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ACCOUNTING FOR BEIJING'S ELECTRICITY-RELATED CARBON EMISSIONS FROM MULTIPLE PERSPECTIVES AND COMPARING TEMPORAL TRENDS

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ABSTRACT

The city and power sectors are major contributors to global carbon emissions. However, there is insufficient research on carbon emission accounting of the urban power sector, and electricity-related carbon emission flows through regional trade are ignored. Using the IPCC method, the network approach and the multiregional input-output model, our study quantifies Beijing's production-based, supply-based, and consumption-based electricity-related carbon emissions between 2007 and 2012. The results show the following. (1) Both supply-based and consumption-based electricity-related carbon emissions were more than three times that of production-based electricity-related carbon emissions. (2) Beijing's production-based electricity-related carbon emissions fell by 4.6% (from 1.73E+07 tons in 2007 to 1.65E+07 tons in 2012), while the supply-based and consumption-based electricity-related carbon emissions increased by 29.4% (from 5.95E+07 tons in 2007 to 7.70E+07 tons in 2012) and 7.3% (from 6.88E+07 tons in 2007 to 7.38E+07 tons in 2012), respectively. (3) The electricity produced locally in Beijing became cleaner (the carbon emission intensity of electricity Beijing produced decreased from 0.76 kg/kWh to 0.57 kg/kWh), but the carbon emission intensity of the electricity Beijing actually used after buying electricity from other provinces increased (the supplied-based carbon emission intensity increased from 0.88 kg/kWh to 0.91 kg/kWh). This study provides a framework for accounting for the electricity-related carbon emissions of different aspects of the city, which can help to allocate the environmental responsibilities between regions and improve the efficiency of China's emission reduction policies.

Keywords: Beijing, power sector, electricity-related carbon emission, multiple perspective, multiregional input-output model

NOMENCLATURE

Abbreviations	
PEE	Production-based electricity-related carbon emissions
SEE	Supply-based electricity-related carbon emissions
CEE	Consumption-based electricity-related carbon emissions

1. INTRODUCTION

Global climate change caused by greenhouse gas emissions (mainly CO_2 emissions) poses a great challenge to human society. At the Paris Climate Conference in 2015, China proposed its Intended Nationally Determined Contributions in which China will achieve a 60%-65% CO_2 emissions reduction per unit of GDP in 2030 [1]. Starting in areas with large emission reduction potential, we can improve the efficiency of emission reduction work. Cities, which are major contributors to global carbon emissions, have explained 85% of China's carbon emissions; thus, cities are considered to be a key area for reduction of China's carbon dioxide emissions [2-4]. At the same time, the power sector, which explained more than 45% of China's national carbon emissions in 2016 [5], is the world's largest carbon emitter [6]. Populations and industries are concentrated

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in cities, and cities consume a large quantity of electricity [7]. Therefore, cities' power sector has significant potential for emission reduction.

CO_2 emission accounting is the basis for implementing emission reduction measures, developing national emission reduction strategies, and assessing the effectiveness of emission reduction policies [8-10]. Due to the existence of cross-regional trade of energy, products and services, regional CO_2 emissions accounted from different perspectives may vary greatly [10-12] and may lead to carbon leakage when only a single aspect of CO_2 emissions is considered [13]. There are already many studies accounting for carbon emissions from the urban power sector from different perspectives. These studies can be divided into two types: production-based electricity-related carbon emissions (PEE) accounting (accounting for carbon emissions from local power generation) [9, 11] and supply-based electricity-related carbon emissions (SEE) accounting (accounting for carbon emissions embodied in the local electricity supply after regional electricity exchange) [14-16]. However, existing studies do not include consumption-based electricity-related carbon emissions (CEE) accounting (accounting for carbon emissions from electricity embodied in products and services used for local final demand).

We chose Beijing, the political, economic, and cultural center of China, as the research object. Beijing is a highly developed metropolis; according to the National Bureau of Statistics, Beijing had a population of 21.54 million, and Beijing's per capita GDP in 2018 was 140,211 yuan per person, the highest ranking in China [17]. Our study uses the IPCC carbon inventory method [18], the network approach [15] and the input-output model [19, 20] to account for Beijing's PEE, SEE and CEE, respectively, from 2007 to 2012. We also analyze the evolution characteristics of Beijing's electricity-related carbon emissions. Some policy recommendations are provided in our discussion. Our work will help to improve the effectiveness of China's emission reduction policies.

The remainder of our study is organized as follows. The methods and data sources of this paper are introduced in section 2 Section 2, the results and discussion are presented in Section 3, and Section 4 shows the conclusions of this paper.

2. METHODS AND DATA SOURCES

2.1 Methods

2.1.1 Using the IPCC carbon inventory method to account for PEE

We use the carbon inventory method provided by the Intergovernmental Panel on Climate Change to account for the carbon emissions caused by regional power generation (PEE). The PEE of a region where *m* kinds of fuels are used for power generation can be calculated as follows:

$$PEE = \sum_{k=1}^{m} ef_k \cdot fm_k \tag{1}$$

where ef_k is the carbon emission factor of the *kth* fuel, and fm_k is the quantity of the *kth* fuel used.

2.1.2 Using the network approach to account for SEE

Electricity produced in different regions has different carbon emission intensities. When this electricity flows through the connected grids, the carbon intensity of regional electricity supplied to local residents and industries is difficult to measure. This paper uses the network method proposed by Qu et al. [14] to track the source of electricity and calculate the carbon emissions intensity of local electricity supplies.

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. The relationship between the region's electricity flows can be described as follows:

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

where t_i is the total electricity flow of region *i; p_i* is the electricity produced in region *i*; $F_{i,j}$ is the amount of electricity flows from region *i* to *j*; and c_i is the electricity consumed by region *i*.

The direct outflow coefficient matrix *B* can be defined as follows:

$$B = \hat{t}^{-1}F = \begin{bmatrix} 0 & \frac{F_{1,2}}{t_1} & \cdots & \frac{F_{1,n}}{t_1} \\ \frac{F_{2,1}}{t_2} & 0 & \cdots & \frac{F_{2,n}}{t_2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{F_{n,1}}{t_n} & \frac{F_{n,2}}{t_n} & \cdots & 0 \end{bmatrix} \tag{3}$$

where the element *B(i,j)* in the *B* matrix represents the proportion of the electricity flows from region *i* to region *j* to the total electricity flow in region *i*. *t* is a diagonal matrix and *t(i,j)*=0 if *i≠j* and *t(i,j)=ti* if *i=j*.

The total outflow coefficient matrix G describes the direct electricity flows and indirect electricity flows between nodes and can be expressed as follows:

$$G=[I-B]^{-1}=I+B+B^2+B^3+\cdots \quad (4)$$

where I is the identity matrix, which represents the power flow inside the grid; B indicates the flow of electricity between regions without passing through the intermediate region; B_2 represents the electricity flows through one intermediate region; and B_3 indicates the electricity flows through two intermediate regions.

To link the regional power generation and electricity consumption, the production-consumption matrix H can be defined as followed:

$$H=G\hat{c}\hat{t}^{-1} \quad (5)$$

where $\hat{c}$ is a diagonal matrix with $c(i,i)=c_i$, $H(i,j)=G_{ij}\cdot c_j/t_j$ and represents the proportion of the electricity consumed by region j from region i to the total electricity region j consumed.

Using the PEE we have already obtained, we can link the CO_2 emissions caused by electricity generation to regional electricity consumption using the following equation:

$$E^C=E^G H \quad (6)$$

where the element $E^C_{i,j}$ in matrix E^C represents the electricity-related CO_2 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 $i\neq j$.

Using the matrix E^C in equation (6), the SEE of region i can be expressed as:

$$SEE=\sum_{j=1}^{n} E^C_{i,j} \quad (7)$$

2.1.3 *Using the multiregional input-output (MRIO) model to account for CEE*

In the MRIO model, the embodied electricity-related carbon emission intensity E can be expressed as:

$$E=C(X-Z)^{-1} \quad (8)$$

where C is a row vector composed of the sectoral SEE; Z is the intermediate flow matrix in MRIO; X is a diagonal matrix whose element $X(i,i)$ is the total output of sector i.

The CEE of region i can be expressed as:

$$CEE=E\times Y_i \quad (9)$$

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

Furthermore, we can trace the source of regional CEE using the following equation:

$$E_i=C_i(X-Z)^{-1} \quad (10)$$

where E_i is the electricity-related carbon emissions embodied in one unit of product from region i and C_i=[(0, … 0), …($c_{i,1}$, $c_{i,2}$, …$c_{i,30}$), …(0, …0)].

The electricity-related carbon emissions that flow from region i to region j, $CEEF_{i,j}$, can be expressed as follows:

$$CEEF_{i,j}=E_i\times Y_j \quad (11)$$

2.2 *DATA SOURCES*

In the process of calculating PEE, we use the provincial energy balance tables from the 2007, 2010, and 2012 China Energy Statistical Yearbooks [21]. The carbon emission coefficient of raw coal used in this paper comes from the research of Liu et al. [22]. The emission factors of other fuels are derived from the World Resources Institute (WRI) [23]. The provincial electricity exchange data used in the calculation of SEE are from the China Electricity Council's 2007, 2010 and 2012 Electricity Industry Statistics Compilations [24], and the data on provincial electricity generation and consumption are derived from China's Energy Statistics Yearbook [21]. In the process of calculating CEE, we used the 2007, 2010, and 2012 Chinese multiregional input-output tables compiled by Liu et al. [25-27].

3. RESULTS AND DISCUSSION

3.1 The PEE of Beijing

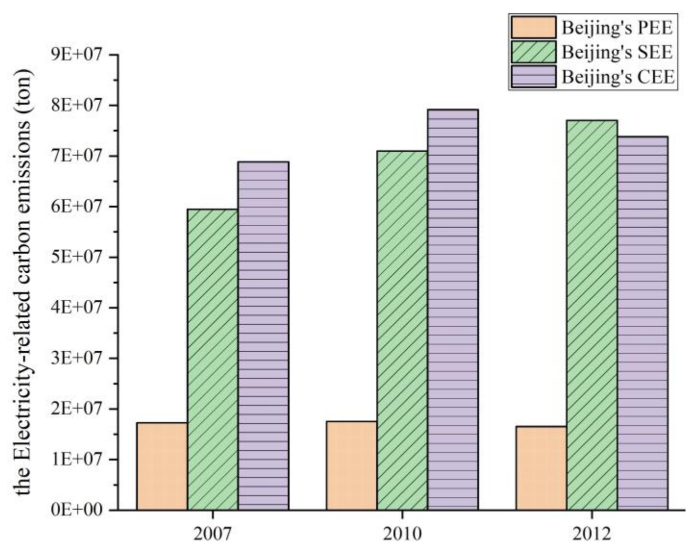

Fig 1 Beijing's electricity-related carbon emissions

The growth rate of Beijing's power generation was lower than the national growth rate during 2007 – 2012. Beijing's power generation accounted for 0.7% (2.28E+10 kWh), 0.64% (2.69 E+10 kWh) and 0.58% (2.91 E+10 kWh) of national total power generation in 2007, 2010 and 2012, respectively. While Beijing's power generation grew slowly, as shown in Figure 1, Beijing's PEE decreased from 1.73 E+07 tons in 2007 to 1.65 E+07 tons in 2012. As shown in Table 1, the carbon emission intensity of electricity produced in Beijing decreased from 0.76 kg/kWh to 0.58 kg/ kWh, which means that the electricity produced in Beijing became cleaner. This finding may be explained by the following two factors. First, the energy structure changed: according to the China Energy Statistical Yearbook, the raw coal consumed by Beijing's power sector had a 20.4% decrease (8.17E+06 tons of raw coal in 2007 and 6.50E+06 tons in 2012). Coal-fired power generation is one of the most carbon-intensive power generation methods [28] and the reduction of coal-fired power generation is conducive to the carbon emission reduction in the power generation. Second, Beijing closed small thermal power plants with low efficiency of power generation, leading to the efficiency improvement in Beijing's power generation.

Table 1 The carbon emission intensity of Beijing's electricity (kg/kWh)

year	the carbon emission intensity of electricity Beijing produced	the carbon emission intensity of electricity Beijing supplied after regional electricity exchange
2007	0.76	0.88
2010	0.65	0.85
2012	0.57	0.91

3.2 The SEE of Beijing

From 2007 to 2012, Beijing's SEE was more than three times greater than its PEE (3.45 times in 2007, 4.05 times in 2010, and 4.66 times in 2012). Beijing's SEE had a continuous growth from 5.95 E+07 tons in 2007 to 7.70 E+07 tons in 2012, and the carbon emission intensity of Beijing's SEE also increased from 0.88 kg/kWh in 2007 to 0.91 kg/kWh in 2012. Beijing's carbon emission intensity of SEE was higher than PEE mainly because the electricity Beijing purchased from other provinces had a higher carbon emission intensity than the electricity produced locally. As shown in Figure 2, Inner Mongolia and Shanxi were the main contributors to Beijing's SEE, and these two provinces accounted for 92.9% (in 2007), 82.8% (in 2010), and 95.4% (in 2012) of Beijing's SEE originating from other provinces. Electricity produced in Inner Mongolia and Shanxi has a high carbon emission intensity due to the dominant position of coal fire power generation in these two provinces. It is worth noting that there was almost no electricity or electricity-related carbon emissions flowing from Beijing to other provinces through the grids from 2007 to 2012.

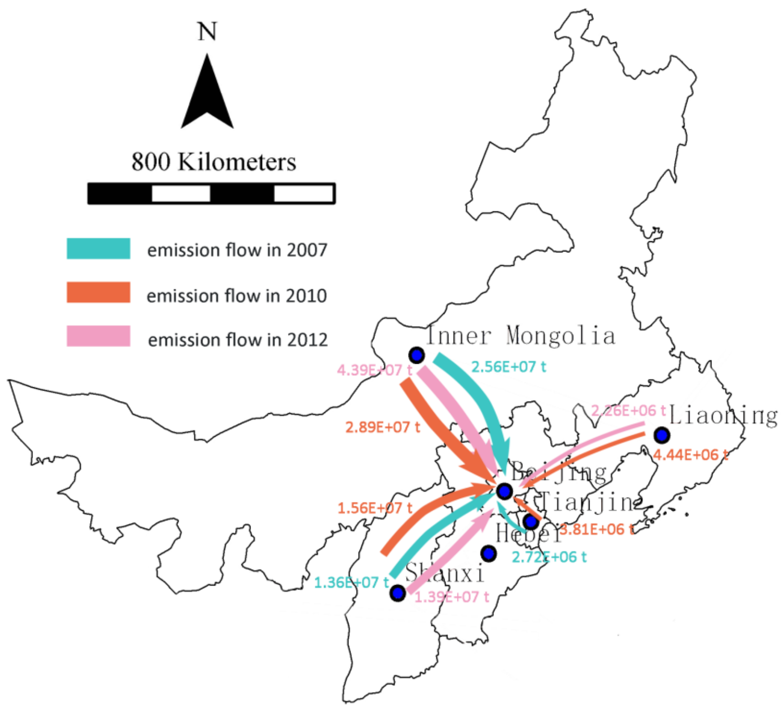

Fig 2 Beijing's electricity-related carbon emission inflows through power grids (emission inflows less than 2.00E+06 tons are not presented)

In addition, many of the products and services produced in Beijing are exported, so there is a large amount of electricity-related carbon emissions embodied in exports flowing from Beijing to other countries. In 2007, 20.4% of Beijing's SEE was exported, 14.6% in 2010 and 26.4% in 2012. The decline of SEE used for export in 2010 may be explained by the global financial crisis, which greatly impacted China's exports.

3.3 The CEE of Beijing

CEE includes electricity-related carbon emissions embodied in electricity used by local residents and products and services used to satisfy local final demand. Beijing's CEE increased by 7.3% from 6.88E+07 tons in 2007 to 7.38 E+07 tons in 2012. Beijing's per capita CEE was much higher than the national average and was gradually declining. Therefore, the gap with the national average is narrowing: Beijing's per capita CEE was 4.11 tons in 2007 (2.95 times the national average) and 3.57 tons in 2012 (1.66 times the national average). In the future, Beijing should pay more attention to promoting the formation of low-carbon consumption habits and lifestyles to reduce CEE.

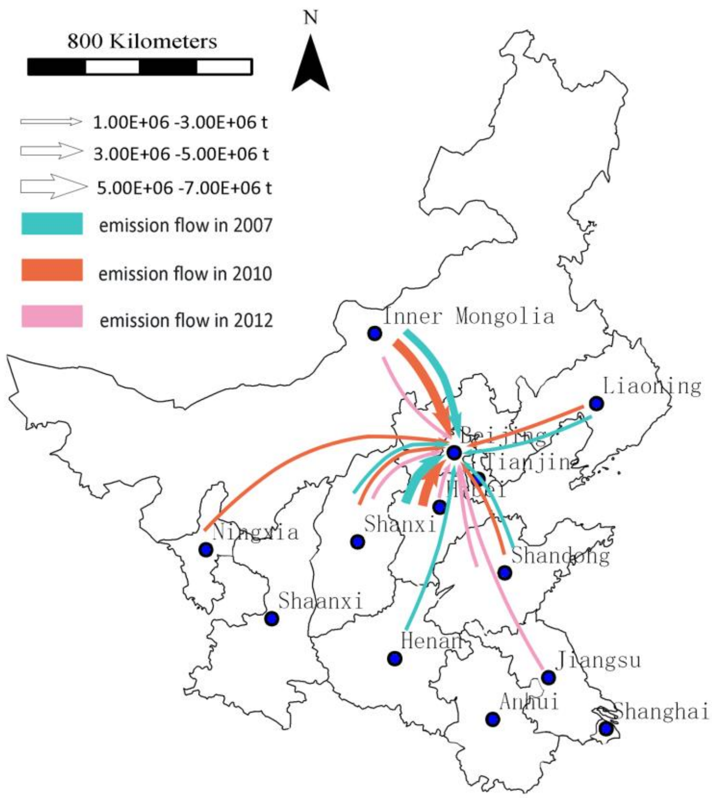

Fig 3 Beijing's net inflow of electricity-related carbon emissions through regional trade (emissions inflows less than 1.00E+06 tons are not presented)

Regional trade can directly affect regional CEE. As a city with the highest per capita GDP in China, Beijing can buy more products than they produce. Therefore, Beijing tends to have a net inflow of electricity-related carbon emissions in regional trade. Beijing had 2.17E+07 tons, 2.15 E+07 tons and 1.12 E+07 tons net inflow of electricity-related carbon emissions through domestic trade in 2007, 2010 and 2012, respectively. As shown in Figure 3, Hebei, Shanxi, Inner Mongolia, and Shandong are the major contributors to Beijing's net inflow of electricity-related carbon emissions through regional trade. These four provinces accounted for 62.9% (in 2007), 74.0% (in 2010) and 72.3% (in 2012) of Beijing's net inflow emissions.

In addition, with the upgrading industrial structure in Beijing, many energy-intensive industries are migrating from the city to other provinces, and Beijing can satisfy local demand for energy-intensive products through regional trade, which is actually a carbon leakage. Therefore, Beijing should assume more responsibilities in China's emission reduction strategy.

4. CONCLUSIONS

This paper accounts for Beijing's electricity-related carbon emissions from 2007 to 2012 from multiple perspectives. The results show the following:

(1) As a highly developed city, the electricity Beijing produces cannot meet its power demand; therefore, Beijing needs to buy electricity from other provinces, which leads to a large amount of electricity-related carbon emissions flowing into Beijing through the grid.

(2) With a high per capita income, Beijing consumes more products than it produces. Therefore, Beijing has a net inflow of electricity-related carbon emissions through regional trade.

(3) The carbon emission intensity of electricity produced in Beijing decreased, but the carbon emission intensity of electricity supplied in Beijing after electricity exchange through the grids increased.

The existing emission reduction policies are mainly production-based [29], which results in an underestimation of Beijing's environmental responsibility. We suggest that the central government should consider the carbon emission accounting results from different perspectives when allocating the emission reduction responsibilities to avoid carbon leakage. Specifically, Beijing should assume more environmental responsibilities.

Our study did not consider the import and export of electricity when calculating SEE and did not consider the carbon emissions embodied in imports when calculating CEE. Future research will incorporate these factors into the model to obtain more accurate results.

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