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Multi-scope electricity-related carbon emissions accounting: A case study of Shanghai

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A B S T R A C T

Electricity-related carbon emissions in a specific region can vary significantly as the scope for emissions accounting changes. Existing studies have mainly focused on carbon emissions caused by local power generation (Scope 1) and carbon emissions embodied in the electricity consumed by a region after cross-regional electricity transmission (Scope 2). Previous studies have ignored the electricity-related carbon emissions induced by regional consumption (Scope 3), leading to carbon emissions leakage. Comprehensively employing the IPCC emissions accounting method, a network approach that simulates cross-regional electricity flow and an environmentally extended input-output model, this study provides systematic electricity-related carbon emissions accounting for regional electricity-related carbon emissions under Scopes 1, 2 and 3 using the case of Shanghai in the period of 2007–2012. The results show that Shanghai has large net inflows of electricity-related carbon emissions through power grids and regional trade, causing Scope 2 and Scope 3 emissions to be significantly larger than Scope 1 emissions in Shanghai. A Logarithmic Mean Divisia Index (LMDI) model is used to analyze the driving factors of carbon emissions under Scope 1, and the driving factors of carbon emissions under Scopes 2 and 3 are evaluated using structural decomposition analysis (SDA). Fuel structure improvement can help to reduce Shanghai's Scope 1 emission, while the power generation volume increase has opposite effect. Power transmission structure and power transmission scale decrease Shanghai's Scope 2 emissions, while the power consumption scale is positive with emission growth. The declining carbon emissions intensity and improving electricity efficiency offset the growth of Shanghai's Scope 3 emissions, while the increase in population and per capita electricity consumption contribute to the increase in Scope 3 emissions. This study could help to enhance the understanding of regional electricity-related carbon emissions and to support comprehensive and systemic carbon mitigation strategies.

1. Introduction

Global warming caused by greenhouse gas emissions poses a serious threat to the sustainable development of human society. It is estimated that the carbon emissions caused by power generation account for more than 40% of China's carbon emissions (Qu et al., 2017a; Tong et al., 2018; Wei et al., 2017). Power generation in China caused 4.39E+03 Mt of carbon emissions in 2016, an amount nearly as large as the total combustion caused carbon emissions in the US in this year (International Energy Agency, 2018). Therefore, reducing electricity-related carbon emissions is critical to achieving China's carbon reduction targets.

Since an emissions inventory provides fundamental information for mitigation policy design, comprehensive and accurate inventories of electricity-related carbon emissions are of great

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significance (Mi et al., 2019; Shan et al., 2018b). Based on the perspective of analysis and the choice of regional boundaries, a carbon emissions inventory can be developed from three scopes (Kennedy et al., 2009; Li et al., 2013; WRI/WBCSD, 2009). Scope 1 includes direct emissions from activities such as fossil fuel combustion or cement processing within regional geographic boundaries (Shan et al., 2018a; Zhou et al., 2019). Scope 2 accounts for emissions from the generation of purchased electricity, which is provided by local and external power plants (Qu et al., 2017a; WRI/WBCSD, 2009). Scope 3 is a broader measure covering the direct and indirect electricity-related emissions embodied in upstream production induced by regional consumption (Kennedy et al., 2009).

Electricity-related carbon emissions accounting has attracted the attention of many scholars, but the existing studies have accounted for only regional Scope 1 and Scope 2 emissions. Some scholars have developed detailed emissions inventories under Scope 1 for China's provinces (Shan et al., 2018b) and cities (Shan et al., 2017) using the IPCC emissions accounting method. Wang et al. (2019) and Liao et al. (2019a) accounted for China's Scope 1 emissions and analyzed the driving forces of these emissions. Some researchers have calculated China's national (Ji et al., 2016; Qu et al., 2018; Zafirakis et al., 2015) and provincial Scope 2 emissions (Lindner et al., 2013; Qu et al., 2017a; Zhang et al., 2020) by considering the cross-regional flows of electricity with different carbon intensities. As the scale of inter-regional electricity transmission increases, electricity flows through power grids will have a greater impact on Scope 2 regional emissions (Ji et al., 2016; Qu et al., 2017b; Wei et al., 2018b). However, research on electricity-related carbon emissions accounting for Scope 3 emissions has remained lacking. Due to the existence of regional trade, regional Scope 3 emissions could be quite different from Scope 2 emissions, and neglecting the impact of regional trade on regional electricity-related carbon emissions will lead to carbon leakage (Feng et al., 2013; Liu et al., 2015; Zhang et al., 2016). Carbon leakage is defined as the shift of carbon emissions from a region with emission constraints to an unregulated region (Naegele and Zaklan, 2019). Specifically, regional Scope 3 emissions can be reduced by purchasing products from other regions, leading to emissions increases in other regions (Li et al., 2018; Meng et al., 2018). Therefore, regional trade can be seen as a process of redistributing energy consumption or carbon emissions across regions (Chen and Chen, 2013; Zhang et al., 2020). A multi-scope electricity-related carbon emissions accounting framework covering all 3 scopes will greatly improve the efficiency of China's carbon emissions mitigation. Fig. 1 shows the connection among Scope 1, Scope 2 and Scope 3 emissions.

We chose Shanghai, one of the most developed regions in China, as our case for multi-scope carbon emissions accounting. In 2018, Shanghai had 24 million usual residents and a gross regional product of 3.27 trillion yuan, and its per capita gross regional product ranks second in China (Shanghai Statistics Bureau, 2018a). Due to its large population and large-scale industries, Shanghai has massive electricity demand, with an electricity consumption of 1.53E+05 GWh in 2017 (Shanghai Statistics Bureau, 2018b). Because of its limited power resources, Shanghai must buy electricity from Hubei, Sichuan, Jiangsu, and Zhejiang every year to meet its local electricity demand. In 2017, Shanghai purchased 6.68E+04 GWh of electricity from other provinces (National Bureau of Statistics, 2018). In addition, as a trade center, Shanghai engages in an enormous number of domestic transactions and international transactions (Wang et al., 2019b). For the above reasons, we believe that accounting for Shanghai's electricity-related carbon emissions could provide us with valuable information.

We establish for the first time a multi-scope electricity-related carbon emissions accounting framework to provide more comprehensive information about and evidence for electricity-related carbon emissions reduction, thereby improving China's emissions reduction efficiency. This study also provides time series emissions accounting from 2007 to 2012, which could help us to discover the evolutionary characteristics of Shanghai's electricity-related carbon emissions. We use the IPCC emissions accounting method to calculate Scope 1 emissions; this method has been widely used to account for regional direct emissions caused by fossil fuel combustion (Liu et al., 2018c; Liu et al., 2018d; Shan et al., 2018b). The network approach is applied to calculate Scope 2 emissions; this approach can help to obtain a more accurate result for considering electricity flows through transit areas (Qu et al., 2017a, 2017b). We use an environmentally extended multi-regional input-output model to calculate Scope 3 emissions; this model has been widely used in research on embodied energy (Chen et al., 2018; Liu et al., 2018a; Wang et al., 2019a; Zhang et al., 2016), virtual water (Zhang and Anadon, 2014) and carbon footprints (Li et al., 2018b; Mi et al., 2019; Wang et al., 2018). Another important innovation of our study is that we conduct a decomposition analysis of the three scope emissions from 2007 to 2012 using LMDI and SDA models, which can help to identify the major driving forces of regional electricity-related carbon emissions (Liang et al., 2019; Ma et al., 2019; Meng et al., 2019).

The remainder of the study is organized as follows. The methodology and data sources are introduced in Section 2. Detailed results are presented in Section 3. The discussion is presented in Section 4, followed by the conclusions.

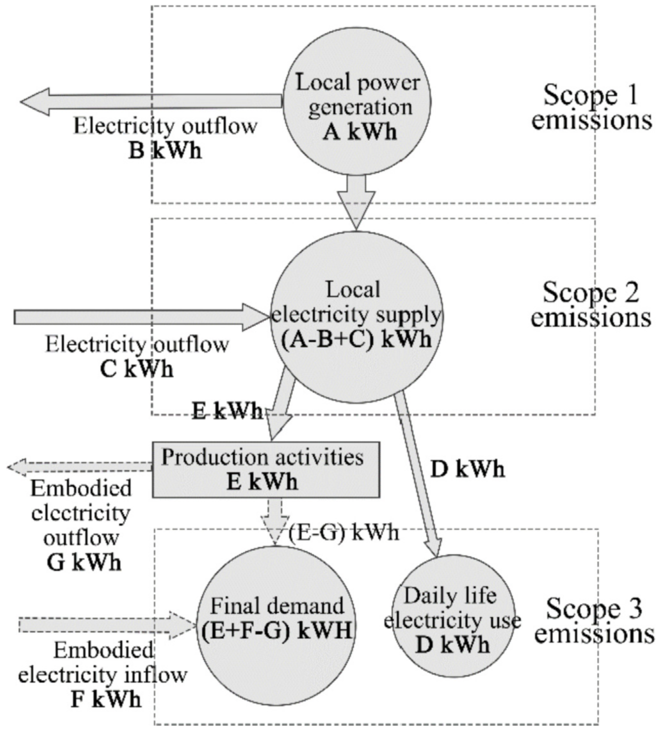

Fig. 1. The connection among the three scope emissions.

2. Methodology and data sources

2.1. Methodology

2.1.1. The IPCC carbon emissions accounting method

The IPCC method was proposed by the Intergovernmental Panel on Climate Change to account for the emissions caused by power generation, and it is the most widely used method worldwide for this purpose (Intergovernmental Panel on Climate Change, 2006). In a region where m types of fuels are used to produce electricity, Scope 1 emissions (PEE) can be calculated as

$$PEE = \sum_{k=1}^{m} AD_k \cdot EF_k \tag{1}$$

where AD_k is the amount of kth fuel consumed in power generation, and EF_k is the carbon emissions intensity of kth fuel.

2.1.2. The network approach

Through interconnected power grids, a region can transfer electricity to another region through a transit region (high-order electricity flow). Without considering the high-order electricity flows, it is actually assumed that the power flowing out from the region is produced locally. Ignoring high-order electricity flows will lead to inaccuracy in calculating Scope 2 emissions. If we suppose that an electricity transit region where there is a large amount of power inflows and outflows produces only hydropower, the carbon emissions intensity of the outflow electricity in this region is 0 kg CO_2/kWh, which is obviously inconsistent with reality. Some researchers have proposed a network approach to solve this problem (Qu et al., 2017a, 2017b).

In the network approach, each region is represented as a node that can produce and consume electricity, and the nodes are connected to each other. For each node, the following equation exists:

$$g_i = p_i + \sum_{j=1}^{n} F_{j,i} = c_i + \sum_{j=1}^{n} F_{i,j} \tag{2}$$

where p_i represents the total amount of electricity produced in region i; $F_{i,j}$ represents the electricity transmitted from region i to j, c_i is the electricity consumption in region i, and g_i is the total amount of electricity flow of region i.

Then, we define direct flow coefficient matrix D as follows:

$$D = \hat{g}^{-1}F = \begin{bmatrix} 0 & \frac{F_{1,2}}{g_1} & \cdots & \frac{F_{1,n}}{g_1} \\ \frac{F_{2,1}}{g_2} & 0 & \cdots & \frac{F_{2,n}}{g_2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{F_{n,1}}{g_n} & \frac{F_{n,2}}{g_n} & \cdots & 0 \end{bmatrix} \tag{3}$$

where element $D(i,j)$ is the proportion of the electricity flowing from region i to region j out of the total amount of electricity flow of region i, and $\hat{g}$ is a diagonal matrix with element $g(i,j) = 0$ if $i \neq j$ and $g(i,j) = g_i$ if $i = j$.

The total flow coefficient matrix Z can be expressed as follows:

$$Z = [I - D]^{-1} = I + D + D^2 + D^3 + \cdots \tag{4}$$

where element $Z(i,j)$ is the proportion of electricity flowing from region i to region j through all possible paths, I is an identity matrix representing the internal electricity flow in the grid, D represents the cross-regional electricity flows without passing through the transit region, D^2 represents the cross-regional electricity flows through one transit region, and D^3 represents the electricity flows passing through two transit regions.

We define the production-consumption matrix H to link regional electricity production and electricity consumption, and matrix H can be expressed as follows:

$$H = Z\hat{c}\hat{g}^{-1} \tag{5}$$

where $\hat{c}$ is a diagonal matrix with $c(i,i) = ci$ if $i = j$ and $c(i,j) = 0$ if $i \neq j$, and $H(i,j)$ is the proportion of the electricity produced by region i and consumed by region j out of the total electricity region j consumed.

Using PEE calculated in Equation (1), the carbon emissions flows through the power grids can be expressed as follows:

$$E^C = E^G H \tag{6}$$

where element $E^C(i,j)$ is the electricity-related carbon emission flows from region i to region j, and E^G is a diagonal matrix where $E^G(i,j) = PEE_i$ if $i = j$ and $E^G(i,j) = 0$ if $i \neq j$.

The Scope 2 emissions (SEE) of region i can be calculated as

$$SEE_i = \sum_{j=1}^{n} E^C_{i,j} \tag{7}$$

2.1.3. The environmentally extended multi-regional input-output model

In the environmentally extended multi-regional input-output table, the embodied carbon emissions intensity EE can be expressed as

$$EE = DE(I - A)^{-1} \tag{8}$$

where DE is a row vector of emissions per unit output of each sector, I is an identity matrix, and A is the direct input coefficients matrix.

The Scope 3 emissions (CEE) of region i can be expressed as

$$CEE_i = EE \times Y_i \tag{9}$$

where Yi is the column vector of the final demand of region i.

We can also trace the emissions flows using the following equation:

$$EF_{ij} = DE_i(I - A)^{-1} Y_j \tag{10}$$

where EF_{ij} is the electricity-related carbon emissions that flow from region i to region j, and DE_i = [(0, …,0), …($c_{i,1}$, $c_{i,2}$, …$c_{i,30}$), …(0, …,0)].

2.1.4. The decomposition analysis

This study uses two methods, LMDI and SDA, to analyze the driving factors of electricity-related carbon emissions. LMDI is used to analyze Scope 1 emissions (PEE), and SDA is used to analyze Scope 2 emissions (SEE) and Scope 3 emissions (CEE). First, we introduce the LMDI method. Based on the study by Liao et al. (2019b), our study analyzes four factors affecting regional PEE:

$$\begin{aligned} PEE &= \sum_{k=1}^{m} PEE_k = \sum_{k=1}^{m} \frac{PEE_k}{E} \times \frac{E}{TP} \times \frac{TP}{EV} \times EV \\ &= \sum_{k=1}^{m} FS_k \times EE \times ES \times EV \end{aligned} \tag{11}$$

where PEE_k is the carbon emissions caused by the kth fuel for power generation, E is the total energy consumption in standard coal used for power generation, TP is the thermal power generation, and EV is the total power generation in the region. FS_k (PEE_k/E) represents the fuel structure, *EE* (*E*/*TP*) refers to energy efficiency in power generation, *ES* (*TP*/*EV*) denotes the local electricity structure, and *EV* is the volume of local power generation.

ΔPEE, the change in regional *PEE* from t_0 to t_1, can be expressed as

$$\Delta PEE = PEE_{t1} - PEE_{t0} = \Delta PEE_{FS} + \Delta PEE_{EE} + \Delta PEE_{ES} + \Delta PEE_{EV} \tag{12}$$

where ΔPEE_{FS}, ΔPEE_{EE}, ΔPEE_{ES}, and ΔPEE_{EV} are the impacts of changes in fuel structure, energy efficiency, power structure, and power generation volume, respectively, on ΔPEE from t_0 to t_1. According to the LMDI model, these four terms can be calculated:

$$\Delta PEE_{FS} = \sum_{k=1}^{m} \omega_i \ln\left(FS_k^T \big/ FS_k^t\right) \tag{13}$$

$$\Delta PEE_{EE} = \sum_{k=1}^{m} \omega_i \ln\left(EE_k^T \big/ EE_k^t\right) \tag{14}$$

$$\Delta PEE_{ES} = \sum_{k=1}^{m} \omega_i \ln\left(ES_k^T \big/ ES_k^t\right) \tag{15}$$

$$\Delta PEE_{EV} = \sum_{k=1}^{m} \omega_i \ln\left(EV_k^T \big/ EV_k^t\right) \tag{16}$$

$$\omega_i = \frac{PEE_k^T - PEE_k^t}{\ln\left(PEE_k^T \big/ PEE_k^t\right)} \tag{17}$$

where equation (17) is called the logarithmic mean weight. A more detailed description of LMDI model can be found in the study by Ang (2015).

Next, we use SDA to analyze the driving factors of Scope 2 and Scope 3 emissions. According to Equations (4)–(7), the Scope 2 emissions (*SEE*) of region *i* can be expressed as

$$SEE = \left(E^G\right)^T G\, \hat{c}\, \hat{x}^{-1} R \tag{18}$$

where *R* is a column vector with $R(i,1) = 1$ and $R(j,1) = 0\ (j \neq i)$, and *R* is used to identify the *SEE* of region *i* from the results including all of the regions' *SEE*.

From t_0 to t_1, the change in the regional *SEE* (ΔSEE) can be expressed as

$$\Delta SEE = SEE_{t1} - SEE_{t0} = \left(E^G{}_{t1}\right)^T G_{t1}\, \hat{c}_{t1}\, \hat{x}_{t1}{}^{-1} R_{t1} - \left(E^G{}_{t0}\right)^T G_{t0}\, \hat{c}_{t0}\, \hat{x}_{t0}{}^{-1} R_{t0} \tag{19}$$

According to Equation (9), regional Scope 3 emissions (*CEE*) can be expressed as

$$CEE = DE \cdot (I - A)^{-1} y \tag{20}$$

where *y* is a $n \times 1$ vector, and we can decompose y into two parts: the consumption structural components *ys* ($n \times m$) and the consumption volume components *yg*($m \times 1$). Therefore, *y* can be expressed as $ys \times yg$. In addition, $DE(1 \times n)$ can be decomposed into $CT(1 \times n)$ and $EP(n \times n)$. *CT* is the carbon emissions intensity of electricity used in each region, and *EP* is a diagonal matrix composed of electricity consumption per unit output of sectors in each region.

Therefore, Equation (20) can be expressed as

$$CEE = CT \cdot EP \cdot L \cdot ys \cdot yg \tag{21}$$

where *L* is Leontief inverse matrix $(I\text{-}A)^{-1}$, which indicates the level of production technology.

From t_0 to t_1, the change in the regional *CEE* (ΔCEE) can be expressed as

$$\Delta CEE = CEE_{t1} - CEE_{t0} = CT_{t1} \cdot EP_{t1} \cdot L_{t1} \cdot ys_{t1} \cdot yg_{t1} - CT_{t0} \cdot EP_{t0} \cdot L_{t0} \cdot ys_{t0} \cdot yg_{t0} \tag{22}$$

The SDA has a non-uniqueness problem, and if there are *n* factors decomposed, there will be *n*! decomposition forms (Dietzenbacher and Los, 1998; Liang et al., 2013; Liang and Zhang, 2011; Rørmose and Olsen, 2005). We use the weighted average decomposition method to solve the non-uniqueness problem; this method calculates the average of all of the possible first-order decomposition forms. A detailed introduction of the weighted average decomposition method can be found in the study by Rørmose and Olsen (2005).

2.2. Data sources

The data on regional power generation, regional electricity consumption and fuel consumption in power generation are derived from the China Energy Statistical Yearbook (National Bureau of Statistics, 2013a), and the carbon emissions factors of fuels are derived from Qu et al. (2017a). We compile the data on China's cross-regional power transmission based on the Electricity Industry Statics Compilation (China Electricity Council, 2008, 2011, 2013). Our study uses China's 2007, 2010, and 2012 multi-regional input-output tables compiled by Liu and colleagues (Liu et al., 2012; Liu et al., 2014; Liu et al., 2018b), and China's 2012 multi-regional input-output table is the latest available table, released in 2018. To match the electricity data, we adjust the sectors in the input-output tables, and detailed information on the sectors can be found in the appendix. To eliminate the impact of the price factor, we use the double deflation method (Nations, 1999; Perers et al., 2007) to convert the 2010 and 2012 tables to the 2007 constant price. The price deflators are calculated according to the China Statistical Yearbook (National Bureau of Statistics, 2013b).

3. Results

3.1. Scope 1 emissions in Shanghai

Scope 1 emissions are carbon emissions caused by regional power generation. The electricity that Shanghai produced increased from 7.39E+04 GWh in 2007 to 8.86E+04 GWh in 2012 (an increase of 19.89%), while Scope 1 emissions increased from 61.4 Mt 2007 to 67.5 Mt in 2012 (an increase of 10.06%). As shown in Fig. 2, the increase in Scope 1 emissions from 2007 to 2010 was mainly caused by the fuel structure change and the increase in power generation scale. From 2007 to 2010, the raw coal used for power generation in Shanghai increased by 24.22%, and the total power generation increased by 18.54%. From 2010 to 2012, the reduction in Scope 1 emissions was due to the fuel structure improvement: there were less raw coal and more natural gas used in Shanghai's power generation (natural gas has relatively high efficiency for power generation (Wei et al., 2018a)).

The lower growth rate of Scope 1 emissions compared to power generation implies that the electricity produced locally in Shanghai has become cleaner. The carbon emissions intensity of locally

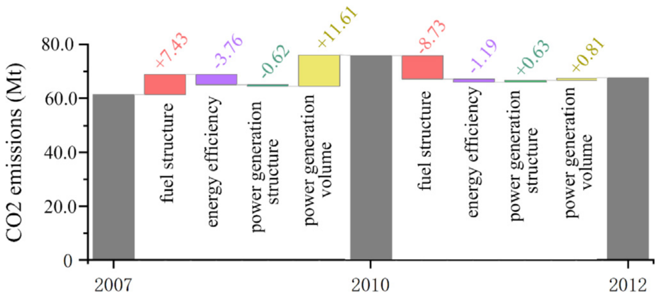

Fig. 2. The LMDI results for Scope 1 emissions in 2007–2012.

produced electricity in Shanghai was 8.30E-04 tons CO_2/kWh in 2007 and 7.62 E-04 tons CO_2/kWh in 2012. During the study period, the carbon emissions intensity of electricity production in Shanghai was greater than the national average. The decline in carbon emissions intensity was partly due to the closure of small thermal power plants with high energy consumption and heavy pollution (Shanghai Government, 2012). Thermal power generation accounted for more than 98% of the electricity that Shanghai produced (National Bureau of Statistics, 2013a), and the efficiency improvement in thermal power plants could promote Scope 1 emissions reductions in Shanghai.

3.2. Scope 2 emissions in Shanghai

Because of its limited power resources, Shanghai relies heavily on electricity supplied by other provinces, and Jiangsu, Zhejiang, Hubei and Sichuan are the major electricity providers to Shanghai. Shanghai's net inflow of electricity through grids was 3.43E+04 GWh in 2007, 3.15 E+04 GWh in 2010 and 4.05 E+04 GWh in 2012. The net inflow of electricity accounted for 32.00%, 24.31% and 29.92% of Shanghai's electricity supply, respectively, in 2007, 2010 and 2012.

Using the network approach to simulate cross-regional electricity flows, we obtain a more accurate Scope 2 emissions accounting inventory for considering the electricity flows through transit regions (Qu et al., 2017b). The results show that the Scope 2 emissions of Shanghai amounted to 81.2 Mt in 2007, 93.1 Mt in 2010 and 82.0 Mt in 2012. According to the SDA results for Scope 2 emissions shown in Fig. 3, the emissions scale and the electricity consumption volume of China's provinces were the main contributors to the growth of Shanghai's Scope 2 emissions from 2007 to 2010, while the structure of electricity transmission and the electricity transmission volume offset some of the growth. The decline in Scope 2 emissions from 2010 to 2012 was mainly caused by the emissions scale of provinces.

The electricity-related carbon emissions net inflow of Shanghai through the grid was 18.9 Mt in 2007 (accounting for 24.44% of Shanghai's Scope 2 emissions), 17.1 Mt in 2010 (accounting for 18.37% of Shanghai's Scope 2 emissions) and 14.4 Mt in 2012 (accounting for 17.62% of Shanghai's Scope 2 emissions). The electricity that Shanghai purchased from other provinces had a lower carbon emission intensity than the electricity that Shanghai produced. The average carbon emissions intensity of purchased electricity was 5.78E-04 tons/kWh in 2007, 5.43 E-04 tons/kWh in 2010 and 3.57 E-04 tons/kWh in 2012. The carbon emissions intensity of electricity that Shanghai supplied was 7.57E-04 tons/kWh in 2007, 7.18 E-04 tons/kWh in 2010 and 6.06 E-04 tons/kWh in 2012, which were smaller than the electricity that Shanghai locally produced. This outcome occurs mainly because Shanghai has purchased a large amount of low carbon emissions intensity electricity from Sichuan and Hubei, which have a large proportion of hydropower. In 2012, Hubei and Sichuan's hydropower generation accounted for 63.24% and 72.64% of the provincial power generation, respectively, while Shanghai's thermal power accounted for 99.60% of its power generation.

In addition, from 2007 to 2012, there was no direct electricity transmission to Shanghai from Shanxi, Anhui, Henan, Chongqing or Shaanxi. However, as shown in Fig. 4, under the network approach, a large amount of electricity-related carbon emissions (1.66 Mt in 2007, 2.25 Mt in 2010, 2.61 Mt in 2012) flowed from these five provinces to Shanghai through transit regions. Therefore, previous studies ignoring electricity flows through transit regions underestimated Shanghai's Scope 2 emissions.

Fig. 5 shows the carbon emissions embodied in the electricity consumed by Shanghai's economic sectors from 2007 to 2012. The total carbon emissions of the 30 sectors was 36.8 Mt in 2007, 43.4 Mt in 2010 and 37.7 Mt in 2012. Among the 30 sectors, the chemical industry (Sector 12), smelting and pressing of ferrous and nonferrous metals (Sector 14), electric power, steam and hot water production and supply (Sector 22), and other service activities (Sector 30) are the four sectors with the largest carbon emissions, accounting for more than half of the total emissions (51.56% in 2007, 53.58% in 2010 and 53.33% in 2012).

3.3. Scope 3 emissions in Shanghai

Shanghai's Scope 3 emissions were 75.7 Mt in 2007, 91.7 Mt in 2010 and 73.4 Mt in 2012. Scope 3 emissions (CEE) consist of two parts: CEE1, the electricity-related carbon emissions caused by Shanghai's final demand; and CEE2, the electricity-related carbon emissions caused by residents' daily lives. CEE1 is the emissions embodied in products and services, and it can flow through regional trade, while CEE2 cannot flow across regions.

3.3.1. CEE1

Shanghai's CEE1 was 65.8 Mt in 2007 (71.87% of CEE1 was from other provinces), 79.6 Mt in 2010 (67.10% of CEE1 was from other provinces), and 62.1 Mt in 2012 (61.49% of CEE1 was from other provinces). This paper considers five factors that influence CEE1: the carbon emissions intensity of electricity, electricity consumption per unit output (electricity efficiency), production technology, consumption structure and consumption volume.

As shown in Fig. 6, CEE1 increased by 13.8 Mt from 2007 to 2010. The consumption volume, consumption structure and production technology were the main driving forces for the growth of CEE1, while the reduction in carbon emissions intensity and electricity consumption per unit output offset some of the growth in CEE1. As a major contributor to the CEE1 increase, consumption volume (final demand) in Shanghai increased by 16.97% from 2007 to 2010. From 2010 to 2012, CEE1 decreased by 17.5 Mt. The carbon emissions intensity, electricity consumption per unit output, production technology and consumption structure were the driving factors for the decline in CEE1, and the electricity consumption volume had a positive impact on the growth of CEE1.

As shown in Fig. 7, Shanghai had a net inflow of electricity-related carbon emissions in regional trade from 2007 to 2012. The net inflow of emissions in Shanghai was 28.7 Mt (accounting for 37.85% of Shanghai's Scope 3 emissions) in 2007, 28.0 Mt (accounting for 30.52% of Shanghai's Scope 3 emissions) in 2010 and 20.2 Mt (accounting for 27.55% of Shanghai's Scope 3 emissions) in 2012. As shown in Fig. 7, Hebei, Inner Mongolia, Jiangsu, Zhejiang and Shandong were the main contributors to Shanghai's net inflow of electricity-related carbon emissions. These five provinces explained 55.53% of Shanghai's emissions net inflow in 2007, 60.39% in 2010 and 62.71% in 2012.

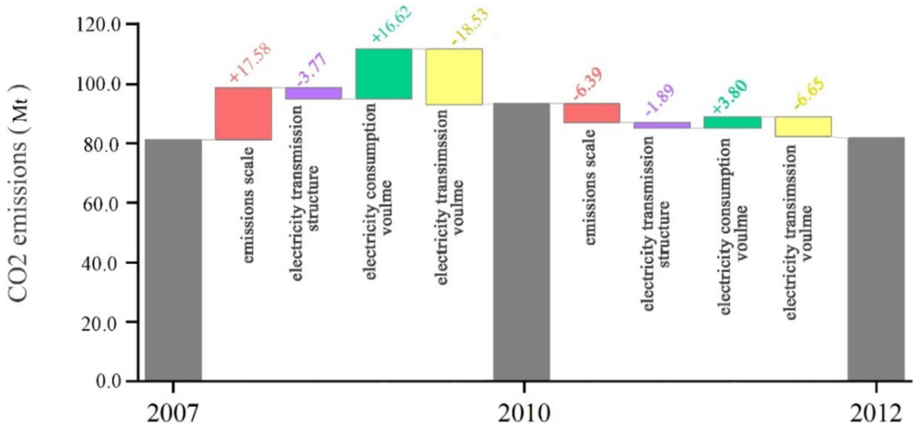

Fig. 3. The SDA results for Scope 2 emissions from 2007 to 2012.

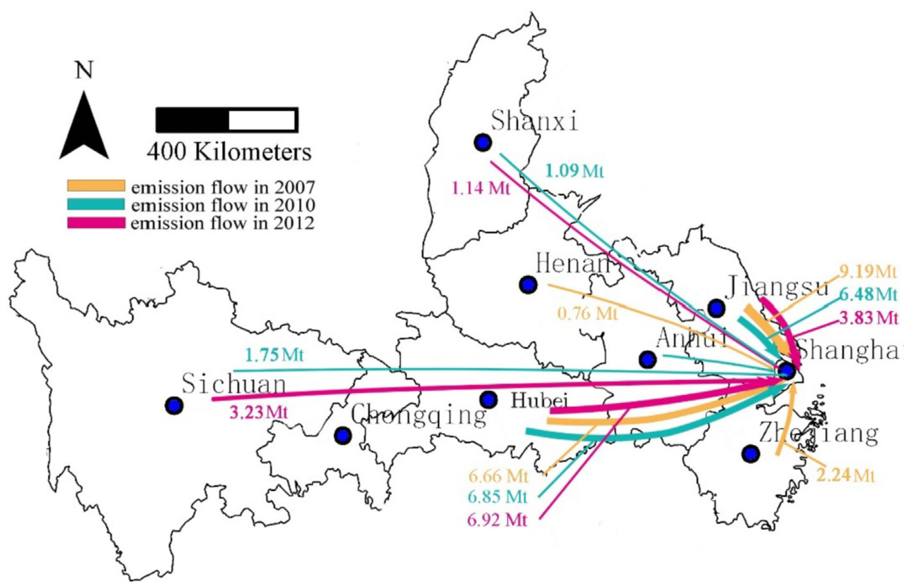

Fig. 4. The net inflow of electricity-related carbon emissions through power grids from 2007 to 2012 (emission flows less than 0.5 Mt are not presented in the figure).

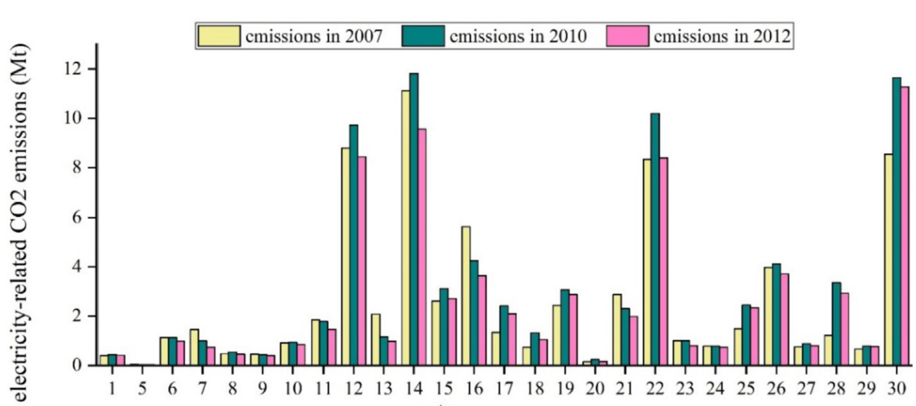

Fig. 5. Carbon emissions embodied in the electricity consumed by sectors in Shanghai from 2007 to 2012 (Sectors 2, 3 and 4 with emissions less than 1.00E+04 tons are not presented; detailed information on the 30 sectors can be found in the appendix).

3.3.2. CEE2

Shanghai's CEE2 was 9.93 Mt in 2007, 12.1 Mt in 2010 and 11.3 Mt in 2012. We analyzed 3 factors that influence CEE2: the carbon intensity of electricity, per capita electricity consumption and the population of Shanghai.

As shown in Fig. 6, CEE2 increased by 2.21 Mt from 2007 to 2010.

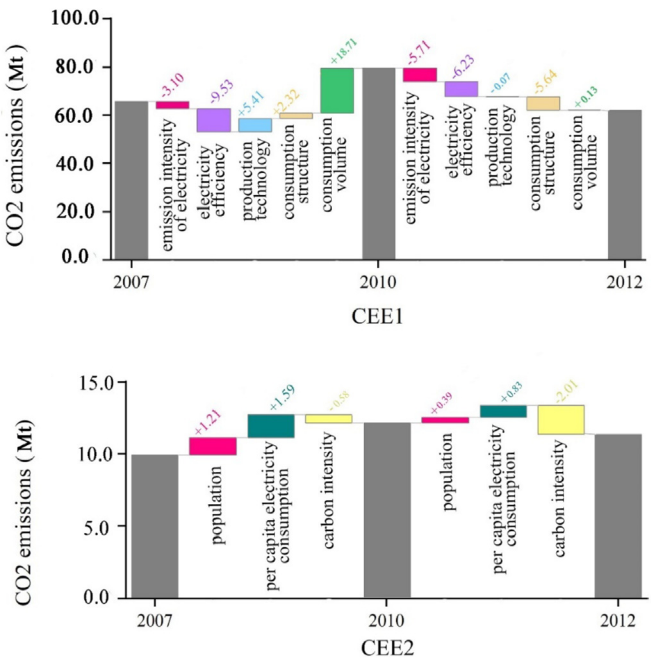

Fig. 6. The SDA results for Scope 3 emissions (CEE1 and CEE2).

The population growth and per capita electricity consumption were the driving factors for CEE2 growth, while the reduction in carbon intensity offset the growth of CEE2. From 2010 to 2012, Shanghai's CEE2 declined by 0.79 Mt, mainly caused by a reduction in the carbon intensity of electricity.

3.4. The electricity-related carbon emissions embodied in exports

As an international metropolis, Shanghai exports a large number of products directly and indirectly. In 2007, Shanghai's total export value was 1.13E+03 billion yuan, and 54.5 Mt of electricity-related carbon emissions were embodied in the exports. In 2010, Shanghai had a total export value of 1.03E+03 billion yuan with 48.4 Mt of embodied electricity-related carbon emissions. In 2012, Shanghai had a total export value of 1.45 E+03 billion yuan with 49.6 Mt of embodied electricity-related carbon emissions. Notably, these electricity-related carbon emissions did not come entirely from Shanghai.

The total export value of China was 9.55E+03 billion yuan with total embodied electricity-related carbon emissions of 657.6 Mt in 2007, 1.09E+04 billion yuan with total embodied electricity-related carbon emissions of 621.7 Mt in 2010 and 1.31E+04 billion yuan with total embodied electricity-related carbon emissions of 630.3 Mt in 2012. Shanghai accounted for 5.50%, 4.79% and 4.78% of the total emissions embodied in China's exports in 2007, 2010 and 2012, respectively.

4. Discussion and policy implications

4.1. Comparison of electricity-related carbon emissions under different scopes

As one of the most developed cities in China, Shanghai has a huge demand for electricity. Shanghai cannot produce adequate electricity to meet local demand, so it must purchase considerable amounts of electricity from other provinces every year. As electricity flows into Shanghai, the carbon emissions embodied in electricity also flow into Shanghai; therefore, Shanghai has larger Scope 2 emissions than Scope 1 emissions. As shown in Table 1, the Scope 2 emissions of Shanghai were 1.32 times the Scope 1 emissions in 2007, 1.22 times in 2010 and 1.21 times in 2012.

The carbon emissions intensity of the electricity Shanghai produced was greater than the electricity that Shanghai supplied after inter-provincial electricity exchange. The carbon emissions intensity of the former was 1.10 times, 1.21 times and 1.26 times that of the latter in 2007, 2010 and 2012, respectively, because Shanghai bought a large amount of electricity with a lower emissions intensity from Hubei and Sichuan. Hubei and Sichuan have a high

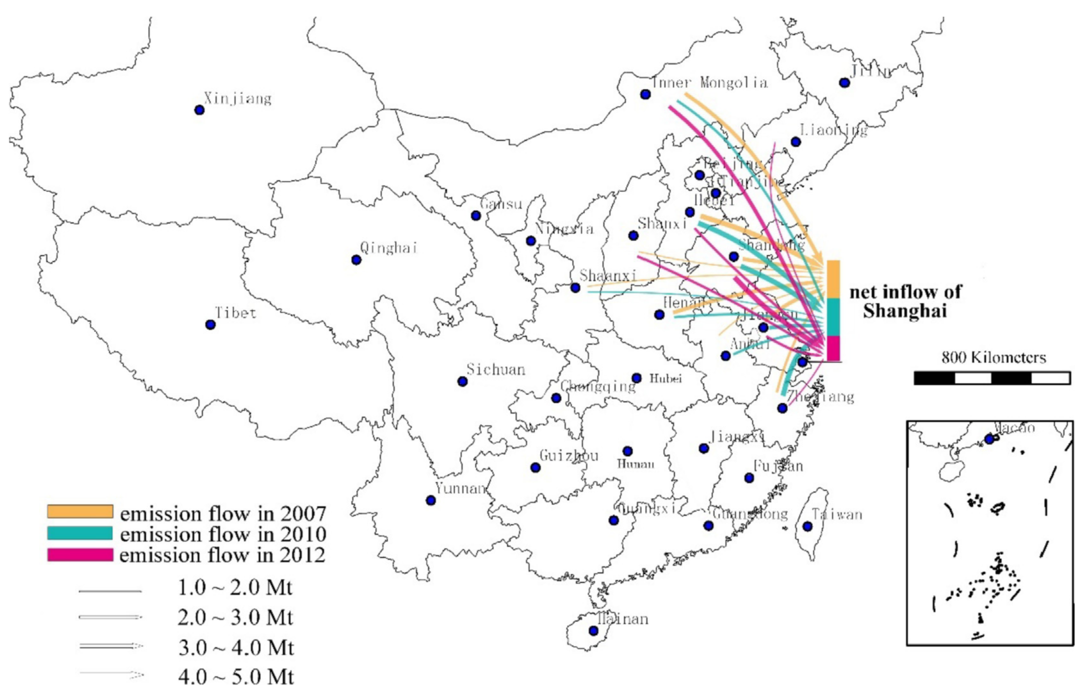

Fig. 7. Shanghai's net inflow of electricity-related carbon emissions through regional trade (emissions flows less than 1.0 Mt are not presented).

Table 1
Electricity-related carbon emissions in Shanghai from 2007 to 2012.

Year	Scope 1 (Mt)	Scope 2 (Mt)	Scope 3 (Mt)
2007	61.36	81.20	75.72
2010	76.00	93.10	91.74
2012	67.53	81.98	73.44

proportion of hydropower generation, so the electricity produced in these two regions has a very low carbon intensity. Shanghai is dominated by thermal power generation, and the electricity produced has a high carbon emissions intensity. The average emissions intensity of Shanghai's power supply declines after Shanghai buys electricity from Hubei and Sichuan.

Because of regional trade, a region can reduce local Scope 3 emissions by buying products from other regions. The Scope 2 emissions of a region will be equal to its Scope 3 emissions if there is no regional trade. With its very high per capita income, Shanghai can buy more products in regional trade to satisfy local final demand; therefore, Shanghai tends to have a net inflow of electricity-related carbon emissions in regional trade. Shanghai's per capita Scope 3 emissions were 2.65 times the national average in 2007, 2.18 times the national average in 2010 and 1.45 times the national average in 2012. Regions with high income levels, such as Shanghai, should focus on promoting low-carbon lifestyles and consumption habits.

4.2. Electricity-related carbon emissions through grids and through regional trade

Electricity-related carbon emission flows through grids (DEFlow) can directly affect regional Scope 2 emissions, while electricity-related carbon emission flows through regional trade (EEFlow) can affect regional Scope 3 emissions. Analysis and comparison of the characteristics of the two types of electricity-related carbon emissions can help us to understand the regional electricity-related carbon emissions more deeply and to develop more effective emission mitigation policies.

Shanghai had net inflows in both DEFlow and EEFlow. For both flows, the emissions net inflow of Shanghai declined from 2007 to 2012, which could be explained by China's increasingly cleaner power generation. The average carbon emissions of electricity in China fell 5.01% from 2007 to 2012, so the products that Shanghai consumed tended to have lower carbon emissions.

Comparing Figs. 4 and 7 reveals that the two types of electricity-related carbon emissions flows have different characteristics. Shanghai's DEFlow was concentrated in a few regions, mainly in the electricity providers of Shanghai (Jiangsu, Zhejiang, Hubei, and Sichuan), and explained 91.14% of Shanghai's net inflows of DEFlow in 2007, 88.21% in 2010 and 96.81% in 2012. The high cost of power infrastructure construction limits the electricity transmission between regions, resulting in fewer electricity suppliers in Shanghai. The concentrated sources of Shanghai's DEFlow indicate that Shanghai's Scope 2 emissions can be effectively reduced by controlling the emissions intensity of electricity in the aforementioned provinces. Conversely, the sources of Shanghai's EEFlow are relatively scattered. In addition to the major contributors, such as Hebei, Inner Mongolia, Jiangsu, Zhejiang and Shandong, there was a large amount of emissions flowing to Shanghai from Shanxi, Henan, Guangdong, Guizhou, Liaoning, Shaanxi, Ningxia and Gansu. The scattered sources of Shanghai's EEFlow cause certain difficulties for Scope 3 emissions reduction in Shanghai.

4.3. The driving forces of Shanghai's electricity-related carbon emissions from 2007 to 2012

We decomposed the changes in the three scope emissions in Shanghai, which could help to identify the main driving factors of the electricity-related carbon emissions and to propose more specific emissions-mitigation suggestions.

The LMDI results show that improvement of fuel structures helped to reduce Shanghai's Scope 1 emissions, while the power generation volume contributed to the emissions increase. The SDA results for Scope 2 emissions show that electricity consumption volume had a positive impact on the growth of Shanghai's Scope 2 emissions from 2007 to 2012, while the electricity transmission structure and the transmission scale offset part of the growth of Scope 2 emissions. This finding indicates that China's inter-provincial electricity transmission could help to reduce regional Scope 2 emissions, at least for Shanghai. The emissions scale of China's provinces had a positive impact on the growth of Scope 2 emissions in 2007–2010, while the impact of the factor reversed in 2010–2012. Since the emissions scale can be influenced by many factors, such as the power generation structure and the fuel mix, further research is needed to clarify the mechanism of the impact of the emissions scale on Scope 2 emissions.

As mentioned above, we divide Scope 3 emissions (CEE) into two parts: CEE1 and CEE2. From 2007 to 2012, both the carbon emissions intensity of electricity and the electricity efficiency of the sectors significantly mitigated CEE1. The improvement of China's power generation technology and the increase in the proportion of clean energy power generation, such as hydropower, have promoted the reduction in the carbon emissions intensity of electricity. Shanghai's expenditures on consumption and investment increased by 31.13% from 2007 to 2012, and it was a major driving force promoting the growth of CEE1. During the same time, the impact of production technology and consumption structure on CEE1 reversed, reflecting the improvement of Shanghai's consumption habits and the progress of energy savings in China's economic sectors (Mi and Coffman, 2019; Li et al., 2019; Zhou et al., 2020). The growth in Shanghai's population and per capita electricity consumption led to the growth of Shanghai's CEE2, while the decline in the emissions intensity of electricity that Shanghai supplied offset part of the growth from 2007 to 2012.

In summary, the Scope 1 emissions could be reduced by improving fuel structure, Scope 2 emissions could be reduced by optimizing the electricity transmission structure and transmission scale, and Scope 3 emissions could be reduced by promoting the formation of low-carbon consumption habits and industrial upgrading.

5. Conclusion

Carbon emissions related to electricity are an important contributor to global warming, and our study has established a multi-scope electricity-related carbon emissions accounting framework to provide comprehensive information about electricity-related carbon emissions reductions. The main results are as follows: (1) there are large differences in the emissions accounting results for the 3 scopes of emissions in Shanghai; (2) Shanghai has a large-scale electricity-related carbon emissions net inflow through power grids and regional trade; and (3) fuel structure improvement can help to reduce Scope 1 emissions; electricity transmission among regions in China is conducive to the reduction in Shanghai's Scope 2 emissions; and the improvement of China's electricity efficiency, the decline in the carbon emissions intensity of electricity and the optimization of consumption structure are the main driving factors for the reduction in Scope 3 emissions.

Because China has large-scale cross-regional electricity transmission and inter-regional trade, policies that do not consider Scope 2 and Scope 3 emissions in the region will lead to emissions leakage. Therefore, emissions reduction policies should be based on multi-scope accounting results. For example, the government should actively develop clean energy, such as hydropower, wind power and solar power, and should optimize the construction of power transmission lines to avoid abandoning light and wind. In addition, the government can promote enterprises to improve the energy efficiency through means such as electricity prices. Conversely, we must adhere to the concept of green and low-carbon living and avoid wasting electricity in daily life.

Due to data availability, our study does not consider electricity-related carbon emissions embodied in imported products, and future research will include this topic in a model.

Author contribution statement

Wendong Wei: Conceptualization, Methodology, Resources, Writing - Original Draft, Writing - Review & Editing, Supervision, Funding acquisition.

Pengfei Zhang: Methodology, Software, Writing - Original Draft, Writing - Review & Editing.

Mingtao Yao: Writing - Review & Editing, Supervision.

Min Xue: Methodology, Software, Writing - Original Draft.

Jiawen Miao: Data Curation, Visualization.

Bin Liu: Writing - Review & Editing.

Fei Wang: Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Sector information for multi-regional input-output analysis.

Code	Sector category
Sector 1	*Farming, Forestry, Animal Husbandry, and Fishery (Agriculture)*
Sector 2	*Coal Mining and Dressing*
Sector 3	*Petroleum and Natural Gas Extraction*
Sector 4	*Ferrous and Nonferrous Metals Mining and Dressing*
Sector 5	*Nonmetal and Other Minerals Mining and Dressing*
Sector 6	*Food Production, Food Processing and Tobacco Processing*
Sector 7	*Textiles*
Sector 8	*Garments and Other Fiber Products, Leather, Furs, Down and Related Products*
Sector 9	*Timber Processing, Bamboo, Cane, Palm & Straw Products, Furniture Manufacturing*
Sector 10	*Papermaking and Paper Products, Printing and Record Medium Reproduction, Cultural, Educational and Sports Articles*
Sector 11	*Petroleum Processing, Coking, and Nuclear Fuel Processing*
Sector 12	*Chemical Industry*
Sector 13	*Nonmetal Mineral Products*
Sector 14	*Smelting and Pressing of Ferrous and Nonferrous Metals*
Sector 15	*Metal Products*
Sector 16	*Ordinary Machinery, Equipment for Special Purposes*
Sector 17	*Transportation Equipment*
Sector 18	*Electric Equipment and Machinery*
Sector 19	*Electronic and Telecommunications Equipment*
Sector 20	*Instruments, Meters, Cultural and Office Machinery*
Sector 21	*Other Industrial Activities*
Sector 22	*Electric Power, Steam and Hot Water Production and Supply*
Sector 23	*Water and Gas Production and Supply*
Sector 24	*Construction*
Sector 25	*Transport and Storage Services*
Sector 26	*Wholesale and Retail Trade*
Sector 27	*Hotels and Catering Services*
Sector 28	*Leasing and Business Services*
Sector 29	*Research and Experimental Development*
Sector 30	*Other Service Activities*

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