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Critical transmission paths and nodes of carbon emissions in electricity supply chain

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Abstract

As the largest contributor to production-based emissions, electricity generation sector has led to huge carbon emission transmissions. This is the first attempt to explore the latest features of carbon emission transmissions from electricity sector to the final domestic consumption of China in 2002-2015, combining MRIO-based Structural Path Analysis and transmission-based emission method. Results show that: (1) Although inter-provincial transmissions are increasing significantly, emission transmissions within intra-provincial trading are dominated. (2) 30 provinces are classified into two types, i.e., consumption centers and production centers. Both the inter-provincial transmission paths in consumption centers and production centers show the grid-level agglomeration and provincial heterogeneity. The inflow paths in consumption centers are mainly sourced from the production of Eastern China and South China, while the outflow paths for production centers are caused by the consumption in Central China, Guangdong and Jiangsu. Inter-provincial linkages are intensified and perform the feature of territorial propinquity. (3) Both intra-grid and inter-grid transmission nodes show an agglomeration trend of "electricity sector<intermediate sectors<electricity sector<consumption". These intermediate sectors include manufacture sectors, energy-intensive sectors and service sector. This paper provides policy implications on promoting low-carbon electricity cooperation across provinces and managing intermediate transmissions along supply chain.

Keywords: Emission transmission; Electricity sector; Multi-regional Input-output table; Structural Path Analysis; Transmission-based emission

1. Introduction

Electricity sector is the largest contributor to production-based carbon emissions in China as well as in the world. Electricity generation sector accounts for 42% of global CO_2 emissions in 2016, i.e. 13.4 gigatons of CO_2 (Gt-CO_2) out of the global total of 32.3 Gt-CO_2 (IEA, 2018). Electricity sector in China accounts for 48.20% of the national CO_2 emissions and 13.60% of the global CO_2 emissions in 2016 (IEA, 2018). Given the importance of carbon emissions from electricity sector, understanding the transmission paths and nodes of carbon emissions from electricity sector to final domestic consumption in China is not only important for controlling the climate warming in China, but for that in the global community.

Electricity sector in 30 provinces of China shows a significant imbalance of demand and supply. Primary electricity supply (i.e., thermal electricity and hydroelectricity) is in the less developed regions with abundant resources, while electricity demand is concentrated in the rapidly growing regions in the southeast coast region (SCIO and NDRC, 2007). Regional mismatch between electricity supply and demand in China forms such a pattern of electricity trade, namely from Northern China to Southern China, and from Western China to Eastern China (Hou and Hou, 2018). Along with the large scale of electricity trade, a mass of embodied emission transmissions of electricity sector occurs from the developed regions to the less developed regions (Zhao et al, 2019).

Under the “*New Normal*” growth model, the critical paths and nodes that contribute strongly to carbon emissions embodied in transmission might be undergoing dramatic changes (Meng et al., 2017). This is related to the regulations on electricity sector, such as expansion of transmission capacity, increasing demand for renewable energy, improvement of consumption mode, etc. (Zhao et al., 2019). Understanding the latest feature of emission transmission changes in electricity supply chain, holds important policy implications for allocating emission-mitigating responsibilities among all participants (rather than sources and destinations) in the supply chain network.

Considering the large scale of carbon emissions embodied in electricity transmission in China, carbon emissions in China's electricity sector have frequently appeared in the literature but gaps remain. Previous studies have placed emphasis on China's carbon emissions from the production side (i.e., direct carbon emissions from production sources) (Lindner et al., 2013; Shao et al., 2018; etc.), or the consumption side (i.e., indirect carbon emissions released to satisfy the final demand of destinations along supply chains) (Mi et al., 2016; 2019; etc.). Very few studies focus on carbon emissions embodied in electricity sector from the transmission side, such as transmission paths from electricity sector to downstream consumers, critical transmission nodes in these paths (i.e., sectors and provinces). If emission-mitigating measures on transmission paths and nodes of top priority within supply-chain networks are adopted, it is expected to efficiently reduce carbon emissions associated with entire supply chains (Hanaka et al., 2017). To fill this gap, this study holistically investigates the transmission paths and nodes of carbon emissions from China's electricity sector to satisfy the final demand of downstream consumers.

Without loss of generality, this study takes final domestic consumption as the research demand. Main reasons are as follows:

(1) With the rapid electrification in China, final domestic consumption increasingly becomes one of the main sources for embodied carbon emissions in China (Cui et al., 2019) and accounts for 38% of China's total carbon emissions in electricity sector. Although investment is the largest demand category to production-based emissions in electricity sector, carbon emissions of electricity sector driven by investment have been discussed by many scholars, such as Mo et al. (2016); Liang et al. (2018); Xu and Liang (2019); etc. While the role of final domestic consumption in carbon emissions of electricity is underestimated, and their transmission paths and nodes are rarely investigated.

(2) Emission-mitigating responsibilities should be assigned to all critical stakeholders and final consumption-driven emissions provide the calculation possibilities to capture these critical stakeholders. Final domestic consumption in provinces performs centralized distribution, such as rural consumption-related emissions in Zhejiang and urban consumption-related emissions in Guangdong are much larger than that in other provinces (Lin and Liu, 2016). While investment-driven emissions are decentralized in most stakeholders which makes it difficult to capture the critical stakeholders.

This study aims to explore the changes of transmission paths and nodes of embodied carbon emissions from electricity sectors to final consumers based on China's MRIO in 2002-2015, thus helping to understand the consumption behaviors and electricity trade pattern, define emission-mitigating responsibilities in critical stakeholders, etc. This study makes the following contributions: (1) This study compiled China's MRIO table in 2015 (see Text S1, Supplementary Materials) to extend the research period and reveal the latest features of carbon emission changes in electricity sector to satisfy final consumption via electricity supply chains. (2) To our knowledge, this is the first attempt to identify both critical transmission paths and nodes of carbon emissions embodied in electricity sector of China from the transmission perspective. By comparing production-, consumption- and transmission-based emissions, this study helps to define the emission-mitigating responsibilities in all stakeholders. (3) Final consumption-driven emissions are increasingly important and are rarely explored. This study enriches the existing studies by tracing the final consumption-driven emission transmissions from electricity sectors to final consumers in 30 provinces of China.

The remainder of this study is organized into six sections. Section 2 reviews the relevant literature review. Section 3 describes the basic methodology and data source. Section 4 presents the main results. Section 5 provides the discussion, while the main conclusions and policy recommendations are drawn in Section 6.

2. Literature review

Previous studies generally used production-based emission (PBE) accounting and consumption-based emission (CBE) accounting to trace carbon emissions. PBE accounting represents carbon emissions from domestic production activities including exports in the producing process as the responsibility of producers (Mi et al., 2019). CBE accounting refers to the total carbon emissions of final products including imports, where environmental responsibility is undertaken by consumers (Meng et al., 2018). Both PBE and CBE accounting highlight the economic and environmental linkages at both ends of supply chains (i.e., the sources and destinations), but neglect the transmission links which are responsible for emission transfer in supply chain (Liang et al., 2016). All participants (rather than sources and destinations) in the production network should be responsible for environmental cost for the consumption of products.

Transmission-based emission (TBE) accounting, is adopted by some scholars to trace the transmission emissions from sources to final destinations in supply chains. This could be conducted in global supply chains (Hanaka et al., 2017; Kagawa et al., 2015), and domestic supply chains (Liang et al., 2016; Shi et al., 2019). However, limited studies adopt the SPA approach to trace environmental impact at the sectoral level, such as the construction industry (Hong et la., 2016), the iron and steel industry (Peng et al., 2018), manufacturing industry (Tian et al., 2018). Electricity sector, as the largest PBE source, is seldom addressed from the perspective of emission transmission. Furthermore, TBE accounting involves in the transmission paths and nodes. Due to the flexibility for result explanations, few studies discuss the transmission paths and nodes in the same framework.

Multi-regional input-output (MRIO) model is widely used to trace sectoral/regional relations along supply chains and link the embodied emissions of original producers and final consumption in an economic system (Xu and Liang, 2019; Liang et al., 2016). MRIO model has a high requirement of data which impedes the extensive application. Some researchers attempt to compile China's MRIO tables, such as Zhang and Qi (2012) compiles China's MRIO tables in 2002 and 2007 for eight regions, Liu et al. (2012; 2014; 2018) constructs China's MRIO table in 2007, 2010 and 2012 for 30 provinces, Mi et al. (2017) provides the framework of MRIO compilation in 2012 and Zheng et al. (2020) compiled China’s MRIO table in 2015, Development Research Center of the State Council of China compiled China’s MRIO table in 2012 (Li et al., 2016), etc.

MRIO table in 2015 is the latest available version for China so far. These institutions adopted different compilation framework and basic data to compile MRIO tables. Using these inconsistent MRIO tables to discuss the variation features in long time periods could generate biased results. To provide relatively consistent MRIO tables, this study attempts to compile China’s MRIO table in 2015 using the proposed compiling framework by Mi et al. (2017) and the basic data from Development Research Center of the State Council of China (Li et al., 2002; Pan et al., 2018; Zheng et la., 2020).

Structural Path Analysis (SPA), first proposed by Lantner (1974), is a prominent tool for economic network analysis in supply chains. The advantage of SPA is to decompose the IO results into specific production layers and paths by extracting the linkages among various regions/sectors in economic system (Liang et al., 2016). SPA in early economic studies highlights the transmission paths from the initial production to final demand (Defourny and Thorbecke, 1984). When the SPA is later extended to environmental issues, the applications focus on the upstream and downstream linkages along transmission process under different production layers (Li et al., 2018). SPA has been widely adopted to explore the environmental impact driven by final demand, such as energy consumption (Zhang et al., 2017), natural resource flows (Wang et al., 2018), water use (Feng et al., 2019), $PM_{2.5}$ (Nagashima, 2018), etc.

A few attempts have been made to combine the merits of MRIO and SPA and to extract the critical transmission links from initial producers to the final consumers. MRIO-SPA could merely qualify the transmission paths and ends (i.e., sources and destinations) in supply chains, while it fails to qualify the transmission nodes in intermediate process (Liang et al., 2016; 2018). To fill this gap, this study extends the application of MRIO-SPA by using the transmission-based betweenness (TBB) model proposed by Liang et al. (2016) and Hanaka et al. (2017), and explores the temporal changes of critical transmissions from the production sources to final destinations in the same framework.

3. Material and methods

3.1 Structural path analysis

The latest available Multiregional Input-output (MRIO) table is used to trace the environmental relations between initial producers to the final demand of goods and services via intricate supply chains (Hong et al, 2016; Cao et al, 2019). MRIO model have row balances described as (consisting of R regions and N economic sectors) (Miller and Blair, 2009),

$$X_i^r = \sum_{s=1}^{R}\sum_{j=1}^{N} a_{ij}^{rs} X_j^s + \sum_{s=1}^{R} y_i^{rs} \tag{1}$$

where X_i^r is denoted as the total output of sector *i* in region *r*. a_{ij}^{rs} is direct requirement coefficient of sector *i* in region *r* for sector *j* in region *s*; y_i^{rs} is the final demand of region *s* by sector *i* in region *r*, including domestic consumption, investment and exports. This study merely considers the final domestic consumption. Total output can be expressed in matrix form,

$$\boldsymbol{X} = (\boldsymbol{I}\text{-}\boldsymbol{A})^{-1}\boldsymbol{Y} \tag{2}$$

where $\mathbf{X}=\begin{bmatrix}\begin{pmatrix}x_1^1\\ \cdots\\ x_n^1\end{pmatrix}\\ \cdots\\ \begin{pmatrix}x_1^r\\ \cdots\\ x_n^r\end{pmatrix}\end{bmatrix}$, $\mathbf{A}=\begin{bmatrix}\begin{pmatrix}a_{11}^{11} & \cdots & a_{1n}^{11}\\ \cdots & \cdots & \cdots\\ a_{n1}^{11} & \cdots & a_{nn}^{11}\end{pmatrix} & \cdots & \begin{pmatrix}a_{11}^{1r} & \cdots & a_{1n}^{1r}\\ \cdots & \cdots & \cdots\\ a_{n1}^{11} & \cdots & a_{nn}^{1m}\end{pmatrix}\\ \cdots & \cdots & \cdots\\ \begin{pmatrix}a_{11}^{r1} & \cdots & a_{1n}^{r1}\\ \cdots & \cdots & \cdots\\ a_{n1}^{r1} & \cdots & a_{nn}^{r1}\end{pmatrix} & \cdots & \begin{pmatrix}a_{11}^{rr} & \cdots & a_{1n}^{rr}\\ \cdots & \cdots & \cdots\\ a_{n1}^{rr} & \cdots & a_{nn}^{rr}\end{pmatrix}\end{bmatrix}$, $\mathbf{Y}=\begin{bmatrix}\begin{pmatrix}\sum_s y_1^{1s}\\ \cdots\\ \sum_s y_n^{1s}\end{pmatrix}\\ \cdots\\ \begin{pmatrix}\sum_s y_1^{rs}\\ \cdots\\ \sum_s y_n^{rs}\end{pmatrix}\end{bmatrix}$

$\mathbf{F}=\left[f_i^r\right]_{1\times RN}$, is defined as the emission intensity generated by unitary output of sector *i* in region *r*. Total carbon emissions of an economy can be expressed as,

$$\boldsymbol{E} = \boldsymbol{F} \times (\boldsymbol{I}\text{-}\boldsymbol{A})^{-1}\boldsymbol{Y} \tag{3}$$

Leontief Inverse matrix in Eq. (3) is expanded using a power series approximation as L=I+A+A^2+A^3+… (Peng et al, 2018). Thus, total carbon emissions can be decomposed into infinite production layers and paths as,

$$\boldsymbol{E} = \boldsymbol{F} \times (\boldsymbol{I}\text{-}\boldsymbol{A})^{-1}\boldsymbol{Y} = \overbrace{FIV}^{\text{Layer 0}} + \overbrace{FAV}^{\text{Layer 1}} + \overbrace{FA^2V}^{\text{Layer 2}} + \overbrace{FA^3V}^{\text{Layer 3}} + \overbrace{FA^4V}^{\text{Layer 4}} + \ldots \tag{4}$$

Carbon emissions for sector *i* in each production layer is expressed in Eq. (5), which represents the carbon emission transmissions embodied in economic sectors for a certain layer.

$$\begin{gathered}E_i^{Layer\ 0}=f_i\sum_{r=1}^{R} y_i^r\\ E_i^{Layer\ 1}=\sum_{j=1}^{R\times N} f_i a_{ij}\sum_{r=1}^{R} y_j^r\\ E_i^{Layer\ 2}=\sum_{l=1}^{R\times N}\sum_{j=1}^{R\times N} f_i a_{ij} a_{jl}\sum_{r=1}^{R} y_l^r\\ \cdots\end{gathered} \tag{5}$$

Total carbon emissions are the sum of direct impact from initial production activities (i.e., Layer 0) and indirect inputs from downstream processes (i.e., Layers 1 and higher layers). These paths explore sectoral and regional connections in different production layers. Each node represents a specific sector in a specific region within economic system. For example, $E_i^{Layer\ 0}$ represents the direct emission to onsite production; $E_i^{Layer\ 1}$ represents the direct emissions required to provide direct inputs to Layer 0. Subsequently, carbon emissions in higher layers can be calculated accordingly and the number of nodes is exponential with the growth of layers (Peters and Hertwich, 2006).

3.2 Transmission-based betweenness

This study employs the transmission-based betweenness method proposed by Liang et al. (2016) and Hanaka et al. (2017) to quantify the role of transmission nodes and paths of carbon emissions. Transmission-based betweenness of nodes is defined as carbon emissions generated by all supply chain paths passing through these nodes (Newman, 2006), which measures the influence a node has over the spread of information through the network (Newman, 2010). Herein transmission nodes occur in the intermediate process. Transmission nodes with high betweenness demonstrate a large impact on emission transmission driven by final domestic consumption (Hanaka et al, 2017). Transmission-based betweenness of sector i, from upstream l_2 sector to downstream l_1 sector can be expressed in Eq.(6) and is shown in Figure 1.

$$
\begin{aligned}
b_i(l_1,l_2) &= \sum_{1\le k_1,\cdots,k_{l_1}\le n}\ \sum_{1\le j_1,\cdots,j_{l_2}\le n}\left(f_{k_1}a_{k_1k_2}\cdots a_{k_{l_1}i}a_{ij_1}\cdots a_{j_{l_2-1}j_{l_2}}y_{j_{l_2}}\right)\\
&= \sum_{1\le k_1,\cdots,k_{l_1}\le n}\left(f_{k_1}a_{k_1k_2}\cdots a_{k_{l_1}i}\sum_{1\le j_1,\cdots,j_{l_2}\le n}a_{ij_1}\cdots a_{j_{l_2-1}j_{l_2}}y_{j_{l_2}}\right)\\
&=\left(\sum_{1\le k_1,\cdots,k_{l_1}\le n}\left(f_{k_1}a_{k_1k_2}\cdots a_{k_{l_1}i}\right)\right)\left(\sum_{1\le j_1,\cdots,j_{l_2}\le n}\left(a_{ij_1}\cdots a_{j_{l_2-1}j_{l_2}}y_{j_{l_2}}\right)\right)\\
&=\left(fA^{l_1}\right)_i\left(A^{l_2}y\right)_i\\
&=fA^{l_1}\mathrm{J}_iA^{l_2}y
\end{aligned}
\qquad (6)
$$

where J_i is a matrix with its $(i,i)_{th}$ element as 1 and other elements are zeros. A^{l_1} and

A^{l_2} separately represent direct requirement coefficients of upstream sector l_2 and downstream sector l_1 of sector i. Transmission-based betweenness of sector i is rearranged as,

$$\begin{aligned} b_i &= \sum_{l_1=1}^{\infty}\sum_{l_2=1}^{\infty} b_i(l_1,l_2) = \sum_{l_1=1}^{\infty}\sum_{l_2=1}^{\infty} fA^{l_1}\mathrm{J}_i A^{l_2}y \\ &= \sum_{l_1=1}^{\infty}\left(fA^{l_1}\mathrm{J}_i\sum_{l_2=1}^{\infty}A^{l_2}y\right) = \left(\sum_{l_1=1}^{\infty}fA^{l_1}\right)\mathrm{J}_i\left(\sum_{l_2=1}^{\infty}A^{l_2}y\right) \\ &= f\left(\sum_{l_1=1}^{\infty}A^{l_1}\right)\mathrm{J}_i\left(\sum_{l_2=1}^{\infty}A^{l_2}y\right) = f\,\mathrm{T}\mathrm{J}_i\mathrm{T}y \end{aligned} \tag{7}$$

where element t_{ij} in matrix T = LA indicates the output of sector i both directly and indirectly caused by the direct upstream inputs used to produce unitary output of sector j. Given that T = L-I, T is the indirect requirements for unitary output of each sector.

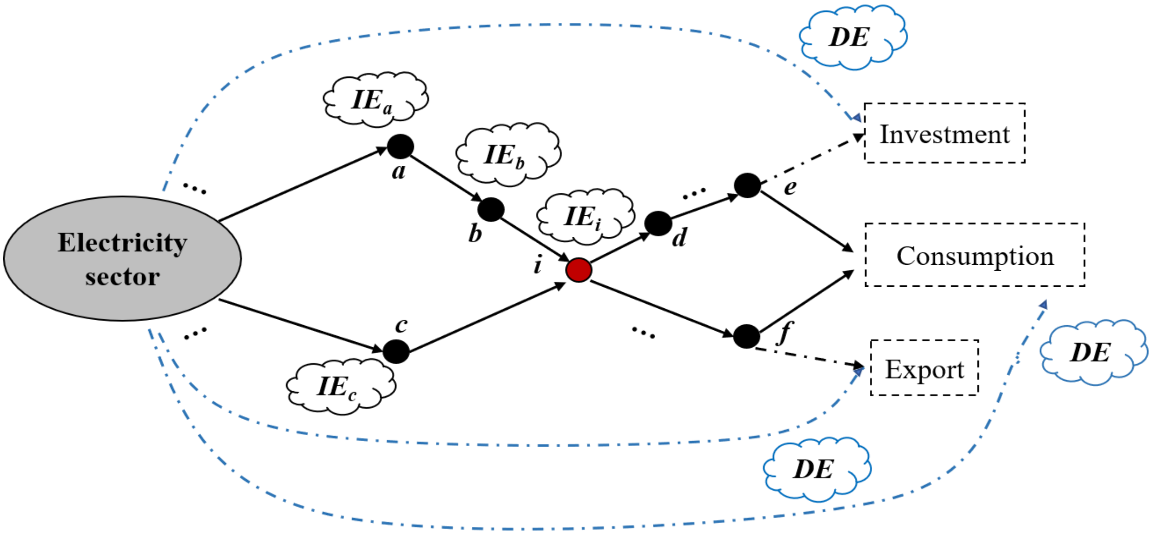

Figure 1. An example of carbon emission transmissions from electricity sector

Note: Embodied carbon emissions include direct emissions (DE) and indirect emissions (IE). Black line and blue dotted line respectively represent the transmission paths of IE and DE. The dots represent sectors, including intermediate transmission sectors and final consumers. The arrows represent the transmission direction, namely from electricity sector to final demand. Final demand is categorized into three types, i.e., consumption, investment and export. Herein, this study merely considers the IE transmissions driven by final consumption and takes transmission sector i as an example.

3.3 Data sources

This study uses two types of data: China's provincial carbon emissions inventories and multi-regional input-output (MRIO) tables. Carbon emissions from energy combustion are obtained from CEADs database[1] (Mi et al, 2017). MRIO tables in 2002, 2007 and 2012 are derived from the Development Research Center of the State Council of China (Zheng et al., 2020; Li et al, 2010; Pan et al, 2018). These MRIO tables cover 24 sectors in 30 provinces of mainland China. To extend the research period, this paper compiles China's MRIO table in 2015 using the compilation framework by Mi et al. (2017) and adjust the MRIO tables in 2002-2015 to be consistent.

MRIO tables at current price are converted into 2007 constant price using the widely adopted double-deflation method (United Nations, 1999). The deflators are obtained from China Price Yearbook and China Statistical Yearbook. The missing deflators at provincial level are assumed to be the same as national ones in the same year. Original MRIO is aggregated into 24 sectors to make the calculation results feasible (see Table S1, Supplementary Materials). To be consistent with China's six regional power grids, 30 provinces are aggregated into six regions (see Table S2, Supplementary Materials). It should be noted that both the eastern and western Inner Mongolia are incorporated in

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[1] http://www.ceads.net/

North China grid due to data limitation. Main abbreviations are described in Table S3 (Supplementary Materials).

4. Results

4.1 Overview

Electricity sector accounts for 43.30% of national carbon emissions in 2015, and is the largest contributor to production-based emissions in China (see Figure 2). Electricity sector is also the basic energy supplier for all economics sectors. Most of production-based emissions in electricity sector are generated to satisfy the final investment demand (i.e., 49.50%) and final consumption demand (38.58%). For the final consumption, S21 (Construction, 36.86%) accounts for the largest proportion, followed by S24 (Service, 13.54%) and S13 (Ordinary and special equipment, 7.44%).

The number of supply chains in each production layer grows at an increasing rate, which causes a substantial decline in the share of carbon emissions by a single path (see Table S4, Supplementary Materials). This study defines the critical supply chain as ones whose carbon emissions account for at least 1% of total carbon emissions in China's electricity sector. High-layer paths have a smaller impact than the low-layer paths. Therefore, this study merely discusses the top five layers (i.e., from Layer 0 to Layer 4) which cover 59.25% of total carbon emissions generated by electricity sector.

This study mainly discusses carbon emissions driven by final domestic consumption. Although total carbon emissions from investment and export take large parts of total emissions in electricity sector (i.e., 49.50% and 20.75%), most of chains from investment and export show emissions less than 1% of total carbon emissions (see Table

S5-S6, Supplementary Materials). These small emissions from investment and export make it difficult to capture the critical transmissions in inter-provincial electricity trading. Moreover, electricity is a basic energy source for all economic sectors. With the rapid electrification in China, the electricity demand in China is growing fast (Lin and Lin, 2016). In this process, carbon emissions generated by electricity transmission to satisfy the final domestic consumption for downstream sectors, are more complicated and deserve further attention.

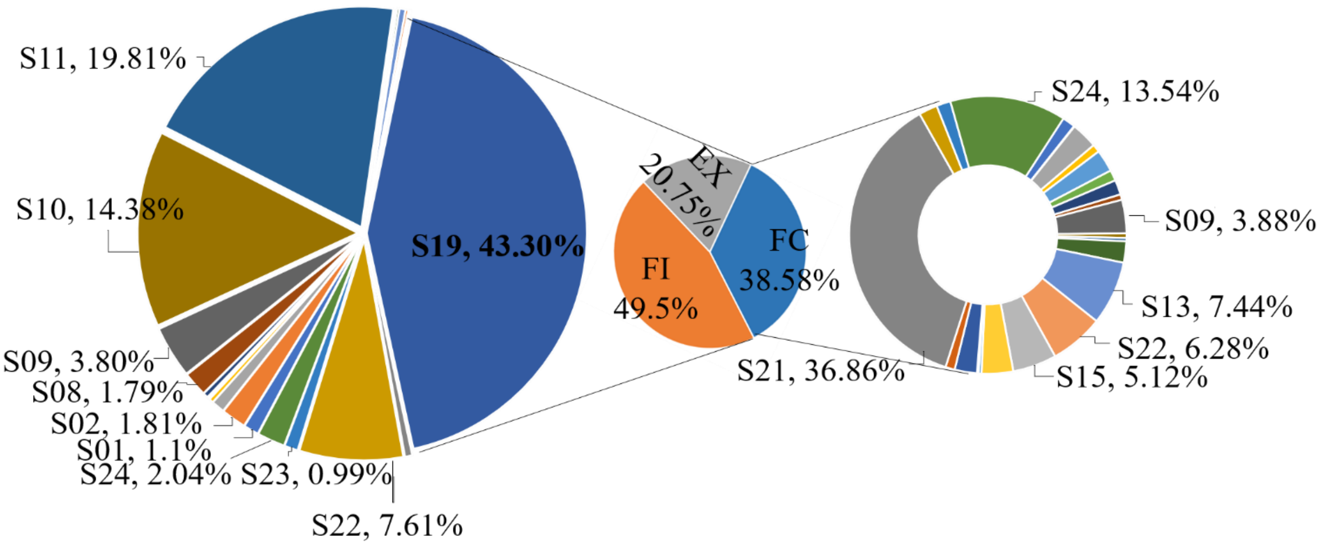

Figure 2. Sectoral carbon emissions and final demand category in 2015

Note: FC, FI and EX respectively represent final consumption, final investment and export. Sector classification is shown in Table S1.

4.2 Carbon emission imbalance of electricity sector

(1) Recognitions of carbon emission centers

China has a huge imbalance for electricity production and consumption, which stimulates Chinese Government to promote inter-provincial connection of electricity system. In 2015, provinces with large production-based emissions of electricity sector

(E-PBE) are mainly aggregated in North China, Eastern China and Guangdong (see Figure 3). E-PBE of 30 provinces shows different variation trend from 2002 to 2015. E-PBE in most provinces of Central China, Northwest and Southwest keep decreasing in 2002-2015, while that in most provinces of Eastern China and Northeast maintain increasing. As for consumption centers, production-based emissions of electricity sector (E-CBE) are generated to satisfy the final consumption in Central China, Eastern China and Guangdong (see Figure 4 and Figure S1).

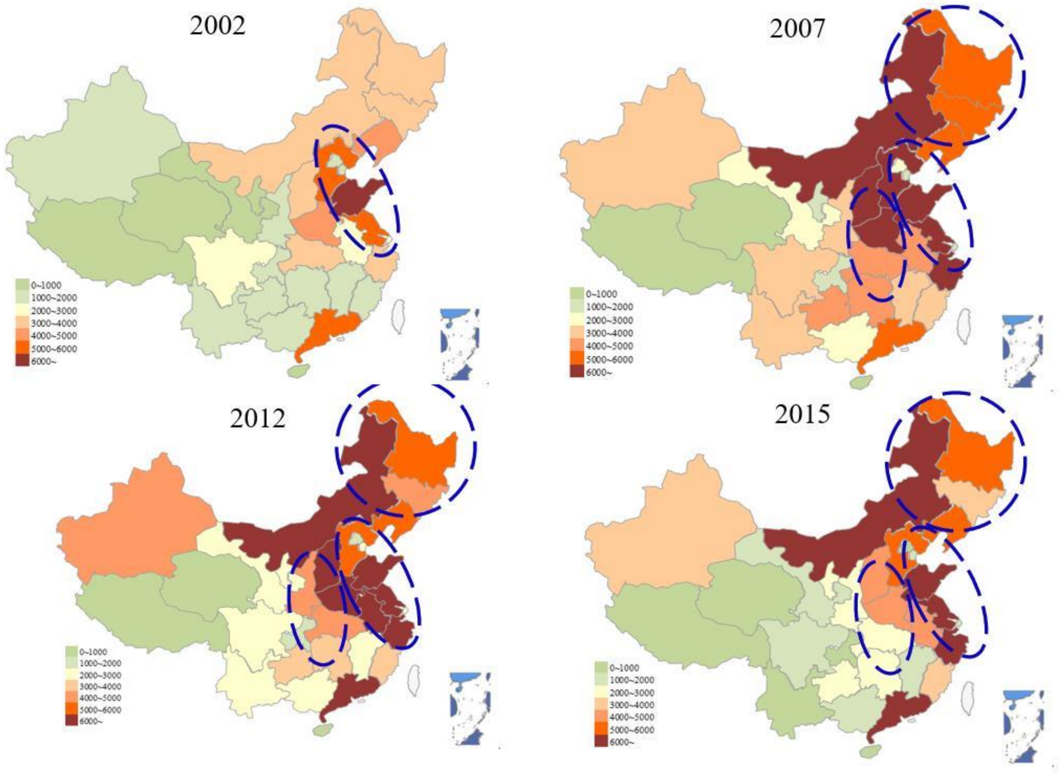

Figure 3. Changes of production centers of electricity sectors in 2002-2015

Note: The unit is million tons (Mt). The regions marked by blue circle are production centers with higher E-PBE than E-CBE.

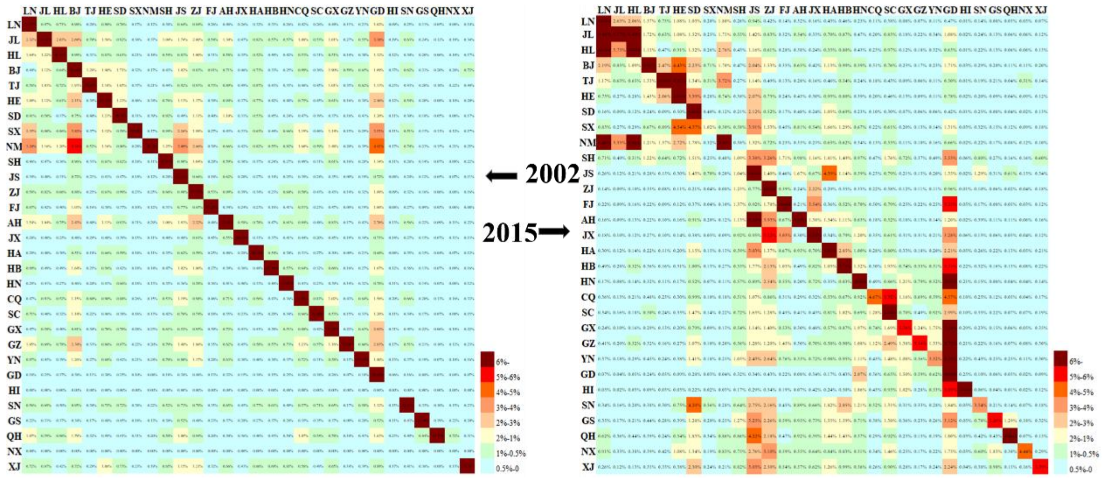

Figure 4. Changes of consumption centers of electricity sectors in 2002 and 2015

Note: Row and column respectively denote the CBE and PBE at each province. Dark color represents the province with high carbon emissions.

Therefore, 30 provinces are then classified into two types according to the imbalance of E-CBE and E-PBE (see Figure 5), including nine consumption centers and 21 production centers. Eastern China and Guangdong are both the critical producers for E-PBE and critical consumers for E-CBE, and the imbalance role is strengthened after 2012. Central China shifts from being the production center to consumption center since 2012 due to economic stimulus and rising electricity demand. E-PBE of North China is decreased since 2012 under the stringent environmental standards in New Normal. Other regions like Northwest and Northeast, have increasing E-CBE to respectively satisfy the rising electricity demand under economic stimulus by *The Belt and Road Initiative* and *Strategy of Revitalizing the Old Industrial Base*.

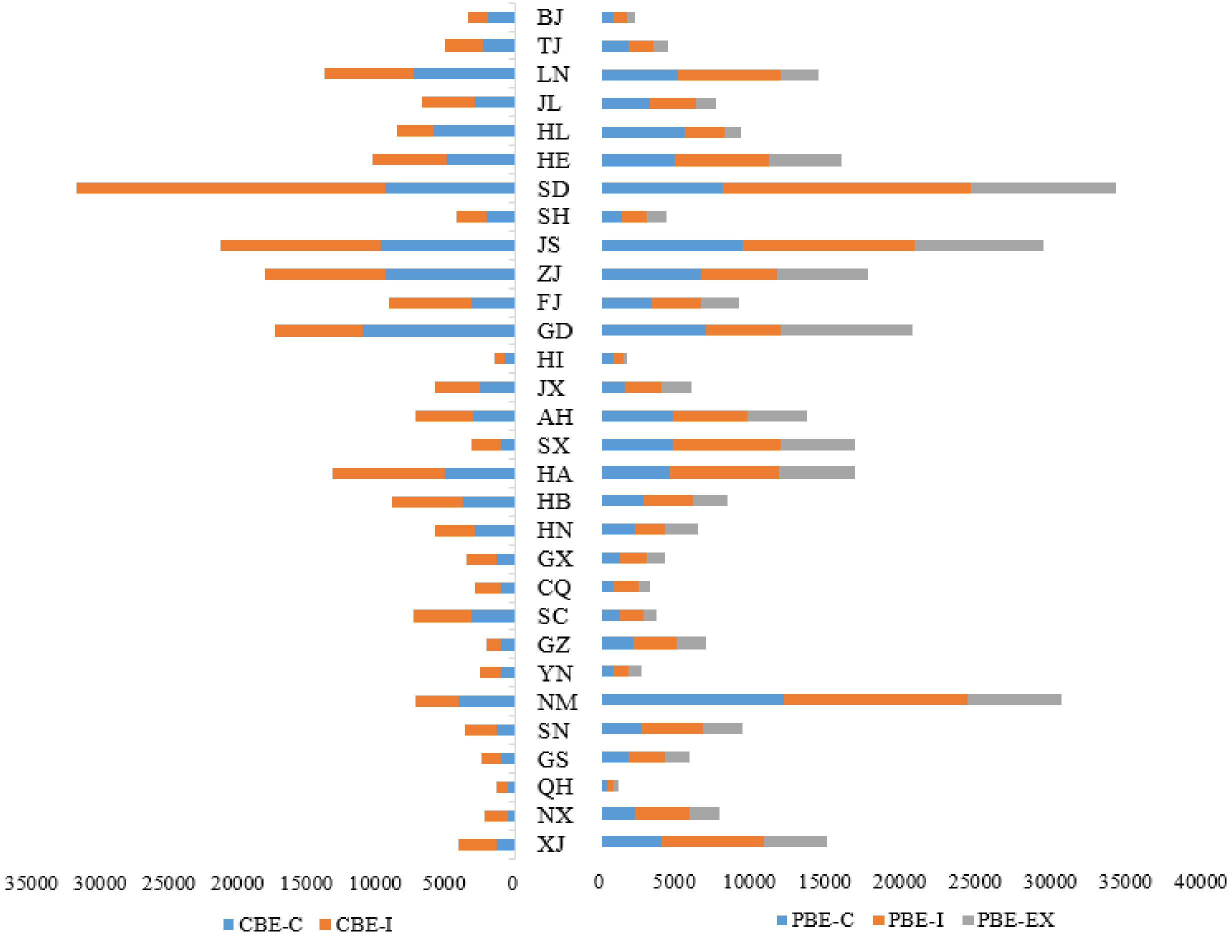

Figure 5. Comparison between E-PBE and E-CBE of 30 provinces in 2015

Note: Nine consumption centers with net emission inflow, including Beijing, Tianjin, Shanghai, Fujian, Zhejiang, Hubei, Sichuan, Yunnan and Qinghai. While 21 production centers are with net emission outflow. The unit is million tons (Mt).

(2) Overall carbon emission transmissions

As for consumption centers, E-CBE inflows to Zhejiang and Fujian increase and the inflows in other consumption centers decrease in 2002-2015 (see Figure 6a). Production source of most consumption centers is strengthened within intra-grid electricity trade, such as inflows from Inner Mongolia to Qinghai, and from Beijing to Tianjin, etc. (Cui et al., 2020). This strengthened intra-grid flows are stimulated by inter-grid limitations of non-uniform electricity trading rules. Among that, increasing intra-grid inflows in

Sichuan and Hubei are related to their abundant hydroelectricity and strong self-supply ability. Inter-grid E-CBE inflows of top three consumption centers (i.e., Zhejiang, Fujian and Hubei) are shifting from North China to Eastern China and Central China.

As for production centers, intra-grid emission outflow range and magnitude are expanding, especially towards Eastern China, Central China and Guangdong (see Figure 6b). The top three production centers with E-PBE outflows include Guangdong, Shandong and Jiangsu. Their E-PBE outflow are aggregated to satisfy the final consumption of Central China, especially Hunan and Henan. At the initial stage of *Central Rising Strategy*, Hunan and Henan strive to establish the advanced manufacturing base and to accelerate the development high technology industries, which generates large electricity consumption and related environmental issues. Among that, Guangdong performs an increasing electricity demand in manufacturing industry under the economic stimulus of *Made in China 2025* and *The Belt and Road Initiative.*

Production centers and consumption centers (i.e., transmission ends) perform distinguished Transmission links through supply chains. This raises the questions about the critical transmission paths and nodes for E-CBE inflows to consumption centers and E-PBE outflows from production centers. Combining production-, consumption- and transmission-based accounting helps to better understand the emission-mitigating responsibilities in all stakeholders of supply chains.

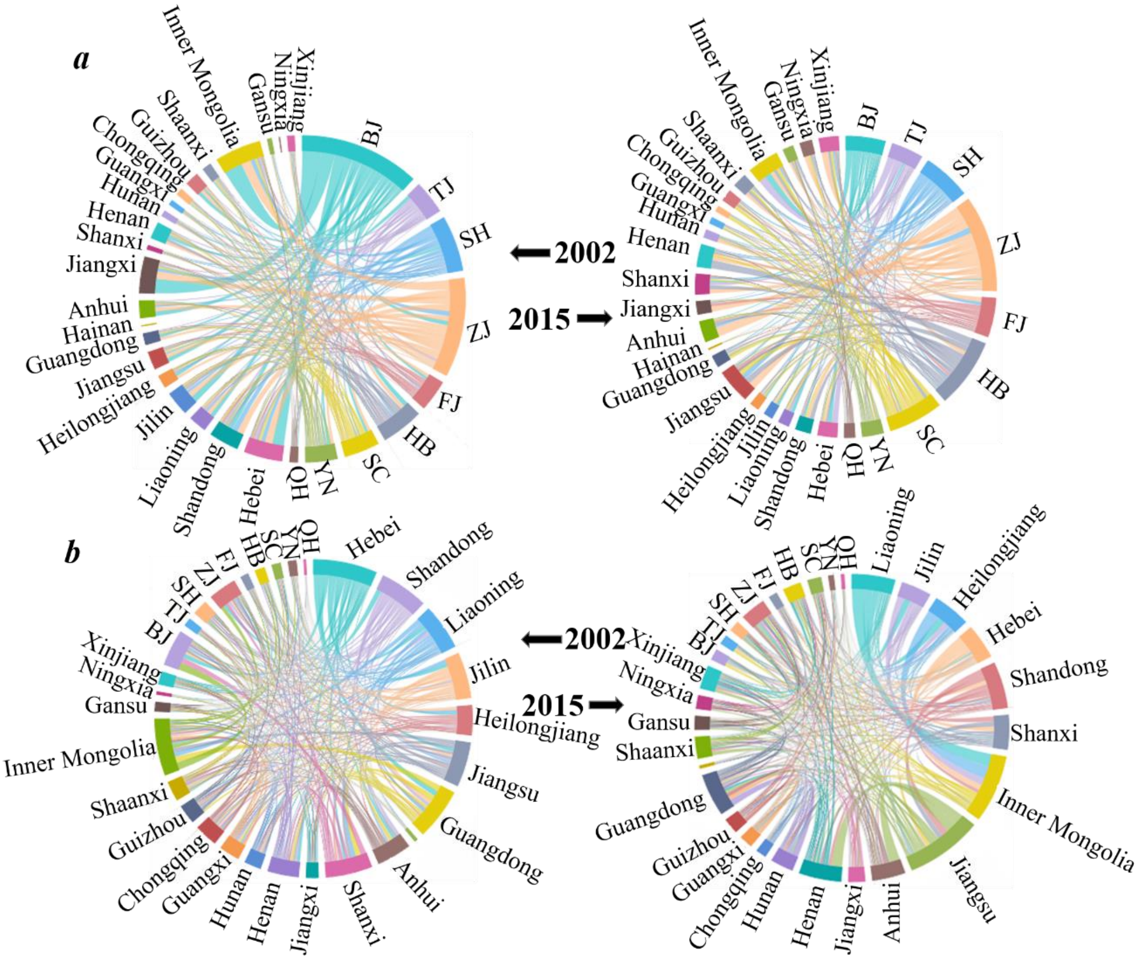

Figure 6. Emission flows in production centers and consumption centers.

Note: Figure 6a illustrates E-CBE inflow to nine consumption centers (abbreviation). Figure 6b illustrates E-PBE outflow from 21 production centers (full name).

4.3 Transmission path changes

Transmission paths are started at electricity sector of production centers and ended at the final consumption demand of consumption centers (see Table S5-S6, Supplementary Materials). Intra-provincial transmissions are dominated and inter-provincial transmissions merely account for a small proportion due to the limitation of inter-provincial electricity trading barriers. Critical E-CBE inflows in most consumption centers are originated from the production of North China and Eastern

China, while most E-PBE outflows to Central China, Jiangsu and Guangdong. Both intra- and inter-grid transmissions show the centralization trend of “electricity sector< intermediate sectors<electricity sector<consumption”. Generally, top production centers and consumption centers are involved in more transmission layers than other centers, thus showing more complicated participation in supply chain.

From E-CBE transmission changes, it can be seen that: 1) Intra-provincial E-CBE transmissions are dominated (i.e., S19<consumption) due to inter-provincial trading barriers. Even though, both inter-provincial E-CBE transmission magnitude and range are increasing greatly. For example, intra-provincial transmissions in Hubei decrease by 30.22%, which are offset by inter-provincial E-CBE transmissions. 2) Most of the critical chains with inter-provincial transmissions are generated by North China and Hubei before 2012. Since 2012, increasing E-CBE inflows are generated from Eastern China due to the increasing clean electricity demand under the stringent environmental requirements. For example, Hubei has redundant hydroelectric resource and facilitates the development of clean electricity (Zhang et al., 2017). 3) Transmission role of electricity sector in intermediate process increased greatly since 2012.

From E-PBE transmission changes in 2002-2015, it can be seen that: 1) E-PBE transmissions from intra-provincial trading are still dominated due to cross-provincial trading barriers. The largest transmission path is “S19<consumption”, namely the direct E-PBE to satisfy intra-provincial consumption demand. Even though, inter-provincial transmissions of E-PBE are increasing greatly. 2) Inter-provincial E-PBE outflows in critical chains are to satisfy final consumption of Central China, Jiangsu and

Guangdong in 2015. In 2002-2015, the outflows to Central China are strengthening and the outflows to Northeast are weakening. 3) E-PBE outflows to Services (S24) are decreasing gradually due to environmental regulations by *Made in China 2025*.

4.4 Transmission node changes

Transmission nodes could be decomposed into inter- and intra-provincial categories. Intra-provincial transmission involves in more transmission sectors, which is more complicated than inter-provincial transmission (see Figure 7 and Figure 8). Since 2007, most provinces tend to increase inter-provincial electricity trading. Both intra- and inter-grid transmissions show the transmission path of "electricity sector< intermediate sectors<electricity sector<consumption". These intermediate sectors are concentrated in manufacturing sector (S02), energy-intensive sectors (S08, S11 and S19) and services (S24).

As for transmission nodes changes of consumption centers (see Figure 7), we can see that: 1) Most consumption centers show increasing inter-provincial transmission magnitude and range, especially in Sichuan, Yunnan and Qinghai. Inter-provincial transmission nodes with top transmission betweenness in 2002-2015 are mainly concentrated in Zhejiang, Beijing and Fujian. E-CBE transmission role of Yunnan is decreasing and the transmission role of Beijing is increasing. 2) Among that, Mining and processing sector (S02), Electricity sector (S19) and Services sector (S24) are dominant in inter-provincial transmission. Transmissions through energy-intensive sectors and services sector are increasing. Electricity sector is dominated in the inter-provincial and intra-provincial transmission nodes, which is stimulated by China's policy encouragement on cross-provincial electricity trading.

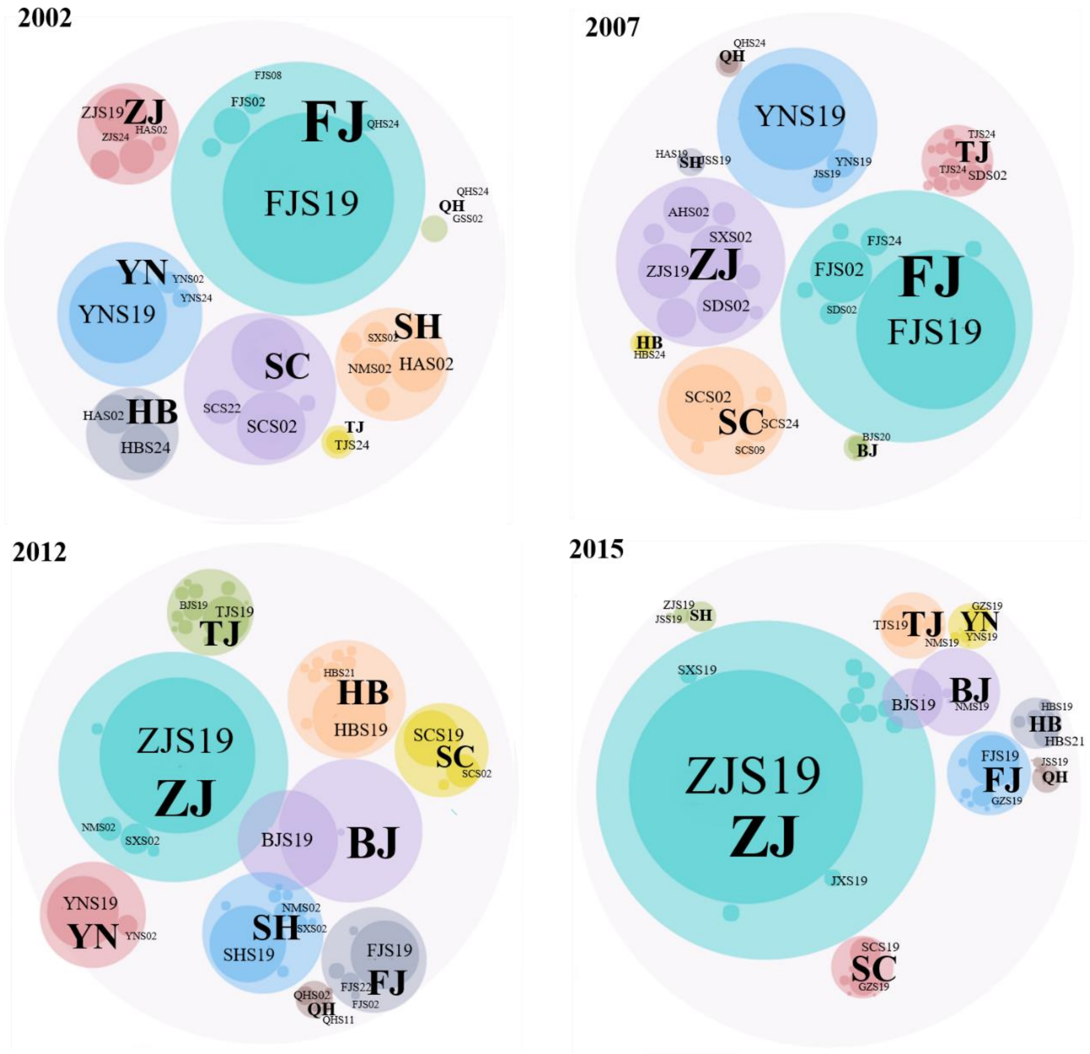

Figure 7. Transmission nodes of consumption centers in 2002-2015.

Note: The circle diameter represents transmission betweenness. Bigger circles illustrate higher transmission betweenness in the nodes (including provinces and sectors).

As for transmission nodes changes of production centers (see Figure 8), we can see that: 1) Guangdong, Heilongjiang and Hebei have higher transmission betweenness than other production centers in 2015. Transmission nodes of inter-grid trading in intermediate process present obvious regional heterogeneity, such as transmission of E-PBE in Northeast, Eastern China and Central China through North China, E-PBE in

South China transferred through Central China, E-PBE in Northwest transferred through Jiangsu and Guizhou, E-PBE in North China transferred through North China and Northeast. 2) Inter-provincial transmissions are limited by cross-provincial electricity trading barriers, especially in Northeast, coast region and Central. Inter-provincial transmissions are concentrated in Mining and processing sector (S02), Electricity sector (S19) and Services sector (S24).

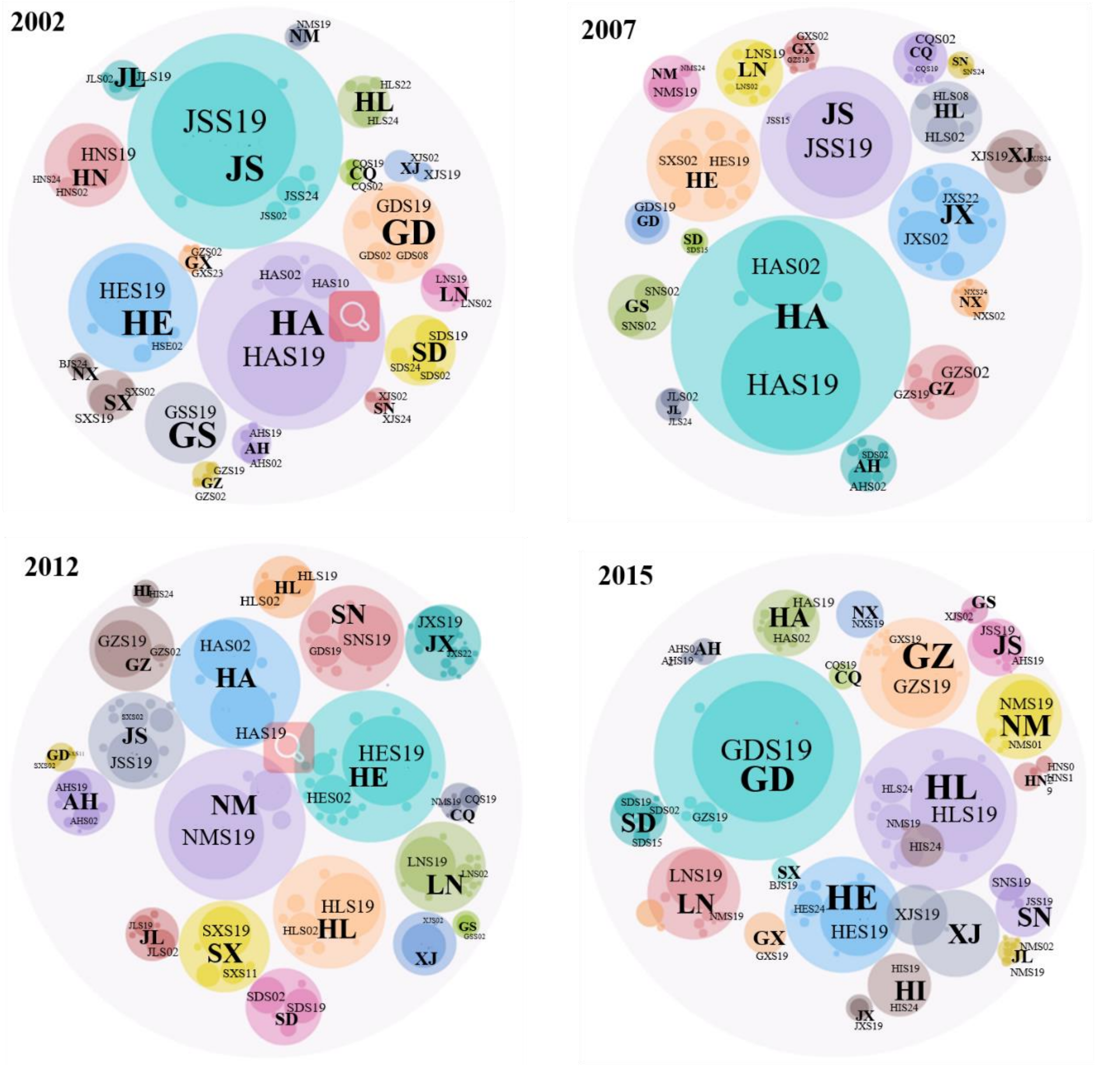

Figure 8. Transmission nodes of production centers in 2002-2015.

5. Discussions

5.1 Limited carbon emission transmission across provinces

There exist large carbon emission transmissions through electricity trade. Although inter-provincial trading in consumption centers is increasing greatly, emission flows from intra-grid trading are still dominated in most provinces. Intra-provincial transmissions involve in more complicated participation in supply chain than inter-provincial transmissions, which is verified by Fei et al. (2014), Lin and Liu (2016), etc. Inter-grid connections make national electricity system one of the most complicated electricity networks in the world. However, inter-provincial transmissions are relatively weakened due to cross-region electricity trading barriers, including technological barriers and institutional barriers. These findings agree with the conclusions of Lindner et al. (2013) and Zhao et al. (2018).

Technological barriers are related to the technologies like ultra-high voltage, energy storage, submarine cables, etc. These immature technologies make it difficult to realize long-distance electricity transmissions and limit the transmission capacity of inter-provincial electricity transmission lines (Zhao et al., 2018). Some resource-rich regions show a conflict between excess production capacity and insufficient transmission capacity due to the limited transmission capacity. For example, Inner Mongolia, as the wind electricity base, performs limited electricity transmission to North China due to the immature energy storage and dispatching bottlenecks in grid system.

Institutional barriers are involved in one-size-fits-all strategies to advance low-carbon electricity cooperation across regions, especially charges on trans-provincial electricity trade and trans-provincial electricity pricing and dispatching systems. Similar to the tariff barriers in international trade, the charges on trans-provincial electricity trade reduces the price competitiveness of electricity suppliers and the market efficiency of trans-provincial electricity trade. With the increasing demand for market-oriented inter-provincial electricity trade, current inter-provincial transmission pricing mechanism (including two fixed prices for capacity plus electricity, as well as single fixed price) will have adaptability problems. For example, single fixed price reduces the market competitiveness of western clean energy in the affected areas of the east, and makes the clean energy consumption dilemma difficult to solve.

To deal with the imbalanced distribution of electricity supply and demand, China actively advances the *West-East Power Transmission Project* and *North-South Power Transmission Project* to balance electricity demand and supply (Zhao et al, 2019). With the advancement of inter-grid connection of electricity system, inter-provincial electricity trading magnitude and range are increasing gradually (Hou and Hou, 2018). To deepen market-oriented reform of electricity, it is urgent to mitigate inter-provincial barriers of electricity trading, such as encouraging direct trading mechanisms, eliminating the charges on trans-provincial electricity trade, forming flexible pricing mechanism, and so on.

5.2 Provincial transmission paths under policy orientation

Inflow paths in consumption centers are mainly originated from the production of Eastern China and South China, while outflow paths in production centers are to satisfy the consumption demand of Central China, Guangdong and Jiangsu. Carbon emission flows of electricity sector are greatly influenced by policies.

As for consumption centers, (1) Central China and Eastern China are the dominated E-CBE production sources for consumption centers, which is related to the rising electricity demand for manufacturing industry expansion under the *Central Rising Strategy* and *Yangtze River Economic Zone*. Eastern China, being in the post-industrial period, has steadily increasing electricity demand for economic development and shoulders more responsibility for electricity transactions. *Central Rising Strategy* stimulated the growth of electricity demand for infrastructure construction in Central China. Besides, China's stringent environmental standards limited the consumption of dirty electricity in Northwest, which provides opportunity for the offset effect of clean energy in Central China. For example, Hubei, as the hub status of *Three Gorges Dam*, expand hydroelectric generation capacity greatly (Wang et al, 2018).

(2) E-CBE from Northwest are decreasing due to the technical improvement and efficiency advancement under the *Great Western Development Strategy*. To achieve emission mitigation targets, Northwest issues stringent environmental standard in energy-intensive sectors, especially in electricity sector. For example, Xinjiang generalized clean energy heating, Gansu issues *Regional Circular Economy Development Plan* in 2009, Inner Mongolia urges wind energy-related infrastructure construction, etc. (Du et al, 2017).

As for production centers, Central China, Guangdong and Jiangsu are the primary E-PBE consumption destinations. Both of Guangdong and Jiangsu have high electricity demand to match the rapid economic growth demand stimulated by *Made in China*

2025, *The Belt and Road Initiative*, *Pearl river delta* and *Yangtze River Economic Delta*. Guangdong, as the largest economy and electricity consumer in China, has a huge electricity import demand (Lin et al, 2019). Electricity imports of Guangdong are mainly from neighboring provinces in China Southern Grid, as well as long-distance provinces by dedicated facilities like *Three Gorges Dam*. As the third-largest thermal electricity, Jiangsu faces an urgent requirement for reducing thermal carbon emissions and supports the use of renewable and clean electricity on *Regulations of Jiangsu Electricity* (Fei et al, 2014). In the short run, however, market-based electricity reforms may increase the coal-fired generation and make the efforts to meet emission mitigation goals complicated (Yan et al, 2019).

Hence, future policy focus should stick to electricity technical innovation in green supply chain, appropriate stringent environmental standards in energy-intensive sectors, market-based electricity reforms based on the reconciliation of economic benefits and environmental costs, etc.

5.3 Agglomeration of transmission nodes

Compared with transmission ends (i.e., E-PBE and E-CBE), critical transmission nodes are concentrated in manufacture, energy-intensive sectors and services. These transmission sectors in intermediate process are crucial for generating upstream carbon emissions but are not identifiable by PBE and CBE accounting. For transmission sectors, it is necessary to improve the production efficiency (i.e., using less carbon-intensive intermediate inputs from upstream sectors to produce unitary outputs), promote industrial upgrading processes and technological innovations, conduct the whole life cycle evaluation, etc. To formulate fair emission reduction policies for all stakeholders, the historical emissions from production-based, consumption-based and transmission-based emissions should be combined as baseline under the grandfather law.

Electricity sector dominants the intra- and inter-provincial transmission nodes, which is stimulated by China's policy encouragement on provincial electricity trading. These findings are consistent with the results of Liang et al. (2016; 2018), etc. Under the strict environmental regulations, electricity-intensive sectors are forced to import electricity from cheaper electricity sources and then to reduce additional environmental costs and increase price pressure. For example, manufacturing sectors in the coastal region are relocated at electricity generation bases to avoid the extra cost of electricity loss in transmission and distribution, such as the Three Gorges Dam (Shao et al, 2018). Another option for electricity-intensive sectors is to promoting cleaner electricity sources through flexible market mechanism, such as direct electricity purchasing contracts for cleaner electricity, etc.

5.4 Methodological uncertainties

MRIO-based SPA approach provides a holistic map to capture the structural linkages among regions and sectors along the supply chain (Nagashima, 2018). Following this framework, a map of sources, destinations, transmission paths and nodes of carbon emissions can be depicted to reflect the transmission mechanism of carbon emissions and fairly allocate emission-mitigating responsibility among all the stakeholders.

MRIO-based SPA shows some uncertainties. SPA uncertainties might be caused by the inherent computational problems as well as the subjective selection of threshold.

This study extracts the critical transmission paths and nodes to minimize these methodological uncertainties, which consistent with the findings of Liang et al. (2016), Li et al. (2018), Nagashima (2018), etc. Besides, this study extracts the critical transmissions sharing at least 1% of total carbon emissions in Layer 0 to Layer 4. Higher-order production layers can be ignored, which will not lead to biased results (Xie, 2014). The validation test for the newly compiled MRIO table in 2015 is shown in Text S1 (Supplementary Materials).

6. Conclusions

Understanding the transmission paths and nodes of carbon emissions from electricity sector to final domestic consumption in China, helps to allocate the emission-mitigating responsibilities in all stakeholders. This study delivers the following conclusions and policy implications:

(1) There exist huge imbalanced production-based and consumption-based emissions in China’s provincial electricity sectors (i.e., E-PBE and E-CBE), which results in huge emission transmissions among interregional electricity trade. Eastern China and Guangdong are both the critical sources for E-PBE and critical destinations for E-CBE. Although both the inter-provincial trading magnitude and range in consumption centers are increasing greatly, emission flows from intra-grid trading are still dominated in most provinces. Strengthened intra-grid electricity transmission is related to the limitation of inter-provincial trading barriers.

(2) Both the emission inflow paths in consumption centers and outflow paths in production centers show a trend of intra-grid agglomeration and provincial

heterogeneity. The inflow paths in nine consumption centers are mainly from the production of Eastern China and South China, while the outflow paths in 21 production centers are to satisfy the consumption demand of Central China, Guangdong and Jiangsu. Inter-provincial linkages are intensified and perform the feature of territorial propinquity, such as the increasing electricity transmission outflow from Inner Mongolia and Shanxi to North China, increasing hydroelectric inflow from Hubei to Guangdong and Jiangsu, etc. Carbon emission flows of electricity sector are greatly influenced by policies, such as the rising electricity supply in Central and Northwest by the *Great Western Development Strategy* and the *Central Rising Strategy*, and the surging electricity demand by *Made in China 2025* and *The Belt and Road Initiative*.

(3) Transmission-based emission accounting helps to identify the critical sectors and provinces in the intermediate process of supply chain networks. Both intra- and inter-regional transmission show the centralization trend of "electricity sector<intermediate sectors<electricity sector<consumption". These intermediate sectors are concentrated in manufacturing sector, energy-intensive sectors and services sector. These transmission sectors generate a large amount of carbon emissions embodied in intermediate inputs of upstream sectors, while they may receive less attention from the production side and demand side. The focus of the transmission sectors should be placed on reducing the requirements of more carbon-intensive intermediate inputs from upstream sectors.

Supplementary Materials

Supplementary Materials is available free of charge, including region and sector classifications (Table S1-S2), abbreviations (Table S3), supplemented analysis (Table S4-S6, Figure S1) and extended results (Text S1). Figures, tables and text support the main text. China's multi-region input-output table in 2015 is openly shared.

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References

Cao, Y., Zhao, Y.H., Wang, H.X., Li, H., Wang, S., Liu, Y., Shi, Q.L., Zhang, Y.F., 2019. Driving forces of national and regional carbon intensity changes in China: Temporal and spatial multiplicative structural decomposition analysis. Journal of Cleaner Production 213, 1380-1410.

Cui, G.X., Yu, Y.D., Zhou, L., Zhang, H.Y., 2020. Driving forces for carbon emissions changes in Beijing and the role of green power. Science of the Total Environment 728, 138688.

Cui, P., Xia, S.Y., Hao, L.S., 2019. Do different sizes of urban population matter differently to CO_2 emission in different regions? Evidence from electricity consumption behavior of urban residents in China. Journal of Cleaner Production 240, 118207.

Defourny, J., Thorbecke, E., 194. Structural path analysis and multiplier decomposition within a social accounting matrix framework. The Economic Journal 94(373), 111-136.

Du, K.R., Lin, B., Xie, C., Ouyang, X., 2017. A comparison of carbon dioxide (CO_2) emission trends among provinces in China, Renewable and Sustainable Energy Reviews 73, 19-25.

Fei, T., Xin, W., Lv, Z.Q., 2014. Introducing the emissions trading system to China’s electricity sector: Challenges and opportunities. Energy Policy 75, 39-45.

Feng, C.Y., Qu, S., Jin, Y., Tang, X., Liang, S., Chiu, A.S., Xu, M., 2019. Uncovering urban food-energy-water nexus based on physical input-output analysis: The case of the Detroit Metropolitan Area. Applied Energy 252, 113422.

Kagawa, S., Suh, S., Hubacek. K., Wiedmann, T., Nansai, K., Minx, J., 2015. CO_2 emission clusters within global supply chain networks: implications for climate change mitigation. Global Environment Change 35, 486-496.

Hanaka, T., Kagawa, S., Ono, H., Kanemoto, K., 2017. Finding environmentally critical transmission sectors, transactions, and paths in global supply chain networks. Energy Economics 68, 44-52.

Hong, J., Shen, G.Q., Guo, S., Xue, F., Zheng, W., 2016. Energy use embodied in China's construction industry: a multi-regional input-output analysis. Renewable Sustainable Energy Review 53, 1303-1312.

Hou, J.C., Hou, P.W., 2018. Polarization of CO_2 emissions in China's electricity sector: Production versus consumption perspectives. Journal of Cleaner Production 178, 384-397.

IEA, 2018. CO_2 emissions from fuel combustion highlights. International Energy Agency, Paris, 2018. URL: https://webstore.iea.org/co2-emissions-from-fuel-combustion-2018.

Lantner, R., 1974. Thiorie de la dominance economique. Dunod, Paris.

Lenzen, M., 2007. Structural path analysis of ecosystem networks. Ecol. Model. 200, 334-342.

Li, S.T., Qi, S., He, J., 2016. Extended Chinese Regional Input-Output Table: Construction and Application (2007). Economic Science Press: Beijing, China.

Li, S., Qi, S., Xu, Z., 2010. Extended Chinese Regional Input-Output Table: Construction and Application (2002). Economic Science Press: Beijing, China.

Li, Y.Z., Su, B., Dasgupt, A.S., 2018. Structural path analysis of India's carbon emissions using input-output and social accounting matrix frameworks. Energy Economics 76, 457-469.

Liang, S., Qu, S., Xu, M., 2016. Betweenness-Based Method to Identify Critical Transmission Sectors for Supply Chain Environmental Pressure Mitigation. Environmental Science and Technology 50, 1330-1337.

Liang, S., Wang, Y.F., Xu, M., Yang, Z.F., Liu, W.D., Liu, H.G., Chiu, A.S., 2018. Final production-based emissions of regions in China. Economic Systems Research 30, 18-36.

Lin, B., Liu, C., 2016. Why is electricity consumption inconsistent with economic growth in China? Energy Policy 88, 310-316.

Lindner, S., Liu, Z., Guan, D.B., Geng, Y., Li, X., 2013. CO_2 emissions from China’s power sector at the provincial level: Consumption versus production perspectives. Renewable and Sustainable Energy Reviews 19, 164-172.

Lin, J., Kahrl, F., Yuan, J.H., Chen, Q.X., Liu, X., 2019. Economic and carbon emission impacts of electricity market transition in China: A case study of Guangdong Province. Applied Energy 238, 1093-1107.

Liu W.D., Tang Z., Chen J., 2012. The Multi-Regional Input-Output Table of 30 Regions in China in 2007. China Statistics Press, Beijing (Chinese).

Liu W.D., Tang Z., Chen J., 2014. The Multi-Regional Input-Output Table of 30 Regions in China in 2010. China Statistics Press, Beijing (Chinese).

Liu W.D., Tang Z., Chen M.Y, 2018. The Multi-Regional Input-Output Table of 30 Regions in China in 2012. China Statistics Press, Beijing (Chinese).

Meng, B., Wang, J., Andrew, R., Xiao, H., Xue, J., Peters, G.P., 2017. Spatial spillover effects in determining China's regional CO_2 emissions growth: 2007-2010. Energy Economics 63, 161-173.

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

Mi, Z.F., Meng, J., Zheng, H.R., Shan, Y.L., Wei, Y.M., Guan, D.B., 2017. A multi-regional input-output table mapping China's economic outputs and interdependencies in 2012. Scientific Data.

Mi, Z.F, Zhang, Y., Guan, D., Shan, Y., Liu, Z., Cong, R., Yuan, X.-C., Wei, Y.-M., 2016. Consumption-based emission accounting for Chinese cities. Applied Energy 184, 1073-1081

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

Miller, R.E., Blair, P.D., 2009. Input-output Analysis: Foundations and Extensions. Cambridge University Press.

Mo, J.L., Agnolucci, P., Jiang, M.R., Fan, Y., 2016. The impact of Chinese carbon emission trading scheme (ETS) on low carbon energy (LCE) investment. Energy Policy, 2016, 89, 271-283.

Nagashima, F., 2018. Critical structural paths of residential PM2.5 emissions within the Chinese provinces. Energy Economics 70, 465-471.

Newman, M., 2010 Networks: An Introduction. Oxford University Press: New York.

Newman, M., 2005. A measure of betweenness centrality based on random walks. Social Networks 27(1), 39-54.

Pan, C., Peters, G.P., Andrew, R.M., Korsbakken, J.I., Zhou, P., Zhou, D.Q., 2018. Structural Changes in Provincial Emission Transfers within China. Environment Science and Technology 52, 12958-12967.

Peng, J.Y., Xie, R., Lai, M.Y., 2018. Energy-related CO2 emissions in the China's iron and steel industry: A global supply chain analysis. Resources, Conservation and Recycling 129, 392-401.

Peters, G.P., Hertwich, E.G., 2008. CO_2 Embodied in International Trade with Implications for Global Climate Policy. Environment Science and Technology 42 (5), 1401-1407.

Peters, G.P., Hertwich, E.G., 2006. The importance of imports for domestic environmental impacts. Journal Industrial Ecology 10, 89-109.

SCIO, NDRC, 2007. State Council Information Office of the People’s Republic of China, Information Office of the State Council of the People's Republic of China National Development and Reform Commission (NDRC). China’s Energy Conditions and Policies. http://www.chinahumanrights.org/Messages/Focus/031/05/t20080229_491522.htm

Shao, L., Li, Y., Feng, K.S., Meng, J., Shan, Y.L., Guan, D.B., 2018. Carbon emission imbalances and the structural paths of Chinese regions. Applied Energy 215, 396-404.

Tian, Y.S., Xiong, S.Q., Ma, X.M., Ji, J.P., 2018. Structural path decomposition of carbon emission: A study of China's manufacturing industry. Journal of Cleaner Production 193, 563-574.

United Nations, 1999. Handbook of input-output table compilation and analysis. Studies in methods. United Nations: New York.

Wang, B., Liu, L., Huang, G.H., Li, W., Xie, Y.L., 2018. Effects of carbon and environmental tax on power mix planning-A case study of Hebei Province, China. Energy143, 645-657.

Xie, S.C., 2014. The driving forces of China’s energy use from 1992 to 2010: an empirical study of input-output and structural decomposition analysis. Energy Policy 73, 401-415.

Xu, M., Liang, S., 2019. Input-output networks offer new insights of economic structure. Physica A 527, 121178.

Yan, Q.Y., Wang, Y.X., Balezentis, T., Streimikiene, D., 2019. Analysis of China's regional thermal electricity generation and CO2 emissions: Decomposition based on the generalized Divisia index. Science of the Total Environment 682, 737-755.

Zhang, B., Qu, X., Meng, J., Sun, X.D., 2017. Identifying primary energy requirements in structural path analysis: A case study of China 2012. Applied Energy 191, 425-435.

Zhang, Y., 2017. Interregional carbon emission spillover-feedback effects in China. Energy Policy 100, 138-148.

Zhang, Y., Qi, S., 2012. China Multi-Regional Input-Output Models: 2002 and 2007. China Statistics Press.

Zhao, Y.H., Cao, Y., Shi, X.P., Li, H., Shi, Q.L., Zhang, Z.H., 2019. How China’s electricity generation sector can achieve its carbon intensity reduction targets? Science of the Total Environment 706, 135689.

Zhao, W.G., Cao, Y.F., Miao, B., Wang, K., Wei, Y-M., 2018. Impacts of shifting China's final energy consumption to electricity on CO_2 emission reduction. Energy Economics 71, 359-369.

Zheng, H., Zhang, Z., Wei, W., Song, M., Dietzenbacher, E., Wang, X., Meng, J., Shan, Y., Ou, J., Guan, D., 2020. Regional determinants of China’s consumption-based emissions in the economic transition. Environmental Research Letters. https://doi.org/10.1088/1748-9326/ab794f

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