computing power. In fact, previous studies often focused on the important sectors and critical supply chain paths. Figure 4 displays the embodied primary energy flows driven by export from the sectoral perspective.

To comprehend the key sectors of the *EEEs*, S2 (Coal mining) and S3 (Petroleum and gas) were identified as the

extraction sectors of primary energy resources. S22 (Electricity and hot water production and supply) was the primary coal consumer in the high layer, indicating that power generation was mainly dependent on coal resources and finally used for other sectors to produce goods for the export. S3 was a major supplier of raw materials for S11 (petroleum refining, coking, etc.), and the energy products in S11 were provided for S25 (transport and storage), S17 (Transport equipment) and S12 (chemical industry). Therefore, S11 and S22 were important intermediate sectors in the supply chain for exports. As for final export, S12 (chemical industry), S19 (electronic equipment), S16 (general and specialist machinery), S18 (electrical equipment) and S14 (metallurgy) were the top five export-related sectors, whose *EEE* were more than 45 Mtce, together accounting for 46.5% of the total *EEE*. These sectors all belong to the heavy industry (also see Table S7).

To exemplify how the export demand drives energy uses in various sectors of each province, we extract critical supply chains from the perspectives of inter-provincial and intra-provincial paths. Table S8 lists the top 30 inter-provincial paths induced by exports. Sixteen of the top 30 ranking paths were transferred from coal mining of Shanxi,



**Fig. 4** Sectoral embodied primary energy flows through the first four layers of the supply chains caused by exports. Note: The left-hand side of the map shows the primary energy input. The intermediate consumption attributions of each aggregated sector at  $PL^1$ ,  $PL^2$ , and  $PL^3$  are indicated by the dark gray ‘flow’ linking back to the final production attribution. An element  $D_s^l$  presents direct primary energy inputs from sector  $s$  at  $PL^l$ . An element  $E_s^l$  at  $PL^l$  represents embodied primary energy uses in the output of sector  $s$  at  $PL^l$ . The flows from  $PL^l$  to  $PL^{l-1}$  ( $E_{ij}^{l \rightarrow l-1}$ ) measure embodied primary energy uses in the output of sector  $i$  at  $PL^l$  purchased by sector  $j$  at  $PL^{l-1}$ . The colorful flows on the right-hand side indicate the embodied primary energy uses of industrial sectors attributed to final export. Detailed sectoral information are provided in Table S2, according to the classification of 30 industrial sectors.

and six of the 30 paths were from coal mining of Inner Mongolia, showing that Shanxi and Inner Mongolia were the most important coal suppliers in terms of embodied primary energy. Six paths were tracked back to the sector of Petroleum and gas in Heilongjiang, Shaanxi and Xinjiang, the main oil and gas providers. In detail, the supply chains from energy-abundant provinces’ S2/S3 to eastern coastal provinces’ S11 (petroleum refining, coking, etc.)/S12 (chemical industry)/S14 (metallurgy) were the main paths driven by export. “Shanxi, S2 → Shanghai, S14” had the largest *EEE* of 0.96 Mtce, followed by “Shanxi, S2 → Jiangsu, S12,” “Inner Mongolia, S2 → Shanghai, S14,” “Heilongjiang, S3 → Shanghai, S11,” and “Inner Mongolia, S2 → Jiangsu, S12.” S22 (electricity and hot water production and supply) was an important intermediate sector in the paths such as “Shanxi, S2 → Jiangsu, S22 → Jiangsu, S19 (electronic equipment).” Similarly, S11 was an intermediate sector between S3 and S25 (transport and storage). For instance, “Heilong-

jiang/Shaanxi, S3 → Shanghai, S11 → Shanghai, S25/S28 (leasing and commercial services)” were important paths for the exports of oil and gas products. Provinces located in the central and western regions that concentrated on producing energy-intensive products were the main sources of export-induced energy requirements covering the supply of intermediate commodities for exports from coastal provinces.

Table S9 lists the top 30 intra-provincial paths induced by export demands. In Shanxi, Tianjin, Hebei, and Hainan, local exports had large shares to their *EEEs*. A large part of industrial products for the exports in Xinjiang were produced by processing and utilizing local energy resources. For instance, “Xinjiang, S2 → S13 (Nonmetal products)” accounted for 9.6% of the total *EEE* in Xinjiang. Inner Mongolia and Anhui also had a portion of their *EEEs* through inner-regional supply chains. It is worth noting that S11 was an important intermediate sector in intra-provincial supply chains.

## 4 Discussion

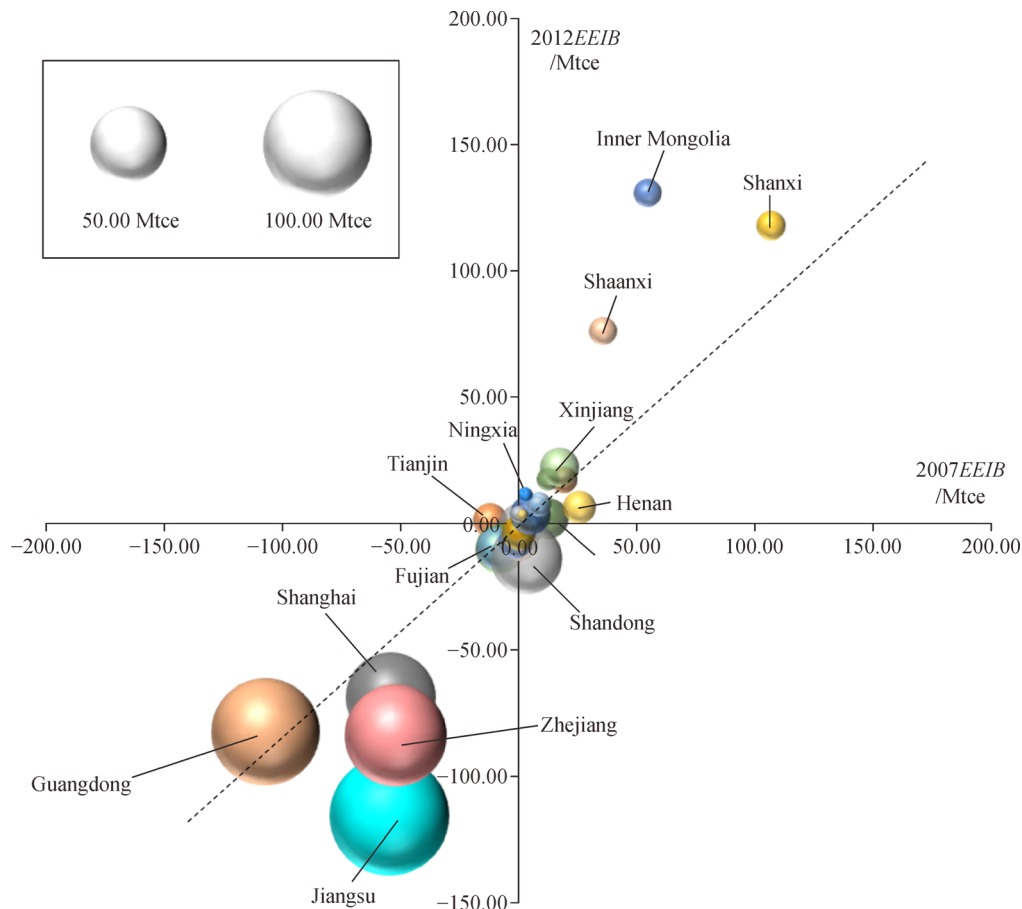
China is the largest primary energy producer in the world, but the relationships between supply and demand in terms of coal, oil and natural gas are all not balanced, with ever-increasing imports of energy resources in recent years. However, China is also a major exporter of embodied primary energy for other foreign countries. It is worth noting that employing different scales of input-output table generates different results of the *EEEs*. Previous studies at the national scale removed the items of imports to isolate the domestic supply chain in China by assuming that each economic sector and domestic demand category utilize sectoral imports in the same proportions (Weber et al., 2008; Tang et al., 2016), which may cause large uncertainties. For instance, Zhang et al. (2017) identified China's primary energy requirements in 2012 using the input-output table at the national scale and reported that the *EEUs* induced by exports was 783.0 Mtce, larger than 633.01 Mtce in this study, resulting from the processing and separation of the import data in the national input-output table. By employing the MRIO table of China in this study, import items were isolated and the sectoral allocation of imported energy inputs in domestic production were avoided. The resulted calculation of the *EEE* was 633.01 Mtce in 2012, compared to 565.15 Mtce in 2007, indicating the increasingly important role of exports in domestic energy supply.

It is worth noting that international import is also essential for clarifying the embodied energy input through the trade linkages between China and other countries. However, the items of international import have been excluded in this study, owing to the nature of the MRIO table. In future studies, the process of international import item can be added during data processing, which can further clarify the complex supply chain between China and other countries. Future studies can build upon existing studies that addressed China's *EEE* to foreign countries by combing the global MRIO models and other accounting methods. In Chen and Chen (2011)'s study on the energy consumption in the globalized world economy, China was regarded as the biggest exporter of embodied primary energy in international trade. Wu and Chen (2017) reported one fifth of the country's total energy use were caused by its exports. Such studies highlight the importance of China's energy exports in the global context. Therefore, both direct energy imports and embodied energy exports should be equally and adequately addressed.

To figure out the evolution of interprovincial embodied primary energy trade, a comparison of the regional net embodied primary energy transfers in interprovincial trade balance (*EEIBs*) between 2007 and 2012 is presented in Fig. 5. The total exports-driven interprovincial transfers of embodied primary energy increased from 406.97 Mtce in 2007 to 509.43 Mtce in 2012. Shanghai, Jiangsu, Zhejiang

and Guangdong were major interprovincial net importers, while Shanxi, Inner Mongolia, Shaanxi and Xinjiang were major net exporters. Jiangsu replaced Guangdong as the largest interprovincial exporter in 2012. For the provinces that lay in the first quadrant and are close to the vertical axis, like Inner Mongolia, Shanxi, Shaanxi and Xinjiang, they assumed production-oriented trading patterns. In interprovincial trade, their trade deficits increased from 2007 to 2012. On the other hand, Shanghai, Jiangsu, Zhejiang and Guangdong were found to have consumption-oriented trading patterns. Their trades mainly focused on finished products that were directly used for exports. Increasing participation of eastern coastal provinces in the global economy, with a large share of manufacturing for exports in their total products, has rapidly increased the embodied primary energy transfers in their trade partners' interprovincial outflows (Zhang et al., 2016).

Eastern coastal regions have gained a large volume of international export and rapid economic growth owing to the preferential government support and historical development advantage as well as geographical advantage (Zhang et al., 2018b). Figure 6 displays the typical patterns of embodied primary energy export in nine eastern coastal provincial regions considering interprovincial trade linkages. Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan are all important hubs for maritime and land transportation. They provide desirable conditions for foreign trade and their *EEEs* contribute 73.6% to the national total. Table S10 lists the top three supply chain paths in nine eastern developed regions in 2007 and 2012. S2 (coal mining) of Shanxi and Inner Mongolia were the main coal supplier, and S3 (petroleum and gas) of Shaanxi was an important oil and gas provider for the eastern regions. Xinjiang and Heilongjiang also became important interprovincial exporters of embodied primary energy in 2012. The total *EEEs* of the nine export regions increased from 402.35 Mtce in 2007 to 466.14 Mtce in 2012, and Shanghai, Jiangsu, Zhejiang and Guangdong were the leading regions. Manufacturing exports provide important economic benefits for coastal regions, however, the export-oriented sectors remain energy- and emission-intensive from the consumer perspective (Zhao et al., 2016). The sub-sectors of heavy industry such as S12 (chemical industry), S14 (metallurgy), S19 (electronic equipment), and the labor-intensive industry such as S7 (textile) and S8 (clothing, leather, fur, etc.) were important exporting sectors of embodied primary energy in both 2007 and 2012, along with severe environmental and health consequences (Jiang et al., 2015). Notably, coastal provinces in the Yangtze River Delta and the Pearl River Delta were specialized in producing high value-added goods and were the main destinations of export-related GDP. Zhang et al. (2018b) reported that Shanghai transferred about 74% of export-related air pollutant emissions while only outsourced 26% of export-related GDP to other regions. By contrast, central



**Fig. 5** Net embodied primary energy transfers in interprovincial trade balance of provincial regions in 2007 and 2012. Note: The size of the sphere represents the volume of provincial *EEI* in 2012. Tibet is excluded in this figure.

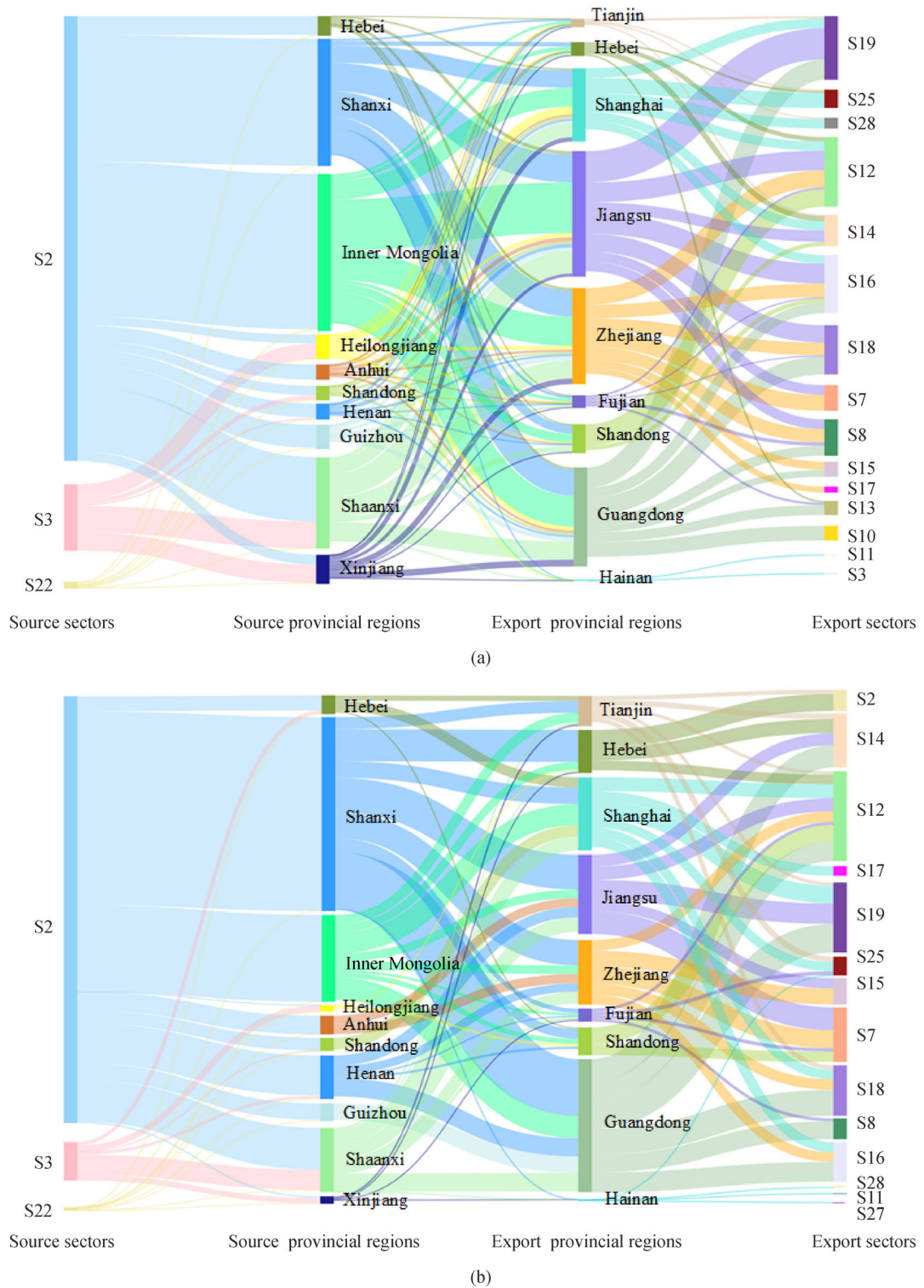
and western regions served as the energy base in China, such as Inner Mongolia (the largest energy supplier in 2012) and Shanxi (the largest energy supplier in 2007). They provided low value-added and high pollution inputs (Zhang et al., 2018b). In addition, their less strict environmental regulations have also attracted energy- and emission-intensive but low value-added enterprises from eastern regions.

Considering exports-driven primary energy requirements is important for policy makers and other stakeholders to recognize visible and hidden energy use along the entire supply chains and address cross-boundary potentials for energy saving and emission reduction. To attain the overall energy-conversion goals, the inter-regional transfer of energy-intensive industries with backward or outdated production capacities should be avoided. Upgrading technologies throughout the interprovincial supply chain, and especially among upstream segments, would significantly improve the adverse environmental effect of China's exports. Since export-related production gains achieved in developed eastern regions are largely based on energy supply in less-developed central and western regions, eastern developed regions are suggested

to engage active efforts in helping the central and western regions to upgrade their local production technologies (Zhang et al., 2013; Jiang et al., 2015). The embodiment analysis on interprovincial embodied primary energy trade pulled by exports contributes to a better understanding of the role of each province and sector in domestic energy supply chains, which should be given special attention in energy policy design.

## 5 Concluding remarks

Through international economic linkages, China not only imports a large amount of energy, but also exports a large quantity of embodied primary energy via exports of commodities and services. In 2012, the domestic *EEI* was 633.01 Mtce, accounting for 17.6% of China's total primary energy supply. From 2007 to 2012, the total exports-driven interprovincial transfers of embodied primary energy showed a rapid growth from 406.97 Mtce to 509.43 Mtce, owing to China's increasing participation in the global economy especially the eastern coastal provinces. As interprovincial net importers, the



**Fig. 6** Typical patterns of embodied primary energy export in nine eastern coastal provincial regions in (a) 2007 and (b) 2012. Note: The 42 industrial sectors in the 2012 MRIO table are merged into 30 sectors (see Table S2), in order to keep consistency with the 2007 MRIO table (Tibet is not included in this table). Energy resources are extracted in the source sectors of the source provinces. The embodied primary energy uses are finally exported by the export provinces through their export sectors.

eastern regions had boosted energy production in the western and central regions that served as interprovincial net exporters, owing to their industrial positions in domestic supply chains. Critical sectors and supply chain paths for China's *EEEs* are identified from a regional perspective. A large number of embodied primary energy exports in the coastal regions can be traced to the inland regions via interprovincial supply chains, such as the paths of "Shanxi/Inner Mongolia, coal mining → Shanghai/Jiangsu, chemical industry/metallurgy." In addition, energy can be exported locally through the intra-provincial supply chains such as "Shanxi, coal mining" and "Xinjiang, coal mining → Xinjiang, nonmetal products."

Recently, China has made considerable efforts to ensure energy security, protect the environment, and reduce emissions of pollutants and greenhouse gases. Accelerating transition to low-carbon energy and reducing exports of energy-intensive products could benefit China in pursuing resource conservation and environment protection. The exports of industrial raw materials, primary machinery and equipment products, and transport and storage services are revealed to contribute to the expanding of primary energy requirements and related trade transfers. Consumption-based accounting of regional energy use highlights the important role of all stakeholders along the entire supply chains, which is essential to assess the optimum energy-conversation targets at both the regional and national levels. Understanding the exports-driven interprovincial transfers of embodied primary energy and the concrete supply chains can help establishing an effective framework for regional collaboration that improves technological provision, financial support, energy security, and trade quality of China.

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