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Interprovincial Metal and GHG Transfers Embodied in Electricity Transmission across China: Trends and Driving Factors

Yawen Han [1], Wanli Xing [2,*], Hongchang Hao [3], Xin Du [1] and Chongyang Liu [4]

[1] School of Economics and Management, Zhejiang Sci-Tech University, No. 928, 2nd Street, Gaojiaoyuan District of Qiantang, Hangzhou 310018, China; yawenhan@zstu.edu.cn (Y.H.); dux19@zstu.edu.cn (X.D.)
[2] Development Research Center of China Geological Survey, No. 45 Fuwai Street, Xicheng District, Beijing 100037, China
[3] School of Earth Sciences and Resources, China University of Geosciences, 29 Xueyuan Road, Haidian District, Beijing 100083, China; 3001200122@cugb.edu.cn
[4] Institute for Energy Development of China Southern Power Grid Company, No. 11 Kexiang Road, Huangpu District, Guangzhou 510700, China; liuzy6@csg.cn
* Correspondence: xwanli@mail.cgs.gov.cn

Abstract: With the increasing proportion of low-carbon power in electricity generation mix, power generation will be transformed from carbon-intensive to metal-intensive. In this context, metal and GHG transfers embodied in electricity transmission of China from 2015 to 2019 are quantified by the Quasi-Input-Output model. Combined with complex network theory, we have distinguished whether metal and GHG transfers show different trends as electricity trade changes. Driving factors contributing to forming the metal and GHG transfers are also explored based on the Quadratic Assignment Procedure. The results show that the electricity trade change has strengthened the metal transfer network significantly, while several key links in the GHG transfer network have weakened. Moreover, we find provincial differences in low-carbon electricity investment contributing to the metal transfer while affecting the GHG transfer little. The above facts imply an expanding embodied metal transfer in the future and shed light on policy making for power system decarbonization.

Keywords: metal transfer; GHG transfer; quasi-input-output model; quadratic assignment procedure; power system decarbonization

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1. Introduction

Global warming is one of the most significant environmental issues the Earth is facing. In this context, the Chinese government announced that it would pledge to achieve the "carbon neutrality" goal by 2060. The realization of "carbon neutrality" will inevitably require deep decarbonization of the power system [1]. To reach net zero emissions in the power system, wind and photovoltaic power generation should account for more than 60% of all power generation [2,3]. However, it is worth noting that wind and photovoltaic power technologies use much larger amounts of copper, nickel, chromium, zinc, etc. than traditional fossil fuel-based power systems [4]. Therefore, many scholars believe that under the goal of "carbon neutrality", the power system will be transformed from carbon-intensive to metal-intensive [5–7]. The energy sector will become the leading consumer of metallic minerals. For example, low-carbon energy technologies' share in global copper demand will be over 40% by 2040, and this proportion will be 60–70% for nickel [4].

In China, many provinces have outsourced carbon emissions to coal-rich provinces by purchasing electricity, so that considerable carbon transfer embodied in electricity trade can be observed among provinces [8]. The analyses of embodied carbon transfer are helpful for the fair distribution of carbon reduction responsibility. Specifically, the price of purchased electricity does not include all external costs incurred by carbon emissions [9]. Therefore, the responsibility for carbon emission reduction being fully borne by electricity producing regions is unfair [10–12]. As the power system is decarbonizing (from carbon-intensive to metal-intensive), the environmental inequality problem related to embodied carbon transfer may weaken, and the similar problem of embodied metal transfer caused by power transmission will become increasingly prominent. Valero et al. proved that significant demand for metals due to solar and wind power development put the supply of the corresponding metals in a high-risk state [13]. Cumulative global demand of metals from 2016 to 2050 would exceed the available reserves for copper, nickel, chromium, zinc, cobalt, silver, etc. Moreover, substitution on an elemental level will be difficult or inefficient [4,14]. Thus, it is not feasible for low-carbon electricity importers to enjoy the benefits of clean power, while low-carbon electricity exporters bear the supply risks, price risks, and the environmental risks of utilizing related metals [15]. If the associated risks cannot be reasonably addressed, the process of decarbonizing the power system will be constrained. In fact, risks directly faced by low-carbon power exporters can be compensated by charging low-carbon power importers higher prices. However, this means higher energy costs in the future, which will threaten economic development. Consequently, how to share and mitigate risks for guaranteeing secure and affordable low-carbon electricity supply is an urgent problem to be solved. We consider that analyzing embodied metal transfer can shed light on this issue.

As most of the ultra-high voltage transmission projects aimed at encouraging the delivery of low-carbon electricity from resource-rich provinces to other regions became smoothly operational after 2014, we select 2015 to 2019 as our study period. In addition, considering the supply risk of the metal and the availability of data, we select copper (Cu), nickel (Ni), chromium (Cr) and zinc (Zn) to reveal the characteristic of metal transfer embodied in electricity flow. The aims of this paper are as follows: (1) explore whether metal transfer embodied in power transmission across provinces in China shows different trends than embodied GHG (greenhouse gas) transfer during recent years. (2) Clarify the different roles of provinces in the metal and GHG transfer networks and identify which provinces are closely linked in the networks. (3) Evaluate if relevant factors have a different impact on the metal and GHG transfer networks. The results can provide insights for policy making on the road to zero carbon emissions.

2. Literature Review

An "embodied" approach is synonymous with all "footprint" analyses and the embodied impact is the impact caused in the supply chain of a product [16]. For example, embodied carbon emission, which is widely discussed, is defined as the carbon emitted from the processes of raw material acquisition, manufacturing, transportation and purchase by consumers [17]. Thus, regional embodied carbon transfer is explained as a region's inflow and outflow of embodied carbon emissions contained in interregional flows of goods and services [18]. This concept also applies to other environmental loads, such as particulate matter 2.5 [19], heavy metal emissions [20], raw material [21], water [22] and land [23]. Herein, the embodied metal consumption is proposed after embodied energy which is the first proposed concept of embodied resources, representing the sum of direct consumption and indirect consumption in the production chain [24–26]. Furthermore, environmental load transfer embodied in regional trade always reveals environmental inequalities [27–29]. For metal consumption, embodied metal transfer analysis reveals indirect consumers of metals, tracks the suppliers of the metal consumption (especially indirect consumption) in a region, and emphasizes that embodied metal inflow regions usually enjoy the benefits of applying the resources, while they do not undertake the corresponding responsibilities and risks [30,31]. It can be seen that the Multi-Regional Input-Output (MRIO) model is widely used to study the environmental load transfer embodied in trade. Since electricity generation can contribute to large-scale regional environmental concerns, researchers have focused only on the environmental impacts of inter-regional electricity trade [10,12,32–36]. Ma L. quantified spatial pattern change of carbon flow embodied in inter-provincial power transmission [36]. Though the MRIO model is a good tool to quantify the inter-regional transfer of environment load embodied in electricity transmission [12,37], other models such as the iterative method [38] and Quasi-Input-Output (QIO) model [39,40] have also been applied to explore the above problems. Qu et al. first proposed the QIO model and pointed out that the iterative method computed an approximation with only finitely many terms or iterations [39]. They also mentioned that traditional MRIO assumed all electricity exports in a region were from local generation, which is inconsistent with the facts. The QIO model has redressed the flaws in the assumptions of the MRIO model and reflected the reality that power outflow from a regional grid was a mix of electricity from multiple grids. Therefore, the QIO model can trace electricity from generation to consumption through pathways in the entire electricity transmission network more realistically. For example, the QIO model was employed to evaluate the emission factors of purchased electricity and furthermore clarify the embodied CO_2 emission flows in electricity trade [35,41]. Liu et al. applied the QIO model and proved that power transmissions in China led to net carbon reduction while net water consumption increased in 2016 [34].

Previous studies have presented an understanding of some environmental load, especially carbon transfer embodied in electricity trade in target regions. In fact, these studies are mainly from the perspective of the environmental impact of traditional thermal power generation, while the environmental impact of low-carbon power systems remain overlooked. It is known that low-carbon power systems in the future will be much more reliant on metals than traditional thermal power [4]. As the installed capacity of solar and wind power increases continuously, the scale of metal transfer embodied in interprovincial power trade is expected to show an upward trend, which has not yet received attention. Therefore, this study will focus on the embodied metal transfer caused by transmission of electricity across provinces using the QIO model. In fact, the material flow analysis reflects the direct flow of metals, and thus the main direct consumers of metals can be discovered [42–45]. The embodied metal transfer caused by transmission of electricity across provinces reveals the indirect consumers of metals. This can be considered complementary to material flow analysis when identifying the responsible subjects of metal utilization.

The characteristic of environmental load transfer embodied in trade can be portrayed by Structural Path Analysis (SPA) [46–50] or complex network theory [51–54], through which the key nodes and links in the flow of environmental load can be identified. Furthermore, the factors affecting the embodied environmental load transfer have also attracted the attention of many researchers. The Logarithmic Mean Divisia Index (LMDI) method and Structural Decomposition Analysis (SDA) are common approaches in investigating driving factors [55,56]. Moreover, the literature shows that parametric models can track various factors affecting embodied environmental load transfer. Through parametric models, M. Li et al. proved that Chinese provinces with more stringent mitigation policies would outsource more CO_2 emissions [57]. Zhong et al. utilized a parametric model to articulate that, as the degree of participation in global value chains rose, the carbon emissions transferred via trade also increased [58]. According to the above literature, the driving factors considered in LMDI or SDA methods depend on the accounting formulas for environmental load transfer. Parameter models can examine how policy, culture factors, etc. impact environmental load transfer. However, the methods of LMDI, SDA, and parametric models fail to reflect the relationship between the outflow and inflow sides of embodied environmental load transfer. The Quadratic Assignment Procedure (QAP) method is a non-parametric method that can consider the influencing factors of environmental load transfer from a relationship perspective. In fact, QAP is a way to study how a series of relationships affect certain relationship in network analysis [59–61]. Few studies have focused on the driving factors of environmental load transfer embodied in electricity trade, especially from a relationship perspective. Therefore, this study will explore the contributing factors for metal and GHG transfers embodied in the electricity trade by employing the QAP method.

Based on the pre-existing literature, our work contributes to previous research as follows: First, to the best of our knowledge, this is the first study to focus on characteristics of metal transfer embodied in the electricity trade in China. We highlight the different characteristics of GHG and metal (including Cu, Ni, Cr and Zn) transfers under the increasing share of low-carbon power in China's electricity generation mix. Second, we analyze the driving factors contributing to the metal and GHG transfer networks from a relationship perspective.

3. Materials and Methods

3.1. Quantifying Metal and GHG Transfers Embodied in Power Trade Based on QIO Model

Considering the advantages of the "QIO model" [39] mentioned in the literature review, we apply it in this study to investigate embodied metal and GHG transfers from electricity producing to electricity consuming provinces. The electricity trade system is commonly represented using a network as an analogy for its structure and flows. It is shown as Equation (1).

$$\boldsymbol{T} = \begin{bmatrix} 0 & T_{12} & \cdots & T_{1n} \\ T_{21} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & T_{(n-1)n} \\ T_{n1} & \cdots & T_{n(n-1)} & 0 \end{bmatrix} \tag{1}$$

The n by n matrix $\boldsymbol{T}$ with zero elements on the diagonal depicts electricity flows among provinces. The non-negative elements T_{ij} denote the electricity volume transferred from province i to province j ($i,\ j = 1,\ 2,\ 3 \ldots\ldots n$). According to the identity relation that the total electricity flow of a province equals the total electricity flowing in or out, Equation (2) can be derived.

$$z_i = p_i + \sum_{j=1}^{n} T_{ji} = c_i + \sum_{j=1}^{n} T_{ij} \tag{2}$$

z_i represents the total electricity flow of province i, which is the sum of the total electricity generated in province i (p_i) and all electricity obtained from all other provinces ($\sum_{j=1}^{n} T_{ji}$), which also equals the total amount of electricity consumption of province i (c_i) plus the electricity exported from province i to other provinces ($\sum_{j=1}^{n} T_{ij}$).

According to the balance of electricity flow, the balance of embodied metal flows or GHG flows can be expressed as Equation (3).

$$\boldsymbol{e}^z = \boldsymbol{e}^p + \boldsymbol{e}^z\boldsymbol{S} \tag{3}$$

where $\boldsymbol{e}^z = \left(e_i^z\right)$ is a 1 by n vector denoting metal or GHG embodied in total electricity flows of province i; $\boldsymbol{e}^p = \left(e_i^p\right)$ is also a 1 by n vector signifying metal or GHG embodied in total electricity generated in province i; $\boldsymbol{S} = \left(S_{ij}\right)$ is an n by n matrix named as the direct outflow coefficient matrix in Qu et al. [39], representing the share of electricity transferred from province i to province j in total electricity flow of province i. Specifically,

$$\boldsymbol{S} = \begin{bmatrix} 0 & \frac{T_{12}}{z_1} & \cdots & \frac{T_{1n}}{z_1} \\ \frac{T_{21}}{z_2} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \frac{T_{(n-1)n}}{z_{n-1}} \\ \frac{T_{n1}}{z_n} & \cdots & \frac{T_{n(n-1)}}{z_n} & 0 \end{bmatrix} \tag{4}$$

Based on Equation (3), metal or GHG embodied in total electricity flows $\boldsymbol{e}^z$ could be calculated as shown in Equation (5).

$$\boldsymbol{e}^z = \boldsymbol{e}^p(\boldsymbol{I} - \boldsymbol{S})^{-1} \tag{5}$$

The QIO model assumes that, if the total electricity flow of a province is a mix of locally generated electricity and electricity received from other provinces, then the electricity used by the local consumers is a portion of the mixed electricity. Consequently, metal or GHG embodied in the electricity consumption of province i $\boldsymbol{e}^c = \left(e_i^c\right)_{1\times n}$ can be calculated by Equation (6).

$$\boldsymbol{e}^c = \boldsymbol{e}^z\boldsymbol{S}^c = \boldsymbol{e}^p(\boldsymbol{I} - \boldsymbol{S})^{-1}\boldsymbol{S}^c \tag{6}$$

where $\boldsymbol{S}^c$ is an n by n diagonal matrix with the elements c_i/z_i on the diagonal. Obviously, c_i/z_i is the locally consumed electricity share of the total electricity flow. Furthermore, metal or GHG embodied in electricity flow *from generation province i to consumption province j* (M_{ij}) can be finally traced by Equation (7).

$$\boldsymbol{M} = \left(M_{ij}\right)_{n\times n} = \widehat{\boldsymbol{e}^p}(\boldsymbol{I} - \boldsymbol{S})^{-1}\boldsymbol{S}^c \tag{7}$$

M_{ij} can be understood as the metal or GHG volume embodied in electricity generated in province i directly and indirectly exported to province j. Note that developed regions usually outsource carbon emissions to the areas endowed with rich natural resources. Therefore, some studies described the carbon flow direction as opposite to the related commodity flow [12,62], while some studies showed that the direction of carbon flow was consistent with that of commodity trade [63,64]. In fact, the essence of what they illustrated was the same. In this study, the GHG flow and metal flow remain in the same direction as that of the related electricity trade. Moreover, $e_i^p = \sum_k h_k p_{ik}$, where h_k is the lifecycle metal consumption or lifecycle GHG emission per unit of electricity generation from fuel type k; p_{ik} is the electricity generation from fuel type k in province i. This study considers electricity from different energy sources, including coal power, natural gas power, other thermal power, hydropower, nuclear power, wind power and solar energy. The above method assumes that the composition of electricity delivered from a certain province to any other province is the same, which is also implied in the previous literature [34,62].

It should be noted that GHG emission is produced mainly during the electricity generation stage; thus, GHG emission per unit of electricity generation can be calculated by total GHG emission of power generation within a year divided by the total electricity generation for that year. However, using the same method to calculate metal consumption per unit of electricity generation is unreasonable because the majority of the metal is consumed during the construction period. The consumption of metal should be apportioned to all electricity produced over the life of the power plant. Lifecycle metal or GHG intensity shows the levels of metals needed or GHG emissions across all life-cycle stages to be produced per unit of electricity production. Life-cycle stages generally include construction, installation, operation, decommissioning, and end-of-life treatment of the power plants. Consequently, lifecycle metal intensity of electricity generation is applied in this study, along with lifecycle GHG intensity of electricity generation, for consistency.

3.2. Identifying Features of Metal and GHG Transfer Networks Based on Complex Network Theory

Provinces are taken as nodes and metal or GHG transfers embodied in the electricity flow from generation province to consumption provinces are taken as edges. The volume of $M_{ij}(i \neq j)$ derived from Equation (7) is defined as the weights of edges. Self-loops are ignored. Thus, we construct metal and GHG transfer networks as weighted and directed networks. The adjacency matrix $\boldsymbol{W}$ is shown as Equation (8). To capture the related changes in metal and GHG transfers embodied in electricity transmission during the study period, we focus on the position metrics such as in-strength and out-strength and integrated metrics such as average weighted degree and community structure.

$$\boldsymbol{W} = \begin{bmatrix} 0 & M_{12} & \cdots & M_{1n} \\ M_{21} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & M_{(n-1)n} \\ M_{n1} & \cdots & M_{n(n-1)} & 0 \end{bmatrix} \tag{8}$$

Strength is defined as the total weights of the edges connecting to one node in directed and weighted networks. Moreover, it should be classified into out-strength and in-strength. In our study, out-strength measures metal or GHG volume embodied in electricity generated in a province directly and indirectly exported to other provinces. On the other hand, in-strength measures metal or GHG volume embodied in electricity directly and indirectly imported from other provinces. The calculation formulas are as follows:

$$SO_i = \sum_{j,j \neq i} M_{ij} \tag{9}$$

$$SI_i = \sum_{j,j \neq i} M_{ji} \tag{10}$$

Average degree refers to the average of the degrees of all nodes in the network. For the directed and weighted network in this study, average weighted degree AD is obtained by Equation (11). It reflects averaged metal or GHG inflow and outflow levels embodied in electricity trade.

$$AD = \frac{\sum_i (SO_i + SI_i)}{2n} \; (n \text{ is the total number of nodes}) \tag{11}$$

The community structure also reflects the overall metric of the complex network. The connections between nodes within a community are relatively tight, and the connections between different communities are relatively sparse. This result can help us classify provinces into several groups according to the closeness of the environmental linkage between the provinces. In this paper, we use software Gaphi 0.9.2 to achieve community structure division by the algorithm of Blondel et al. [65].

3.3. Exploring Factors Influencing Metal and GHG Transfer Networks Based on QAP Method

The metal and GHG transfer embodied in electricity transmission in China is determined by the combined effects of many factors. Under the net-zero carbon dioxide emissions target, the decarbonization rate of electricity system in each province is not necessarily the same. Therefore, we are curious about how differences in the decarbonization effort of provinces affects metal or GHG transfer. It seems that the dependent variable and key independent variable are all relational data. The QAP algorithm is a nonparametric method, which takes relational data expressed in matrices as the research object. Furthermore, the QAP method can overcome the multicollinearity issue [18,60]. Thus, "QAP regression analysis" is used to study the relationship between metal or GHG transfer network and the influencing factors. The principle of this method can be found in previous research [60,66].

We selected the control variables influencing the metal and GHG transfers embodied in electricity trade based on the gravity model. The model states that the size of bilateral trade flows is determined by supply conditions at the origin, demand conditions at the destination and the driving forces of the trade flows [67]. Enlightened by the model, the control variables reflect the following aspects: difference in power generation characteristics, economic development gap and grid connection. For the influence mechanism, see the Supplementary Information (SI). Table 1 shows the definition of influential factors.

Table 1. Definition, measurement and abbreviation of the influential factors.

Influential Factors	Variables	Measurement	Abbreviation
Provincial difference in decarbonization effort	Investment on low-carbon electricity [1]	Low-carbon electricity investment's share in power generation investment	*PI*
	Elimination of backward thermal production capacity	The proportion of the capacity of thermal power plant retirements in total installed capacity of thermal power	*RC*
	Innovation in low-carbon power technologies	The number of authorized green patents related to electricity [2]	*PT*
Provincial difference in power generation characteristic	Total power generation	Total electricity generated locally	*PG*
	Power generation structure	Share of low-carbon electricity in total electricity generation mix	*PS*
	Power price	Weighted average of on-grid price of different types of electricity. (The weight is percentage of electricity production that comes from different fuels)	*PP*
Provincial difference in economic development	Economic scale	Gross domestic product	*GDP*
Grid connection between provinces	Whether there is direct power transmission relationship between provinces	\	*RE*

Note: [1] Low-carbon electricity includes hydropower, nuclear power, wind power and solar power. [2] The green patents related to electricity includes the categories of Alternative Energy Production, Nuclear Power Generation, and Storage of Electrical Energy belonging to Energy Conservation.

The QAP regression model can be demonstrated by Equation (12).

$$\boldsymbol{W'}_{\mathbf{metal}} \text{ or } \boldsymbol{W'}_{\mathbf{GHG}} = f(\boldsymbol{PI},\ \boldsymbol{RC},\ \boldsymbol{PT},\ \boldsymbol{PG},\ \boldsymbol{PS},\ \boldsymbol{PP},\ \boldsymbol{GDP},\ \boldsymbol{RE}) \tag{12}$$

where data for all the variables are matrices. We set the amount of metal transfer matrix $\boldsymbol{W'}_{\mathbf{metal}}$ or GHG transfer matrix $\boldsymbol{W'}_{\mathbf{GHG}}$ as the dependent variable. Since this paper is intended to study the formation of interprovincial metal or GHG transfer, bilateral transfer volume can be considered to reflect the linkage between two provinces [59]. The elements of $\boldsymbol{W'}_{\mathbf{metal}}$ or $\boldsymbol{W'}_{\mathbf{GHG}}$ are $W'_{ij} = W'_{ji} = M_{ij} + M_{ji}$ and $W'_{ii} = 0$. $\boldsymbol{RE}$ is grid connection matrix with zero elements on the diagonal. If there is direct power transmission relationship between province i and province j, $RE_{ij} = RE_{ji} = 1$, otherwise, $RE_{ij} = RE_{ji} = 0$. $\boldsymbol{PI}$, $\boldsymbol{RC}$, $\boldsymbol{PT}$, $\boldsymbol{PG}$, $\boldsymbol{PS}$, $\boldsymbol{PP}$ and $\boldsymbol{GDP}$ are expressed by the absolute value matrix of the differences between provinces. For example, the ijth elements of matrix $\boldsymbol{PI}$ $PI_{ij} = PI_{ji} = |PI_i - PI_j|$, and $PI_{ii} = 0$. In this study, the variables from 2015 to 2019 are averaged, and then a "difference matrix" is constructed using the absolute values of the differences in the above average values across provinces [60]. QAP regression of this paper are performed in UCINET by randomly permuting the data 2000 times.

3.4. Materials

The national electricity grid is divided into 31 sub-grids based on provincial administrative boundaries (Table S1). The power grids of Hong Kong, Macao, and Taiwan are not covered because of data deficiency. We have obtained the provincial electricity generation,

generation mix, electricity consumption and inter-provincial electricity transmission data from China electricity council [68–72].

de Koning et al., Watari et al. and IEA provide the data on the levels of lifecycle metal intensity in different electricity generation technologies (Table S2) [4,73,74]. Lifecycle GHG emission intensity of each electricity generation technology is given by the world nuclear association [75] (Table S3). In fact, there are relatively large differences in the life-cycle metal/GHG intensity reached by different studies. The boundary selection of lifecycles leads to a broader range in results. For example, some studies included end-of-life treatment in the scope, while some excluded this stage [76,77]. Moreover, the selection of facilities and site-specific or region-specific factors are the most prominent factors influencing the results [75]. Thus, mean values of the lifecycle metal and GHG intensity presented in the literature are adopted in this study. The precision of these data is low. However, the differences between the metal or GHG intensities of competing electricity generation technology is sufficiently great that it is still possible to draw meaningful conclusions [78]. Metal efficiency improvement (e.g., dematerialization and substitution) that helps reduce the use of metal is not considered in this study. First, accurate collection of the lifecycle metal intensity change within the study period is challenging. Second, metal intensity is relatively stable in the short run, and Cu, Ni and Cr show poor progress in substitution [4,79]. For example, aluminum wires are cheaper while requiring higher maintenance than copper wiring [80]. Likewise, lifecycle GHG emission intensity change within the study period is neglected. Thus, this study highlights the role of electricity mix changes on metal demand and GHG emissions.

Moreover, the basic data about influential factors in QAP regressions including low-carbon electricity investment's share in power investment, the proportion of the capacity of thermal power plant retirements in total installed capacity of thermal power, direct power transmission relationships between provinces, total power generation by province, and share of low-carbon electricity to total electricity generated in each province can be derived from the data from China electricity council [68–72]. GDP (gross domestic product) and relevant GDP index are from the China Statistical Yearbook [81–85]. We convert GDP at current prices to GDP at constant (2015) prices. Power price is obtained from the China Electric Power Yearbook [86–89] and it is also deflated based on the 2015 constant price by producer price indices for power industry by region. Price indices can be obtained from the China Price Statistical Yearbook [90–94]. Due to a lack of power price data for 2019, the power prices from 2015 to 2018 are averaged. Statistics on China's green patents related to electricity come from CnOpenData's green patent sub-region statistics (www.cnopendata.com, accessed on 14 March 2022).

4. Results and Discussion

4.1. Changes in Metal and GHG Embodied in Electricity Consumption

We estimated several metals (Cu, Ni, Cr, and Zn) requirement and GHG emissions of electricity consumption in China from 2015 to 2019. A 27.3% increase (from 5693.5 TWh to 7248.4 TWh) in electricity usage caused a growth in associated metal demand by 74.2% (from 0.23 Mt to 0.40 Mt), and an 18.9% increase in GHG emissions (from 3569 Mt to 4243 Mt). For the specific metals, Cu and Zn saw significantly larger increases of 171% and 137%, respectively. Ni and Cr also increased by 31% and 71% (Table S4). Moreover, there was an upward trend in metal intensity of electricity consumption in the period from 2015 to 2019 (from 40 t/TWh to 55 t/TWh), yet there was a downward trend in GHG intensity (from 627 Kt/TWh to 585 Kt/TWh) (Table S5). The increase in metal intensity occurred for each metal we studied, with the most significant increase in copper intensity (from 7.94 t/TWh to 16.92 t/TWh) (Figure 1). These results indicate weak decoupling of electricity consumption increases and associated GHG emissions. However, decoupling is always accompanied by a rising reliance on metals, caused by an increase in the share of solar and wind power in the electricity consumption mix.

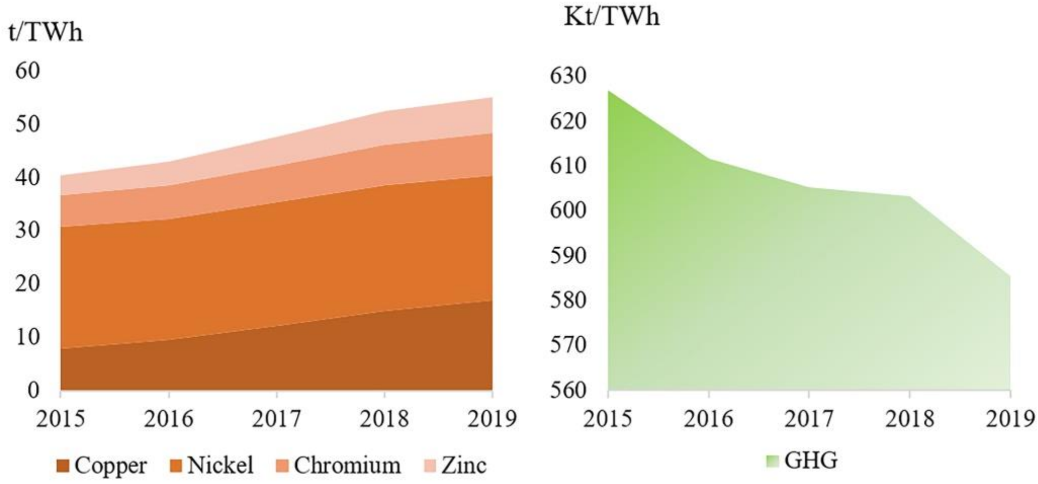

Figure 1. Metal and GHG intensity of electricity consumption in the period from 2015 to 2019.

Metal or GHG intensity of electricity consumption in a province is defined as metal requirement or GHG emissions embodied per unit of electricity consumption in a province. Metal or GHG intensity of electricity production is defined as metal requirement or GHG emissions caused per unit of electricity production in a province. Thus, the metal or GHG intensity of electricity consumption can truly reflect a province's dependence on metal or carbon. However, we find that the gap between environmental load intensities of electricity generation and consumption exists in many provinces. See SI for details by province.

4.2. Trends of Inter-Provincial Metal and GHG Transfers in China

The gap between the environmental load intensities of electricity production and consumption is caused by environmental load transfers embodied in the electricity trade. In 2015, total transferred metal including Cu, Ni, Cr, and Zn embodied in cross-province electricity trade was 31.96 Kt, accounting for 14% of the metal requirement of national power consumption. In 2019, total transferred metal volume had more than doubled to 71.22 Kt, accounting for 18% of the metal requirement of national power consumption. Furthermore, the total GHG transfer embodied in the electricity trade increased by 48%, from 455 Mt (13% of the GHG emission of national power consumption) in 2015 to 672 Mt (16% of the GHG emission of national power consumption) in 2019, displaying a growth rate slower than total metal transfer. For more details including individual metal transfer, see Tables S6–S11.

We further summarize transfer pathways for both metal and GHG emission flows. The results demonstrate that metal and GHG emissions were generally transferred from western and central China to the eastern coast. The flow of the individual metal exhibits similar characteristics with the total; therefore, we analyze the transfer of the sum of metals. In Figure 2, the 20 highest transfers of metal and GHG in 2015 and 2019 are illustrated to identify the changing trend of the flows. The transferred volume of metal of the top 20 metal flows was more than 70% and 60% of the total transferred volume in 2015 and 2019, respectively, and so was GHG flow volume. With 5 years of change in the volume and structure of electricity trade, the key transfer pathways had demonstrated a rapid increase in their embodied metal flows. Metal transfer from Inner Mongolia to Hebei, the largest flow, had increased by 15%. However, in terms of GHG transfers, this period witnessed a decline of GHG emission flow in several key pathways such as Inner Mongolia to Hebei, Guizhou to Guangdong, Shanxi to Hebei, etc. (the pathways in orange in Figure 2). In the pathway with the largest flow, Inner Mongolia to Hebei, GHG emission embodied in the electricity transfer declined by 5%, from 56.7 Mt to 53.7 Mt. This was caused by the rising share of low-carbon power in the electricity trade. We can infer that a great increase in the proportion of low-carbon power in major electricity transmission channels can mitigate environmental inequities caused by GHG transfers between regions.

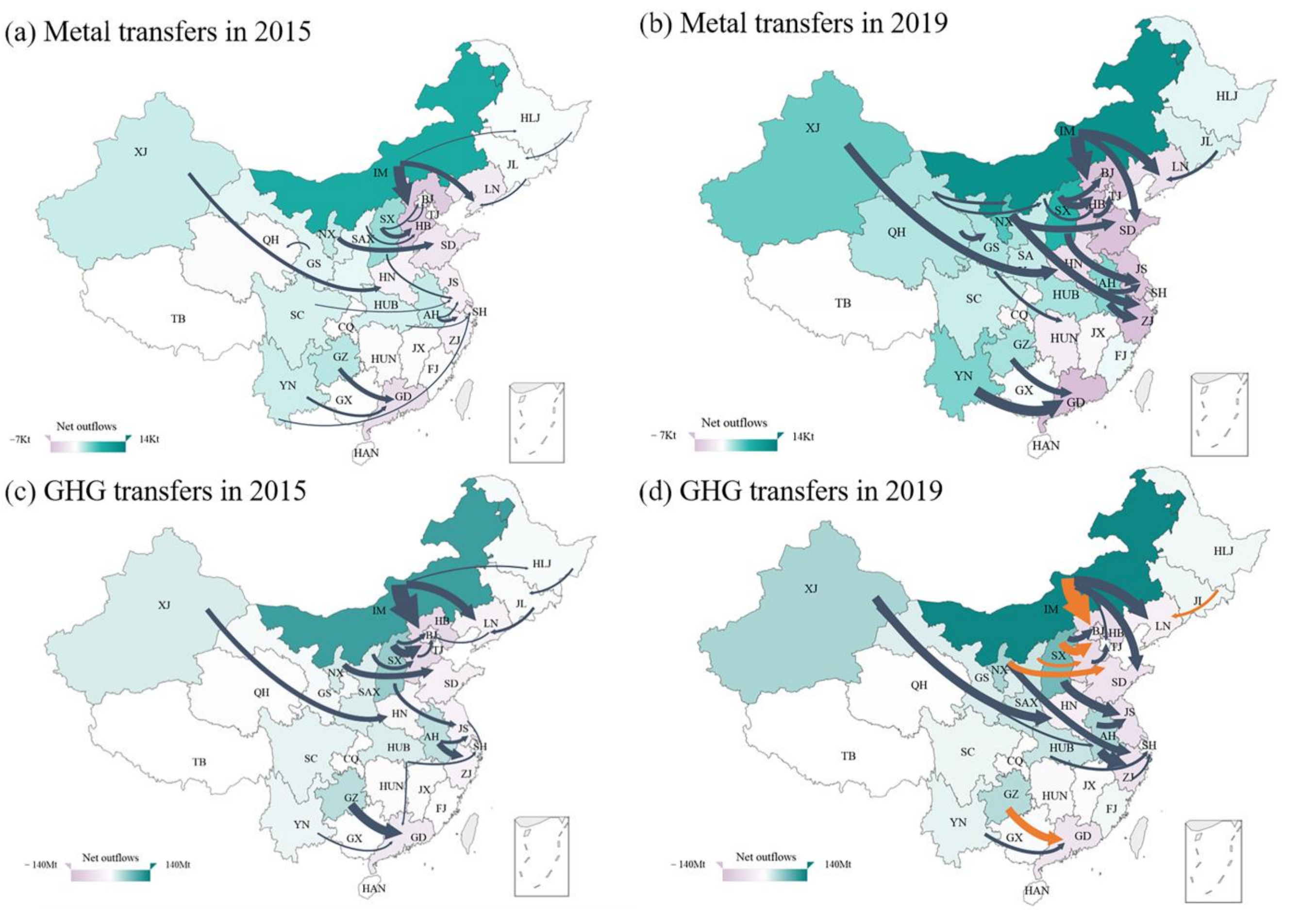

Figure 2. Twenty highest metal and GHG transfers in 2015 and 2019.

The abbreviations of the provinces are shown in Table S1.

4.3. Characteristics of Metal and GHG Transfer Networks

Figure 3 shows that Inner Mongolia and Hebei were the most important exporter and importer, respectively, of embodied metal and GHG emissions. During the period from 2015–2019, the out-strength of several provinces, including Inner Mongolia, Shanxi, and Ningxia, in the metal transfer network, had a significant upward trend, while most other provinces had only a slight increase. The in-strength of most provinces in the metal transfer network also witnessed a growth, especially Zhejiang, Guangdong, Jiangsu, and Shandong, which experienced a rapid climb. Compared to the upward trend of out-strength in metal transfer network, the out-strength of most provinces in the GHG transfer network demonstrated more moderate growth. However, the in-strength of most provinces in the GHG transfer network did not show a sharp ascent, and it is worth reporting that some regions such as Hebei and Beijing even displayed a slight decline during the study period. Especially for, Hebei, acting as the largest GHG importer and net importer, the inflow reduced by 4% from 100.80 Mt to 96.89 Mt and net inflow also declined by 11% to 74.57 Mt. In terms of the metrics of the whole network, the average weighted degree of the metal transfer network was more than ten percentage points faster than the growth of the average weighted degree of the GHG transfer network (Table S12). The direct cause behind the change in metal and GHG network is known to be the variation in electricity trade. However, the same change in electricity trade enhanced the embodied metal transfer network greatly while indicating the potential to suppress the growth of embodied GHG transfer network.

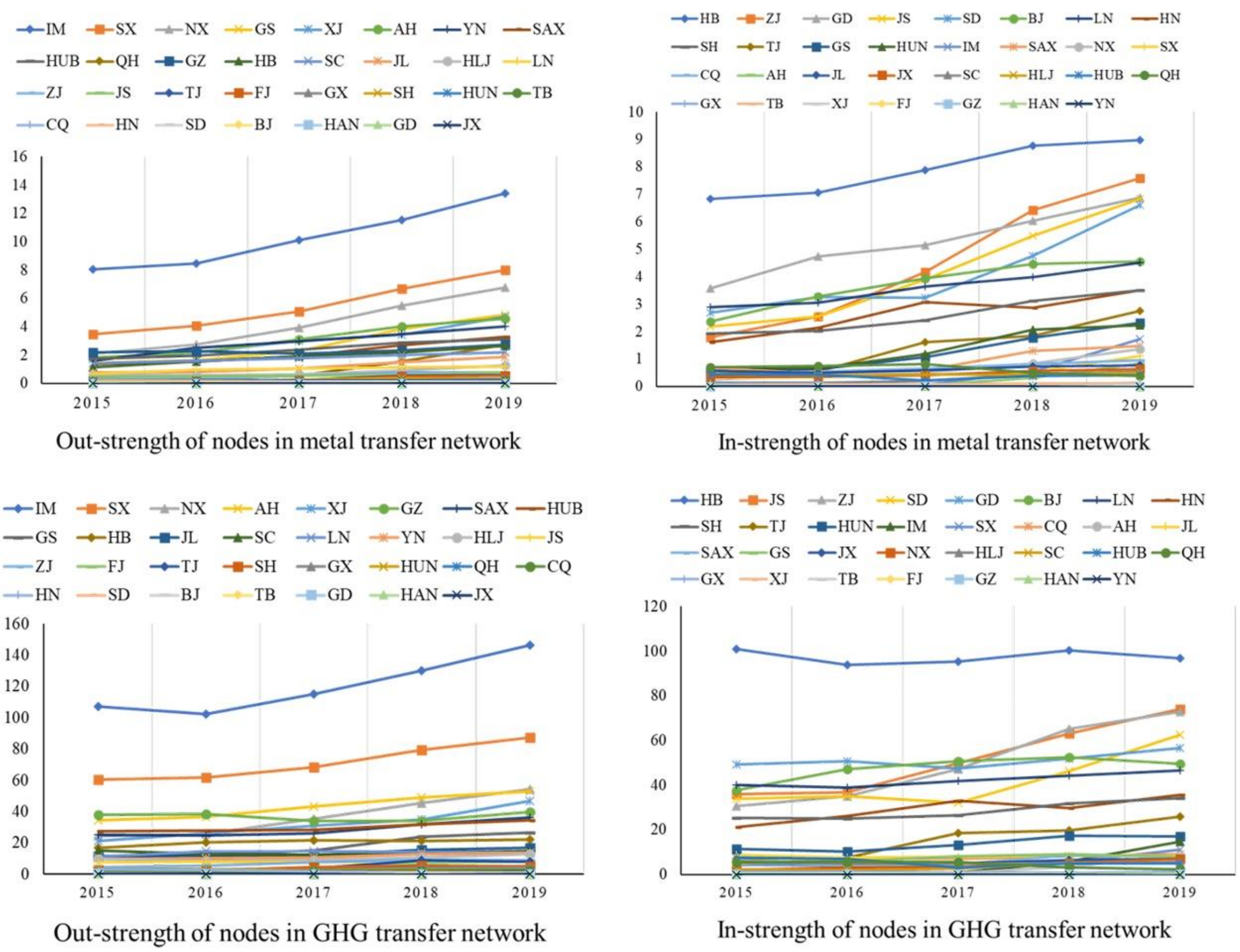

Figure 3. Out-strength and In-strength of provinces (nodes) in metal or GHG transfer network from 2015 to 2019.

The abbreviations of the provinces are shown in Table S1.

Based on the modularity algorithm, the community division from 2015 to 2019 is shown in Tables 2 and 3. The nodes are divided into five or six communities. The community division results for metal and GHG networks show high similarity due to the underlying electricity trade relationship. Even though certain provinces (e.g., Ningxia, Shaanxi, Hunan) belonged to different communities during the study period, the community structure was still regarded as stationary during the networks' evolution, with the nodes/provinces most probably remaining in the same community. Five main communities are discovered in the networks. We name them based on the location of most members in the community (Tables 2 and 3).

Table 2. Community division of metal transfer network from 2015 to 2019.

Communities	2015	2016	2017	2018	2019
North	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Shaanxi	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Shaanxi	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang
Northeast	Liaoning, Jilin, Heilongjiang	Liaoning, Jilin, Heilongjiang	Liaoning, Jilin, Heilongjiang	Liaoning, Jilin, Heilongjiang	
Southeast	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Chongqing, Sichuan	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Chongqing, Sichuan	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Hubei, Chongqing, Sichuan, Ningxia	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Hubei, Chongqing, Sichuan, Ningxia	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Hubei, Chongqing, Sichuan, Ningxia
South	Guangdong, Guangxi, Hainan, Guizhou, Yunnan, Hunan	Guangdong, Guangxi, Hainan, Guizhou, Yunnan, Hunan	Guangdong, Guangxi, Hainan, Guizhou, Yunnan	Guangdong, Guangxi, Hainan, Guizhou, Yunnan	Guangdong, Guangxi, Hainan, Guizhou, Yunnan
West-(1)	Shaanxi, Shandong, Ningxia, Tibet, Gansu, Qinghai	Henan, Xinjiang, Tibet, Gansu, Qinghai	Henan, Xinjiang, Tibet, Gansu, Qinghai, Hunan	Henan, Xinjiang, Hunan, Tibet, Shaanxi, Gansu, Qinghai	Hunan, Tibet, Shaanxi, Gansu, Qinghai
West-(2)	Henan, Xinjiang	Shandong, Ningxia			Henan, Xinjiang

Table 3. Community division of GHG transfer network from 2015 to 2019.

Communities	2015	2016	2017	2018	2019
North	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Shaanxi	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Shaanxi	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Shaanxi	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Shaanxi	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Shaanxi
Northeast	Liaoning, Jilin, Heilongjiang	Liaoning, Jilin, Heilongjiang, Shandong, Ningxia	Liaoning, Jilin, Heilongjiang	Liaoning, Jilin, Heilongjiang	Liaoning, Jilin, Heilongjiang
Southeast	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Chongqing, Sichuan	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Sichuan	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Sichuan	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Chongqing, Sichuan, Ningxia, Shandong	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Sichuan, Ningxia, Shandong
South	Guangdong, Guangxi, Hainan, Guizhou, Yunnan, Hunan	Chongqing, Guangdong, Guangxi, Hainan, Guizhou, Yunnan, Hunan	Chongqing, Guangdong, Guangxi, Hainan, Guizhou, Yunnan, Hunan	Guangdong, Guangxi, Hainan, Guizhou, Yunnan, Hunan, Tibet, Gansu, Qinghai	Chongqing, Guangdong, Guangxi, Hainan, Guizhou, Yunnan
West-(1)	Henan, Xinjiang, Tibet, Gansu, Qinghai	Henan, Xinjiang, Tibet, Gansu, Qinghai	Henan, Xinjiang, Tibet, Gansu, Qinghai		Hunan, Henan, Xinjiang, Tibet, Gansu, Qinghai
West-(2)	Shandong, Ningxia		Shandong, Ningxia	Henan, Xinjiang	

4.4. Influencing Factors on Metal and GHG Transfer Networks

According to QAP analysis results (Table 4), whether the dependent variable is metal or a GHG transfer network, grid connection is the most influential factor, followed by the difference in economic development and difference in power generation characteristic, while the difference in decarbonization effort has a much weaker effect. The coefficient of the grid connection is significantly positive at the 1% level and occupies the majority, indicating that direct power transmission relationships between provinces play a significant role in promoting the formation of metal and GHG transfer networks. Metal and GHG transfer networks carry a positive relationship with GDP gap. This is because in order to meet demand, developed regions need to buy more electricity from less-developed regions where locally produced electricity cannot be consumed because of excessive production in comparison to consumption. Meanwhile, more electricity trade volume represents more embodied metal and GHG transfers. In terms of factors of difference in power generation characteristic, we find the significant positive effect of difference in *PP* on metal and GHG transfer networks, which shows that two provinces with significant power price differences are more likely to form an electricity trade, contributing to metal and GHG flows. The difference in *PS* shows a significantly negative impact on metal and GHG transfer networks. We find that the provinces with high *PS* often have abundant low-carbon energy, while the provinces with lower *PS* have access to adequate coal resources. This reduces the possibility of electricity trade between the provinces and lowers the metal and GHG flows. *PG* has no significant impact on the metal and GHG transfer networks.

Table 4. QAP results of factors influencing the embodied metal and GHG transfer networks.

Influencing Factors and Determination Coefficients		QAP Regression Analysis (Metal Transfer Network)		QAP Regression Analysis (GHG Transfer Network)	
		Standardized Coefficient	Significance (*p* Value)	Standardized Coefficient	Significance (*p* Value)
Difference in decarbonization effort	*PI*	0.0689 *	0.084	0.0454	0.181
	RC	−0.0297	0.277	−0.0204	0.356
	PT	−0.0727	0.136	−0.0289	0.370
Difference in power generation characteristic	*PG*	−0.0329	0.239	−0.0122	0.422
	PS	−0.1016 **	0.013	−0.1195 ***	0.006
	PP	0.1106 **	0.033	0.0773 *	0.083
Difference in economic development	*GDP*	0.1418 **	0.012	0.0976 *	0.055
Grid connection	*RE*	0.5452 ***	0.000	0.5284 ***	0.000
	R^2	0.327		0.311	
	Adjusted R^2	0.322		0.306	

*** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

Interestingly, as a factor of difference in decarbonization effort, the coefficient of *PI* difference is positive when the dependent variable is the metal transfer network. There is a non-significant result about the coefficient of *PI* difference when the dependent variable is GHG transfer network. This finding suggests that the provincial difference regarding low-carbon electricity investment strengthens the embodied metal flows to some extent while insignificantly affecting the GHG transfers. Reviewing the related data, many net electricity exporting provinces are found to have a high share of low-carbon electricity in the power generation investment mix. For example, the provinces of Shanxi, Xinjiang, etc., received more low-carbon electricity investment proportion than the corresponding electricity importing provinces (Jiangsu, Henan, etc.). This could facilitate the interprovincial transmission of solar and wind electricity which is metal intensive but almost carbon free.

In addition, the differences in *RC* and *PT* have no significant impact on the metal and GHG transfer networks.

Under the carbon neutrality target, provinces tend to accelerate the development of low-carbon electricity. It is proved that tremendous low-carbon electricity capacities should be installed in areas where natural conditions are more suitable. Thus, through flexible electricity trade among regions, the national average low-carbon electricity penetration rate could be successfully improved [95]. Accordingly, there are bound to be gaps in the degree of promotion of low-carbon energy in different provinces due to different resource endowments, entailing that considerable interprovincial low-carbon electricity transmission as well as metal transfer could be inevitable.

4.5. Discussion

In line with previous research [64,96], the results of this study for GHG transfer do not support that the allocation of carbon reduction responsibility should be implemented under the production-based framework. The consumption-based framework is regarded as fairer. However, W. Li et al. argued that carbon reduction responsibility allocation according to consumption-based criterion would encounter intricate calculations and "double counting" issues; thereby, under this circumstance the consumption-based principle was suggested as a supplement when allocating responsibility [62]. Although the scale of GHG transfer embodied in electricity trade is shrinking in several key pathways with the development of low-carbon electricity, similar to the declining of carbon flows embodied in the interprovincial trade [63], the carbon emission outsourcing problems will remain significant for decades to come. Thus, we suggest that provinces with close GHG linkage within a community should form a partnership. For instance, the development of China's carbon credit market should be vigorously promoted. In this case, large electricity consumers of Zhejiang can cooperate at the project level by providing funding and green electricity technology to Ningxia and Anhui which are the main electricity suppliers of Zhejiang to obtain certified emission reductions, as well as take the corresponding carbon reduction responsibility. The provinces with different roles in the same community are suggested to act in unison and take coordinated measures so that the flexibility of the power system can be improved from the power supply side, the grid side, and the user side. The above-mentioned cooperation between electricity consumers and producers will promote the replacement of carbon-intensive traditional thermal power with climate beneficial low-carbon electricity. Through collaboration, electricity consumers can bear partial responsibility for reducing GHG emissions.

In addition to mature technology and a sufficiently flexible power system, achieving high penetration of low-carbon electricity may also be affected by certain metals. The embodied metal transfer analyses enlighten us to the fact that the embodied metal inflow provinces have the responsibility to share the foreseeable risk associated with metal utilization. Currently, there is no "metal credit market". When metal resources are scarce, a similar credit system for the vast amount of depletion of metals may appear for more efficient usage of metals. In this case, large electricity consumers can invest in important metal mining projects or metal recycling technology for achieving "certified metal sustainability". This is also a measure to share the metal supply-chain risks in the future, which is significant for energy security. For example, the capital in Zhejiang is encouraged to support the metal mining project of Jiangxi Copper which is a mining company located in the area of the Southeast community. Moreover, school-enterprise coordination and inter-enterprise cooperation mechanisms within a community should be established to help the power plant be rationally designed, improve metal recovery technology and optimize metal resource management for efficient metal utilization. It is worth noting that power plant design and metal intensity are closely linked. For example, the increase in wind turbine nameplate capacities can reduce the cost per unit of electricity but may represent an increase in copper intensities [80,97].

Comparing metal and GHG networks, we find that provinces presenting close metal association usually exhibit strong GHG linkage. Moreover, the environment load transfer trend and driving factors analyses prove that, even if the GHG transfers among provinces tend to become weaker over time, the metal transfers will always exist and be even more crucial. Accordingly, the long-term regional partnership aims for supporting low-carbon electricity development are suggested to be established based on community division of metal transfer networks. Suitable cooperation models and policies should be explored so that the economic development can be facilitated by cheap, clean electricity. The North and the Southeast communities are suggested as pilot zones, because Inner Mongolia and Hebei of the North community have the largest out-strength and in-strength, respectively. Ningxia and Zhejiang in the Southeast community also have high out-strength and in-strength growth trends, respectively. In addition, the embodied metal and GHG transfer studied in this research is just part of the metal extraction cycles and carbon flows. It will be a voluminous but meaningful task to integrate provincial electricity production and consumption into the world's supply chains and ecosystems. Certainly, with the advancement of digital technology, both metal and GHG transfer data should be tracked more precisely so that more equitable policies based on consumption-based criterion can be designed holding stakeholders accountable for the green future.

5. Conclusions

This study applies the QIO model to analyze metal and GHG emissions embodied in the cross-provincial electricity transmission in China. The driving factors that contributed to the metal and GHG emission transfers are also explored through the QAP method. Several conclusions can be drawn from the study:

First, embodied metal and GHG always flow from the resource-rich western provinces to the economically developed eastern provinces. During the study period, changes in the electricity trade have resulted in a significant increase in embodied metal transfer volume, much higher than the growth rate of embodied GHG transfer volume. Further, networks analyses reveal that the change in electricity trade strengthens the metal transfer network and has the potential to weaken the GHG transfer network. Though GHG linkage among provinces has remained an important issue for a long time, metal linkage should be of great concern in the future.

Second, the difference in low-carbon electricity investment between provinces helps increase the metal transfers while failing to affect the GHG transfers. Power system decarbonization cannot be achieved by indiscriminate promotion of low-carbon electricity across provinces, and tremendous low-carbon electricity capacity should be newly installed in the areas with resource advantages. As a consequence of this fact, differences in power investment structure will exist for a long time, which will further boost the embodied metal flows.

Finally, close environmental linkage between provinces implies that decarbonization of the power system requires regional cooperation. The long-term regional partnership aims for achieving high penetration of low-carbon electricity are suggested to establish based on community division of metal transfer network. The communities of the North and the Southeast are recommended to be set as the pilot area to explore the cooperative mode for technology breakthroughs, grid flexibility improvement, and related metal security guarantee. Specifically, the cooperation of a pair of provinces with the largest environmental linkage within a community, such as Inner Mongolia and Hebei in the North community and Ningxia and Zhejiang in the Southeast community, should play a leading role in the community.

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