# Do electricity flows hamper regional economic–environmental equity?

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## Abstract

Inter-regional electricity flows have mitigated the mismatch between electricity generation and demand. However, not only environmental impact transfers but also economic benefits are embodied in electricity flows. Whether electricity flows affect the equity of regional economic-environmental sustainability, the exploration is not sufficient. In this paper, a multi-model framework has developed to trace the transfers of electricity environmental impacts (measured by metal-water-carbon) and economic benefits (measured by valued added) and the degree of equity in the economic–environmental sustainability embodied in electricity flows of China. The results reveal significant asymmetry between where the electricity metal-water-carbon and the electricity value added embodied in electricity flows are transferred. In total, 15.0%, 17.4% and 13.1% of consumption-based electricity metal-water-carbon were outsourced through the electricity flow network, respectively, while only 9.3% of consumption-based electricity value added was outsourced. Wealthier provinces (e.g., Beijing and Guangdong) outsourced a large share of electricity metal-water-carbon to other provinces through the electricity flow network but retained a large share of electricity value added. The REI index between the electricity metal-water-carbon and the electricity value added indicates that money and environmental impacts flowing in the opposite directions have higher inequity. Some provinces, including Shaanxi (the highest REI value at 2.02 was observed for Shaanxi-Gansu), have gained economic benefits from electricity flows, exploiting the advantages of their electricity structures. This study offers insights into helping policymakers better address the potential environmental and economic implications of electricity flows to ensure the sustainable growth of electricity production and consumption.

# 1. Introduction

## 1.1 Motivation

Due to issues such as energy crisis, air pollution and climate change, the energy systems have faced enormous challenges [1, 2]. Electrification will play a critical role in decarbonizing energy systems and as a central strategy for emissions mitigation policies [3-5]. While end-use electrification reduces emissions from the downstream demand sectors, it often results in soaring electricity demand and a greater need for electricity generation [6-10]. The spatial separation between electricity production and consumption thus requires electricity flow among different regions to guarantee power supply security [11-13]. Inter-regional electricity flow via an electric grid changes the imbalanced spatial distribution of the power industry and sorts electricity demands [14]. However, it also leads to the separation of environmental impacts of upstream power generation from downstream electricity demand [15]. Exploring embodied environmental impacts in electricity flows reveals the environmental externalities between separated electricity production and consumption [16-18]. Combining environmental footprint analysis with network properties provides important insights into the embodied electricity environmental impacts in inter-regional electricity flows [19].

In addition to environmental impact asymmetries, asymmetric transfers of the economic gains embodied in inter-regional electricity flows are neglected [20]. Exporting electricity also stimulates economic growth in power generating regions. Power producers have gained economic welfare along with the negative environmental impacts from increased electricity production. Considering only the environmental impacts but neglecting the economic gain will not fully reveal the disparity in the distribution of economic–environmental externalities caused by electricity flows [21]. Whether electricity flows hamper economic–environmental equity by shifting the environmental burden to poor regions should be further explored [22, 23].

## 1.2 Literature review

Numerous studies have focused on the environmental impacts of power generation as a key sector in climate-change mitigation [24]. Existing studies have quantified carbon emissions, air pollutions, water, and metal use in the power sector at the global and regional scales [25, 26]. In China, some representative studies, such as one by Liao et al. [27], have estimated water consumption associated with China's thermoelectric power generation and showed that 4.64 bn $m^3$ of national surface water was consumed in 2014. They also investigated historical changes in water use by China's thermal power sector at the regional scale [28]. Wei et al. [29] analysed the greenhouse gas emissions resulting from the construction of China's power transmission infrastructure, and they found that cumulative embodied GHG emissions reached 0.89 $GtCO_2$-equivalent in 2017. Li et al. [30] investigated the material stocks and flows of the power infrastructure developed in China and found that material stocks increased to 573 Mt in 2018.

The aforementioned studies have contributed profoundly to the understanding of the environmental impacts of upstream power generation and infrastructure. Meanwhile, a growing number of studies have explored the separation of environmental impacts in upstream power generation from downstream electricity demand. They have mainly focused on the embodied carbon and water of electricity transfers (or called 'electricity purchased') [31]. Because of the simplicity of proposed hypotheses, some studies have applied a direct trade-adjustment approach. This approach assumes that all electricity imports are consumed in conjunction with all electricity exports originating from the exporter's electricity generation. Based on this assumption, Song et al. [32] calculated the emission factors of electricity purchased in China. Lindner et al. [33] adopted the same hypothesis to calculate the electricity-derived $CO_2$ emissions from the perspectives of production and consumption. Jin et al. [11] and Zhu et al. [34] quantified virtual water transfers via power transmission in China. Being aware of the limitations of the direct trade-adjustment approach, Qu et al. [15] revealed that it leads to inaccurate results, as it ignores inter-regional transmissions across the electricity grid. They proposed a network approach that considers the indirect imports and exports of electricity, to evaluate the $CO_2$ emissions embodied in inter-provincial electricity transmissions in China [31, 35]. Other Studies have evaluated the embodied water and carbon associated with electricity transfers in China using fixed methodological applications in network analysis [35-37]. Zhang et al. [36] constructed a node-flow model of inter-provincial electricity flows to estimate the virtual water embodied in an electricity flow network. They revealed that the total inter-provincial virtual water embodied in electricity flows in 2011 was 623 million $m^3$ [36]. Zhang et al. [14] described the interprovincial virtual water transfer in an electricity-trade network. Liao et al. [38] estimated water use in electricity-exporting provinces as well as water saving in the receiving provinces. They highlighted that electricity transmissions generated the co-benefit of saving 20.1 billion $m^3$ of water nationally in China in 2014 [38]. Wang et al. [37] explored the relative contributions to changes in GHG emissions of inter-regional electricity grids in China during 2008-2015 using the network approach.

In addition to the embodied environmental impacts of electricity flows, the electricity flows provide economic gains. However, few studies have focused on the transfer of economic gains associated with environmental impacts. Empirical studies on the theoretical notion of ecologically unequal exchange (EUE) and the newly developed global value chain analysis of trade in value added (TiVA) provide methodological feasibility for addressing this issue [39]. The theory of EUE proposes wealthier developed regions are more likely to gain access to resources that are relevant to achieving economic growth, and that these resources are more highly compensated than those in poor regions [22]. A range of case studies have provided empirical evidence for the presence of EUE in fields such as carbon emissions and air pollution [40]. A study by Prell et al. [41] highlighted that core countries with higher volumes of exports increase their share of global economic wealth faster than their share of environmental pollution. Another term, TiVA, which is also called the “value-added footprint” and proposed in the multi-regional input-output analysis (MRIO) framework, accounts for the monetary value added embodied in the trade of global goods [42-44]. Studies on TiVA have clearly captured cross-border value-added flows and explored how one country's value added is absorbed by another country's final demand [45]. Yu et al. [46] assessed the unequal exchange between China and the rest of the world using the value added and four environmental indicators, based on the global MRIO model. Zhao et al. [47] found that exports contributed 55-62% of Beijing-Tianjin-Hebei's air pollution emissions but accounted for 54% of its value added. Zhang et al. [48] traced the valued added and air pollution emissions in China's domestic supply chains. These studies on the coupling of the TiVA with EUE provide a front view for exploring the economic gains and environmental impacts of electricity flows.

### 1.3 Contributions

Based on the mentioned literatures, several gaps have been identified and are listed as follows:

1. Although some studies have focused on the separation of environmental impacts of upstream power generation from downstream electricity demand, there is a lack of exploration of economic gains transferred through inter-regional electricity flows.
2. Whether electricity flows hamper regional economic–environmental equity remains unclear. Which regions benefit from the electricity flows, and what are the mechanisms of equity in the electricity flows?

To fill this gap and explore whether electricity flows hamper regional economic–environmental equity, this study investigates the environmental impacts and economic benefits embodied in electricity flows in China at the provincial scale in 2015. To the best of our knowledge, this was the first analysis of the regional economic-environmental equity embodied in electricity flows. Deepening the reform in the power sector and transforming to decarbonized electricity has become a major task given the coal-fired power-dominated electricity mix in China [49, 50]. Decarbonized electricity requires the expansion of renewable power capacity, especially wind power and solar power technologies [51, 52]. Some studies have pointed out that renewable power systems could reduce carbon emissions, but there are other unknown resource and environment risks [26, 53, 54]. Thus, we chose metal use, water use and $CO_2$ emissions to characterize the environmental impacts of China's power system. This study uses the term "electricity metal-water-carbon" to represent these environmental impacts.

In the developed framework, firstly, D-MFA (Dynamic material flow analysis) model, water use accounting model and $CO_2$ emissions accounting model were expanded and built to quantify the electricity metal-water-carbon impacts of power generation in China. Thereafter, referring to TiVA and EUE theory, an electricity flow network model is constructed and highlighted the economic gain and environmental impacts embodied in China's electricity flows. Based on the multi-model assessment, a comprehensive exploration of the economic and environmental behaviours of China's interprovincial electricity flows could clarify the equity existing in electricity production and consumption. Moreover, coupling electricity flows, environmental flows, and value flows and understanding hidden economic–environmental mechanisms could help provide further suggestions for power policies and power compensation mechanisms.

## 2. Methodology

### 2.1 Electricity metal-water-carbon of power generation

This study first uses dynamic material flow analysis, the water use accounting model and the $CO_2$ emissions accounting model to calculate the metal demand, water use and $CO_2$ emissions of power generation in 31 provinces in China. The results of these models were used as input parameters for subsequent models. Accordingly, the results are expressed as electricity metal-water-carbon power generation throughout this study to characterize the environmental impacts of electricity systems.

Dynamic material flow analysis (D-MFA) accounts for the flows and stocks of metal resources within system boundaries defined in a specific space and time [55]. Specifically, the D-MFA model is adopted to estimate three key parameters of power installed capacity: stocks, inflows and outflows, which represent the accumulation, newly added and retired demolished power installed capacity, respectively [26]. By simulating the three key parameters of power installed capacity, metal demand for power generation can be quantified. The function model of D-MFA is shown as [26]:

$$I^{(m)}(t)=\mathrm{K}^{(m)}(t)-K^{(m)}(t-1)+O^{(m)}(t) \quad (1)$$

where m denotes the metal resources, and t refers to the year; $I^{(m)}$ is the inflows of metal, $K^{(m)}$ is the stock of metal and $O^{(m)}$ is the outflow of metal. Assuming that all inflows depreciate, the model is a convolution [55]:

$$K^{(m)}(t)=\sum_{\chi=t_0}^{t}[F^{(m)}(t-\chi)\times I^{(m)}(\chi)] \quad (2)$$

where the stock $K^{(m)}(t)$ is the sum of the remaining fractions of past inflow vintages $\chi$, from the initial time step $t_0$ to the simulated time t. The remaining fraction of each past inflow vintage was calculated using the probability lifetime distribution $F^{(m)}$. In this study, a normal distribution function was used to determine the lifetime distribution and the corresponding survival function [30].

The water use accounting model was used in this study to account for the water use in power generation [27, 56]. Water use in power generation can be quantified according to the equation below [27]:

$$W = \sum_i E_i \times P_i \qquad (3)$$

where W is the total water use; i represents the type of power generation; $P_i$ denotes the power production of generation type i; and $E_i$ is the power production's water intensity. Thermal power water intensities vary primarily by cooling technology [57]. This study distinguishes three cooling technologies for thermal power: air cooling, once-through cooling and recirculating cooling [58]. In addition, considering that the gas thermal power capacity is smaller than the coal thermal power capacity and limited in specific regions, this study assumes that gas thermal power has the same water use intensity as coal thermal power [28]. In terms of renewable energy power generation, water use intensities are subject to many methodological disputes and uncertainties [59]. Thus, this study uses the water use intensity applied in the previous literature [60, 61]. In addition, the same amount of water use has much greater impacts in water-scarce regions than in water-abundant regions [38, 62]. Water use is adjusted to scarcity-adjusted water use by multiplying it by the Water Stress Index (WSI) [63].

$CO_2$ emissions from power generation were estimated by applying the $CO_2$ emissions accounting model. In this study, renewable energy power generation was deemed a noncarbon emissions source. Thus, this study only considers the direct $CO_2$ emissions from thermal power generation, and they are based on the methodology proposed by the IPCC [64]:

$$F_{CO_2} = \sum_{i=1}^{n} C_i \times EF_i \times O_i \times M_i \qquad (4)$$

where $F_{CO2}$ denotes $CO_2$ emissions; subscript i represents the energy consumption type; $C_i$ is the energy consumption of fuel type i; $EF_i$ is the carbon emissions factor of fuel type i; $O_i$ is the oxidation rate of fuel type i; and $M_i$ is the molecular weight ratio of carbon dioxide to carbon [65, 66].

## 2.2 Constructing the electricity flow network model

Zhang et al. used a node-flow model to depict China's power system and the virtual water transfers embodied in interprovincial electricity transmission [36]. This study adapts their methodology and apply it to describe the electricity flow network, in which each province is characterized as a node, and interprovincial electricity transmissions are characterized as flows. The electricity inflows and outflows for each node are balanced through interprovincial electricity transmissions, which can be expressed as [36]:

$$x_i = p_i + \sum_{j=1}^{n} Q_{ji} = c_i + \sum_{j=1}^{n} Q_{ij} \qquad (5)$$

where i and j are nodes representing province i and province j; $x_i$ is the total electricity of node i; $p_i$ is the total electricity generated within province i by domestic power plants; $c_i$ is the total electricity consumed in province i by all end-users; and $Q_{ij}$ is the electricity flow from node i to node j. Assuming there are N nodes in the electricity flow network, 1×N vectors X, P and C represent the total electricity, electricity generation and electricity consumption, respectively. Let N×N matrix Q represent the electricity flows in the electricity flow network; thus, Q can be expressed as [36]:

$$Q = \begin{bmatrix} 0 & Q_{12} & \cdots & Q_{1n} \\ Q_{21} & 0 & \cdots & Q_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Q_{n1} & \cdots & Q_{n(n-1)} & 0 \end{bmatrix} \qquad (6)$$

Qu et al. proposed a quasi-input-output model to calculate the virtual carbon flows embodied in interprovincial electricity transmission based on the Ghosh form [35]. In this study, a Leontief-Quasi-Input-Output model is used to describe the virtual flows embodied in an interprovincial electricity flow network. Using matrix notation, Equation (1) can be written as [37]:

$$X = Q + C = AX + C \qquad (7)$$

where A is defined as the direct inflow coefficient matrix and can be expressed as [37]:

$$A = Q\hat{X}^{-1} \qquad (8)$$

in which element $A_{ji}$ represents the share rate of the electricity flow from node j to node i in the total electricity flow of node i. Thus, equation (3) can be written as [37]:

$$X = (I - A)^{-1} C \quad (9)$$

where I is the identity matrix, and $L = (I - A)^{-1}$ is the total inflow coefficient matrix of the electricity flow network.

The embodied environmental impacts in the electricity flow network can be calculated by [37]:

$$E^{C} = \varepsilon^{X} (I - A)^{-1} \hat{C} \quad (10)$$

where $\varepsilon^{X}$ is the environmental intensity of the total electricity. In this study, $\varepsilon^{X}$ refers to the metal-water-carbon intensity of the total electricity.

### 2.3 Electricity metal-water-carbon and economic gain transfers

The REI index (Regional environmental inequality index) has been employed in some EUE studies to evaluate unequal transfers between environmental impacts and value added associated with interprovincial or inter-regional trade [48, 67]. In this study, the "electricity REI index" is also employed to evaluate unequal transfers between electricity metal-water-carbon and economic welfare transfers. Based on the TiVA frameworks, this study needs to first calculate the transfers of electricity value added embodied in the electricity flow network [48]:

$$V_{C}^{RS} = \hat{d}^{S} (I - A)^{-1} C^{R} \quad (11)$$

$$V_{C}^{SR} = \hat{d}^{R} (I - A)^{-1} C^{S} \quad (12)$$

$$V_{C-\mathrm{Net}}^{RS} = V_{C}^{RS} - V_{C}^{SR} \quad (13)$$

where $\hat{d}^{R}$ and $\hat{d}^{S}$ represent the diagonal matrixes of the electricity value-added intensities of region R and region S, respectively, with zeros for all other regions. $V_{C}^{RS}$ represents the electricity value added of region S driven by the electricity demand of region R. $V_{C-\mathrm{Net}}^{RS}$ represents the net flows of electricity value added between region R and region S. If $V_{C-\mathrm{Net}}^{RS}>0$, then electricity value-added flows from region R to region S. If $V_{C-\mathrm{Net}}^{RS}<0$, then electricity value-added flows from region S to region R. Similarly, $E_{C-\mathrm{Net}}^{RS}$ represents the net flows of electricity metal-water-carbon between region R and region S.

Assuming that there is an N×N matrix $W_{N\times N}$ and normalizing all elements of W to range from 0~1 [48]:

$$f\left(w\right)=\frac{w-w_{\min}}{w_{\max}-w_{\min}} \qquad (14)$$

Where $w_{max}$ and $w_{min}$ represent the maximum and minimum values of W, respectively. Therefore, the REI matrix of electricity metal-water-carbon and electricity value added $REI^{RS}$ can be obtained [48]:

$$REI^{RS}=\begin{cases} f(E_{C-Net}^{RS}/V_{C-Net}^{RS}),\ if E_{C-Net}^{RS}>0\ and V_{C-Net}^{RS}>0 \\ f(E_{C-Net}^{RS})+f(V_{C-Net}^{RS})+1,\ if E_{C-Net}^{RS}>0\ and V_{C-Net}^{RS}<0 \end{cases} \qquad (15)$$

$$REI^{RS}=\begin{cases} \frac{E_{C-Net}^{RS}/V_{C-Net}^{RS}-n_1}{N_1-n_1}, if E_{C-Net}^{RS}>0\ and V_{C-Net}^{RS}>0 \\ \frac{E_{C-Net}^{RS}-n_2}{N_2-n_2}+\frac{|V_{C-Net}^{RS}|-n_3}{N_3-n_3}+1,\ if E_{C-Net}^{RS}>0\ and V_{C-Net}^{RS}<0 \end{cases} \qquad (16)$$

where $\left|V_{C-Net}^{RS}\right|$ represents the absolute value of $V_{C-\mathrm{Net}}^{RS}$. $n_1$, $n_2$ and $n_3$ are the minimum values of $E_{C-\mathrm{Net}}^{RS}/V_{C-Net}^{RS}$, $E_{C-\mathrm{Net}}^{RS}$ and $\left|V_{C-Net}^{RS}\right|$, respectively. $N_1$, $N_2$ and $N_3$ are the maximum values of $E_{C-\mathrm{Net}}^{RS}/V_{C-Net}^{RS}$, $E_{C-\mathrm{Net}}^{RS}$ and $\left|V_{C-Net}^{RS}\right|$, respectively. When $E_{C-\mathrm{Net}}^{RS}$ and $V_{C-Net}^{RS}$ are both positive, which means that both electricity metal-water-carbon and electricity value added are outsourced from region R to region S, the ratio of $E_{C-\mathrm{Net}}^{RS}/V_{C-Net}^{RS}$ is normalized to 0~1. When $E_{C-\mathrm{Net}}^{RS}$ is positive but $V_{C-Net}^{RS}$ is negative, electricity metal-water-carbon is outsourced from region R to region S, but region R gains electricity value added from region S. This study normalizes both $E_{C-\mathrm{Net}}^{RS}$ and $V_{C-Net}^{RS}$ and sum them in addition to adding 1 to the values.

## 2.4 Data sources

The data necessary for this analysis are of two types: electricity data and socio-economic–environmental target data (i.e., electricity metal-water-carbon data and value-added data). The analysis time is set at 2015. The first type of electricity data exists in three different forms: electricity generation data at the provincial level, electricity consumption data at the provincial level, and inter-grid electricity transmission data. The China Electricity Power Year Book provides provincial electricity generation and consumption data for thermal power, hydropower, nuclear power, wind, solar and biomass [68] According to Qu et al., due to differences in statistical calibre, there are minor differences (less than 2%) between the sum of electricity generation and imports and the sum of electricity consumption and exports [35]. This study adjusts the provincial electricity consumption by the electricity generation, imports and exports data. Interprovincial electricity transmission data in 2015 were obtained from the China Electricity Council [68]. Most of the transmission data are recorded at the provincial level. Some transmission data are from the subnational grid and are disaggregated to the provincial level based on actual electricity transmission situations [36].

The second type of data are provincial electricity metal-water-carbon data and electricity value-added data. In this study, electricity metal-water-carbon refers to metal used in power construction, and water use and $CO_2$ emissions in electricity generation. Provincial metal use in power construction is based on dynamic material flow analysis (D-MFA) [30]. We choose the copper, iron and aluminium as the calculated metal in this study. Water use data are quantified by electricity generation based on the water consumption intensity data collected from the relevant literature (e.g., thermal power [28, 36]; hydropower; nuclear; wind; solar and biomass). Provincial $CO_2$ emissions in electricity generation are calculated based on provincial fuel combustion and emission factors [65].

## 3. Results

### 3.1 Mismatch between value added and the environmental impacts of electricity production and consumption

Regions with different economic income levels play different roles in electricity flow networks. Figure 1 depicts the interprovincial electricity flow and structure ratios in China in 2015. This study defines “total electricity” to characterize the electricity flow structure of each province. The total electricity of a province is equal to the sum of its electricity production and imported electricity, as well as the sum of its electricity consumption and exported electricity [35]. In 2015, the electricity production of China was 5470 TWh, of which 14.9% (856 TWh) flowed between provinces. From the perspective of imports, Beijing, Shanghai, Hebei and Guangdong imported more than 30% of their total electricity, accounting for 54.7%, 38.1%, 35.2% and 30.8%, respectively. From the perspective of exports, Guizhou, Sichuan and Inner Mongolia exported more than 30% of their total electricity. Provinces with higher import shares are also more often high-income regions, which need large amounts of imported electricity to satisfy their local electricity demand. Most of the provinces with higher export shares, which are mainly located in the central and north-western regions, have higher power production.

To make it easier to compare transfers of value added and environmental impacts, in this study, this study defines the concept of the “transfer ratio” (shown in Figure 2). The transfer ratio refers to the proportion of the difference between the consumption-based and production-based electricity metal-water-carbon and value added at the consumption-based electricity metal-water-carbon and value added. It reflects the proportion of the electricity metal-water-carbon and value added transferred or accepted by a province in its overall consumption-based electricity metal-water-carbon and value added. A positive value for the transfer ratio means that the province has net transferred electricity metal-water-carbon and value added to other provinces (red bars in Figure

2), while a negative value means that the province has received the net transferred electricity metal-water-carbon and value added from other provinces (green bars in Figure 2). Detailed information on the electricity metal-water-carbon and valued added in the electricity flow network of 31 provinces in China in 2015 is depicted in Figure 2. The coloured rectangular bars represent the production-based electricity metal-water-carbon and value added, and the hollow rectangular bars represent the consumption-based electricity metal-water-carbon and value added.

The asymmetry in the distribution of socio-economic–environmental impacts is especially apparent in the direct comparison between electricity metal-water-carbon and value added from the two opposing perspectives. The proportion of electricity value added outsourced from wealthier provinces is much lower than the proportion of electricity metal-water-carbon outsourced. Wealthier provinces (Beijing and Tianjin, southern coastal provinces, etc.) have higher consumption-based than production-based electricity metal-water-carbon and value added. Beijing, for example, the transfer ratios of electricity metal-water-carbon are 57.1%, 31.3% and 91.3%, respectively. The production-based electricity value added of Beijing is 20.2 billion RMB, the consumption-based electricity value added is 28.8 billion RMB and the transfer ratio of electricity value added is 29.8%. This means that Beijing net-outsourced more electricity metal-water-carbon than electricity value added, in particular, electricity $CO_2$ emissions. The transfer ratios of electricity metal-water-carbon in Guangdong are 34.4%, 28.4% and 16.8%, respectively. The production-based electricity value added of Guangdong is 164.8 billion RMB, while its consumption-based electricity value added is 186.5 billion RMB, and the transfer ratio of electricity value added is 11.6%. These wealthier provinces tend to retain electricity value added within their territories and outsource electricity metal-water-carbon to other provinces through electricity flow networks. Less-developed provinces do not obtain equivalent economic benefits while receiving electricity metal-water-carbon outsourced from wealthier provinces. This undoubtedly increases the degree of inequality between the electricity resource and environmental effects and the economic benefits in different regions. This inequality is also caused by intensive resource and environmental effects and low value added in power production in less developed regions.

In addition to the mismatch between the spill-over of electricity economic benefits and the overall electricity metal-water-carbon impacts, there are situations where the spill-over proportion of economic benefits is equivalent to one or two electricity environmental elements but seriously mismatched with the others. Shanghai, Jiangsu and Zhejiang, located in the eastern coastal region, show a serious mismatch between the embodied electricity value added and the electricity scarcity-adjusted water use outsourced in the electricity flow network. The transfer ratios of electricity scarcity-adjusted water use in Shanghai, Jiangsu and Zhejiang are 85.1%, 34.9% and 94.3%, respectively, while the transfer ratios of electricity value added are 19.4%, 7.8% and 12.3%. The proportion of outsourced electricity scarcity-adjusted water use is significantly higher than that of electricity value added. This means that these provinces outsourced a high amount of electricity scarcity-adjusted water use to other provinces, but the receiving provinces did not obtain equivalent economic benefits through an electricity flow network. The gap between these two values is very large, which means that there is a significant degree of inequality between electricity scarcity-adjusted water use and economic benefits. The transfer ratio of electricity metal-carbon in Shanghai, Jiangsu and Zhejiang is roughly the same as that of the transfer ratio of electricity value added, which is basically at the 10% level. This also reflects that the imported electricity in Shanghai, Jiangsu and Zhejiang is mainly scarce water intensive and low value added.

In contrast, Gansu, Ningxia, and others located in the northwest region, receive more than one certain outsourced electricity environmental element. The transfer ratios of electricity metal-water-carbon in Gansu and Ningxia are -14.7%/-30.2%, -8.7%/-34.0% and -15.3%/-4.2%, respectively, while the transfer ratios of electricity value added are -7.1%/-27.9%. Ningxia receives more net-outsourced electricity value added through the electricity flow network, as it was higher than the received net-outsourced electricity scarcity-adjusted water use but lower than received net-outsourced electricity metal use and $CO_2$ emissions. This means that there is significant inequality between electricity metal-carbon and the economic benefits received by Ningxia through an electricity flow network.

In some provinces with a large proportion of power production, such as Inner Mongolia and Shanxi, relatively equivalent electricity resource and environmental effects and economic benefits were identified. The transfer ratios of electricity metal-water-carbon in Inner Mongolia and Shanxi are -53.5%/-37.2%, -53.8%/-40.3% and -53.6%/-37.2%, respectively, while the transfer ratio of electricity value added is -52.2%/-37.3%. Inner Mongolia and Shanxi are the two largest power production bases in China, which indicates that expansion of their power capacity would help them obtain more equivalent electricity economic benefits by receiving outsourced electricity resources and environmental effects.

The transfer direction of the electricity metal-water-carbon and electricity value added of each province are mostly the same, that is, a province that outsources/receives electricity metal-water-carbon to/from other provinces through the electricity flow network also outsources/receives electricity value added to/from other provinces. Heilongjiang and Shaanxi, however, are special cases. Heilongjiang's consumption-based electricity metal use and $CO_2$ emissions are lower than its production-based electricity metal use and $CO_2$ emissions, while its consumption-based electricity scarcity-adjusted water use is higher than its production-based electricity scarcity-adjusted water use. The transfer ratios of electricity metal-water-carbon in Heilongjiang are -7.4%, 24.2% and -6.5%, respectively. The production-based electricity value added is 22.1 billion RMB, and the consumption-based electricity value added is 19.7 billion RMB, while the transfer ratio is -12.3%. The proportion of the electricity value added received by Heilongjiang through the electricity flow network is significantly higher than the proportion of the received electricity metal use and $CO_2$ emissions. Meanwhile, it also outsources electricity scarcity-adjusted water use to other provinces through an electricity flow network. Such phenomena can also be found in Shaanxi. The transfer ratios of electricity metal-water-carbon in Shaanxi are -5.9%, 30.0% and -22.9%, respectively. The production-based electricity value added is 40.0 billion RMB, the consumption-based electricity value added is 31.9 billion RMB, and the transfer ratio is -25.3%. From the perspective of the electricity carbon effect, the economic benefit of Shaanxi is equal to the proportion of the electricity carbon effect received. However, considering the electricity resource effect, the proportion of economic benefits received by Shaanxi is significantly higher than the electricity received, and a reverse outsourced spill-over of electricity scarcity-adjusted water use is also observed.

### 3.2 Directions of value-added flows and environmental flows in electricity flows

Figure 3 shows the directions of electricity metal-water-carbon flows and value-added flows embodied in China's interprovincial electricity flows in 2015. The black arrow in the figure represents the direction of the power flow (i.e., power exported to power imported), and the numbers on the arrows represent the embodied electricity metal-water-carbon and value added. The embodied electricity metal-water-carbon and value added flow in the opposite direction (i.e., power imported to power exported). The colours of each base map indicate the province's net embodied electricity metal-water-carbon and value added (i.e., the difference between production-based and consumption-based electricity metal-water-carbon and value added).

The electricity value added is mainly transferred from the southeast coastal provinces to the southwest and central provinces and from Beijing-Tianjin-Hebei to other regions in the north (Figure 3d). For electricity metal-water-carbon, embodied electricity metal use is mainly transferred from Guangdong to the southwest and central provinces; embodied electricity scarcity-adjusted water use is mainly transferred from Jiangsu, Zhejiang and Shanghai to Sichuan; embodied electricity $CO_2$ emissions are mainly transferred from Beijing-Tianjin-Hebei to other regions in the north. These flows can be summarized as occurring along three “corridors”: the northern corridor, the southern corridor and the central corridor [69].

The northern corridor refers to the transfers from the Beijing-Tianjin-Hebei metropolitan area to northwest coal-abundant provinces. Hebei is an important province for the spill-over of electricity value added, of which the highest electricity value added is transferred to Shaanxi (5.78 billion RMB). Inner Mongolia is an important province of electricity value added receivers; these receive electricity value added transferred from Hebei (5.50 billion RMB), Beijing (2.71 billion RMB) and Tianjin (1.60 billion RMB). There are electricity value-added transfers between Beijing-Tianjin-Hebei internally. Among them, the highest electricity value-added transfer pair of provinces is Beijing to Tianjin (2.33 billion RMB), followed by Beijing to Hebei (1.90 billion RMB) and Tianjin to Hebei (1.44 billion RMB). Meanwhile, the highest electricity $CO_2$ emissions transfers are in the northern corridor (Figure 3c). The pairs of provinces with the highest electricity $CO_2$ emissions transfers are Hebei to Inner Mongolia (41.2 Mt), Hebei to Shanxi (29.7 Mt), Beijing to Inner Mongolia (23.3 Mt), and Tianjin to Inner Mongolia (13.8 Mt). The northwest provinces have gained economic benefits by meeting Beijing-Tianjin-Hebei’s power demand along with receiving electricity $CO_2$ emissions.

The southern corridor refers to the transfer from the southwest grid to the Pearl River Delta region. Guangdong consumes electricity from Hubei, Hunan, Guizhou and Yunnan provinces through electricity flows and spills the electricity value added to these provinces. The highest pairs of transferring provinces are Guangdong to Yunnan (6.00 billion RMB), followed by Guangdong to Guizhou (5.51 billion RMB), Guangdong to Hubei (3.88 billion RMB) and Guangdong to Hunan (3.13 billion RMB). As seen from Figure 3a, there is also a significant transfer of electricity metal use between Guangdong and these provinces. The highest value existed in Guangdong to Yunnan (51.2 kt), followed by Guangdong to Guizhou (33.3 kt) and Guangdong to Hubei (8.1 kt). Guangdong transfers 17.1%, 11.1% and 2.7% of the electricity metal use to Yunnan, Guizhou and Hubei, respectively, but only 3.2%, 3.1% and 2.7% of the electricity value added. This indicates that there is a certain degree of unequitable transfer embodied in these electricity flows.

The central corridor refers to the transfer from the central grid (e.g., Sichuan Province) to the Yangtze River Delta. The electricity value added transferred from Jiangsu-Zhejiang-Shanghai to Sichuan is the peak of regional transfer, while the highest transfer pairs of provinces is Jiangsu to Sichuan (7.02 billion RMB), followed by Zhejiang to Sichuan (6.15 billion RMB) and Shanghai to Sichuan (5.59 billion RMB). As seen from Figure 3b, scarcity-adjusted water use is also transferred from Jiangsu-Zhejiang-Shanghai to Sichuan. Jiangsu-Zhejiang-Shanghai transfers 33.0%, 81.7% and 90.2% of the electricity scarcity-adjusted water use to Sichuan, respectively, but only 4.2%, 11.5% and 5.8% of electricity value added. Sichuan has not gained equal economic benefits through electricity flows.

### 3.3 Unequal and imbalanced electricity flows, environmental flows and value-added flows

To capture the equity of socio-economic–environmental sustainability in electricity flows, this study obtains the REI between electricity metal-water-carbon and electricity value added to compare the degree of equity among different pairs of provinces. Higher REI values indicate more serious electricity metal-water-carbon impacts and value-added imbalances between a pair of provinces. When a pair of provinces has an REI index value between 0 and 1, net electricity metal-water-carbon and net value added are both outsourced at the same time, and they are called a Category I pair of provinces in this study. In contrast, when the value is greater than 1, the province suffering inequality not only receives electricity metal-water-carbon inflows but also outsources the value added to the corresponding province, and they are called a Category II pair of provinces in this study. The REI matrix of electricity metal-water-carbon and electricity value added are shown in Figure 4.

Seventeen pairs of provinces fall into Category I, with inflows of electricity value added and outflows of electricity $CO_2$ emissions, while there are 17 pairs of provinces in electricity scarcity-adjusted water use and 5 pairs of provinces in electricity metal use. The provincial pair with the highest REI value is Shaanxi-Gansu (REI=2.02). In 2015, Shaanxi outsourced 1.22 Mt net electricity $CO_2$ emissions, 0.3 billion $m^2$ and 8.3 kt electricity metal use to Gansu but received 0.61 billion RMB electricity value added from Gansu through the electricity flow network. Due to disadvantages in the structure of the electricity flow, Gansu receives outsourced net electricity $CO_2$ emissions from Shaanxi but does not obtain economic benefits; instead, there is a simultaneous net electricity value-added transfer from Gansu to Shaanxi. Other higher REIs in Category I include Sichuan-Shaanxi (REI=1.94, carbon), Jilin-Inner-Mongolia (REI=1.61, carbon), Hubei-Henan (REI=1.47, carbon), Shanghai-Zhejiang (REI=1.20, water), Henan-Hubei (REI=1.09, water), Qinghai-Ningxia (REI=1.01, water), Jilin-Inner-Mongolia (REI=1.13, metal) and Sichuan-Gansu (REI=1.03, metal). That inequality occurred not only between developed provinces and less developed provinces but also between less developed provinces and developed provinces.

A total of 432 pairs of provinces (carbon), 442 pairs of provinces (water) and 457 pairs of provinces (metal) fall into Category II, with inflows of electricity value added and inflows of electricity metal-water-carbon impacts. The provincial pair with the highest REI value in Category II is Sichuan-Ningxia (REI=1.00). In 2015, Sichuan outsourced 0.02 Mt net electricity $CO_2$ emissions and 0.5 million RMB to Ningxia through an electricity flow network. Another high REI index in Category II is Shaanxi-Ningxia. The share of net electricity $CO_2$ emissions outsourced from Shaanxi to Ningxia is 19.5%, while the share of net electricity value added is 5.0%.

## 4. Discussion and policy implications

The asymmetry in the distribution of electricity socio-economic–environmental equity is especially apparent in the direct comparison between embodied electricity metal-water-carbon and valued added. The results show that, in total, 15.0% (540.8 kt), 17.4% (1.55 billion $m^3$) and 13.1% (440.2 Mt) of consumption-based electricity metal-water-carbon were outsourced to other provinces through the electricity flow network in 2015. However, only 9.3% (138.8 billion) of consumption-based electricity value added was outsourced to other provinces. This observation means that many provinces supply electricity to other provinces and receive outsourced external electricity metal-water-carbon, but they do not gain equivalent economic benefits. This asymmetry is a structural feature of electricity trade relations, and coupling exists in the electricity economic–environmental inequity embodied in such an unequal exchange.

This goes beyond other recent studies that only simply capture the environmental impacts of electricity transmission and flow. This analysis referred to ecologically unequal exchange theory and TiVA global value chain theory and methodologically fitted them to electricity flow networks. The use of these models provided a systematic perspective on electricity socio-economic–environmental equity. The results found significant differences in the value-added compensation of electricity metal-water-carbon, and these differences were mostly determined by a region's economic level. Wealthier provinces outsourced a large share of consumption-based electricity metal-water-carbon to other provinces through electricity flow networks but retained a large share of electricity value added. For example, the consumption-based electricity metal-water-carbon of Beijing is 1.46-fold~11.7-fold that of its production-based electricity metal-water-carbon. In 2015, Beijing outsourced 91.3%, 31.4% and 48.3% of consumption-based electricity metal-water-carbon to other provinces, respectively, but over 70% of consumption-based electricity value added was retained. In addition, the ratio range of each province's consumption-based and production-based electricity metal-water-carbon is higher than the ratio range of consumption-based and production-based electricity value added. More resource-intensive and environment-intensive but low-value-added electricity is transferred between all provinces through the electricity flow network.

With regard to the equitable level of socio-economic–environmental sustainability in the electricity flow network, the REI between electricity metal-water-carbon and electricity value added indicates that money and environmental impacts flowing in opposite directions depict higher inequity, while flows of money and environmental impacts aligned in the same direction have lower inequity. Some provinces, such as Shaanxi, make use of advantages in the electricity structure and have gained economic benefits from electricity flows. This study found that inequality occurred not only between developed and less developed provinces but also between less developed provinces and developed provinces.

Economic and environmental inequality among regions is a manifestation of China's long-term unbalanced regional development and power planning [48]. Over the past few decades, electricity flows have been associated with the movement of resources and environment-intensive power production from developed regions to the central, northwest and northeast regions. They provided electricity for coastal developed provinces, and at the same time, they achieved the associated power economic pulling effect. However, because of the low technical efficiency and power economic value added, they did not obtain equivalent economic benefits, and thus, regional electricity socio-economic–environment imbalances still existed. This inequity is continuing and creates a dilemma between economic development and environmental sustainability [70, 71].

To eliminate the dilemma and solve the problem of inequity in the socio-economic–environmental sustainability embodied in electricity flow, it is essential to implement more targeted environmental and economic policies for power systems. The central, northwest and northeast regions, which undertake the main responsibility for power production, need to vigorously develop advanced, more efficient, and low environment-intensive power production technology. While reducing the negative effects on the environment, technological progress of power production could promote the development of the regional economy and deliver higher economic value added. In the long run, more reforms to the electricity market are needed. Although the power price in China is formed partly by certain market factors, it is mainly controlled by the government rather than determined by supply and demand, which makes the power production enterprises in the central and western regions reluctant to pay greater environmental governance costs [48]. At present, in the face of this problem, researchers have carried out many studies to promote the reform of China's electricity market [50]. If the electricity price can be determined based on the market pricing mechanism, the price could be adjusted according to the environmental cost [72]. Although this approach cannot guarantee the internalization of all external environmental costs, it can to a certain extent help solve the environmental problems brought by the power industry. In the relationship between supply and demand, people should strengthen demand-side responsibility, promote the adoption of corresponding ecological and resource compensation strategies, and encourage wealthier provinces to reduce the environmental effects of power generation on less affluent regions by providing funding and technologies [73]. At the same time, power enterprises should also strengthen supply chain management and solve problem by strengthening their own environmental responsibility that of other enterprises upstream and downstream in the supply chain [48, 74, 75].

## 5. Conclusions

This study proposed a multi-model framework to trace the transfers environmental impacts (measured using metal-water-carbon) and economic benefits (measured using valued added) of electricity as well as the degree of equity in the economic–environmental sustainability embodied in electricity flows in China in 2015. The results reveal whether electricity flows affect the equity of regional economic–environmental sustainability. From the analysis and discussion of regional economic–environmental equity, the main achievements can be summarised as follows:

1. In total, 15.0%, 17.4% and 13.1% of consumption-based electricity metal-water-carbon were outsourced to other provinces through the electricity flow network in 2015, respectively, while only 9.3% of the consumption-based electricity value added was outsourced. The electricity value added is mainly transferred from the southeast coastal provinces to the southwest and central provinces and from Beijing-Tianjin-Hebei to other regions in the north. More resource-intensive and environment-intensive, but low-value-added, electricity is transferred across all provinces through the electricity flow networks.

2. Asymmetry in the distribution of socioeconomic and environmental impacts is especially apparent. The proportion of electricity value added outsourced from wealthier provinces is much lower than the proportion of outsourced electricity metal-water-carbon.

3. In addition to the mismatch between the spill-over of electricity economic benefits and the overall electricity metal-water-carbon impacts, there are situations where the spill-over proportion of economic benefits is equivalent to one or two electricity environmental elements but seriously mismatched with the others. In some provinces with large proportions of power production, such as Inner Mongolia and Shanxi, relatively equivalent electricity resource and environmental effects and economic benefits were identified.

4. Regional economic–environmental inequity exists in bilateral electricity flow. Higher REI values indicate more serious electricity metal-water-carbon impacts and value-added imbalances between two provinces. The provincial pair with the highest REI value is Shaanxi-Gansu (REI=2.02). Owing to the disadvantages in the structure of its electricity flow, Gansu receives outsourced net electricity $CO_2$ emissions from Shaanxi but does not obtain economic benefits; instead, there is a simultaneous net

electricity value-added transfer from Gansu to Shaanxi.

This study explores the regional economic–environmental equity hampered by some unsustainable electricity flows. It offers insights to help policymakers to better address the potential environmental and economic implications of electricity flows to ensure the sustainable growth of electricity production and consumption. To eliminate the dilemma and solve the problem of inequity in the economic–environmental sustainability embodied in electricity flow, it is essential to implement more targeted environmental and economic policies for power systems. The results of analysis will be also helpful for similar investigation in each country/region in the future.

## Nomenclature

| | |
|---|---|
| REI index | Regional environmental inequality index |
| EUE | Ecologically unequal exchange |
| TiVA | Trade in value added |
| MRIO | Multi-regional input-output |
| D-MFA | Dynamic material flow analysis |

| | |
|---|---|
| $I^{(m)}$ | inflows of metal |
| $O^{(m)}$ | outflow of metal |
| $K^{(m)}$ | stock of metal |
| $F^{(m)}$ | probability lifetime distribution |
| $\chi$ | past inflow vintages |
| W | total water use |
| $E_i$ | power production’s water intensity |
| $P_i$ | power production |
| $F_{CO2}$ | $CO_2$ emissions |
| $C_i$ | energy consumption |
| $EF_i$ | carbon emissions factor |
| $O_i$ | oxidation rate |
| $M_i$ | molecular weight ratio of carbon dioxide to carbon |
| $x_i$ | total electricity |
| $p_i$ | total electricity generated by domestic power plants |
| $c_i$ | total electricity consumed by all end-users |
| $Q_{ij}$ | electricity flows |
| X | total electricity vector |
| P | electricity generation vector |
| C | electricity consumption vector |
| Q | electricity flows matrix |
| A | direct inflow coefficient matrix |
| $A_{ji}$ | share rate of the electricity flow |
| I | identity matrix |
| L | total inflow coefficient matrix |
| $E^C$ | embodied environmental impacts |
| $\varepsilon^X$ | environmental intensity of the total electricity |
| $\hat{d}^R$ | diagonal matrixes of the electricity value-added intensities of region R |
| $\hat{d}^S$ | diagonal matrixes of the electricity value-added intensities of region S |
| $V_C^{RS}$ | electricity value added of region S driven by the electricity demand of region R |
| $V_{C-Net}^{RS}$ | net flows of electricity value added between region R and region S |
| $E_{C-Net}^{RS}$ | net flows of electricity metal-water-carbon between region R and region S |
| $w_{max}$ | maximum values of matrix W |

| | |
|---|---|
| $w_{mIN}$ | minimum values of matrix W |
| $REI^{RS}$ | REI matrix of electricity metal-water-carbon and electricity value added |
| $\left\|V_{C-Net}^{RS}\right\|$ | absolute value of $V_{C-Net}^{RS}$ |
| $n_1$ | minimum values of $E_{C-Net}^{RS}/V_{C-Net}^{RS}$ |
| $n_2$ | minimum values of $E_{C-Net}^{RS}$ |
| $n_3$ | minimum values of $\left\|V_{C-Net}^{RS}\right\|$ |
| $N_1$ | maximum values of $E_{C-Net}^{RS}/V_{C-Net}^{RS}$ |
| $N_2$ | maximum values of $E_{C-Net}^{RS}$ |
| $N_3$ | maximum values of $\left\|V_{C-Net}^{RS}\right\|$ |

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## References

[1] Ahmadi SE, Sadeghi D, Marzband M, Abusorrah A, Sedraoui K. Decentralized bi-level stochastic optimization approach for multi-agent multi-energy networked micro-grids with multi-energy storage technologies. Energy. 2022;245.
[2] Nasiri N, Zeynali S, Ravadanegh SN, Marzband M. A hybrid robust-stochastic approach for strategic scheduling of a multi-energy system as a price-maker player in day-ahead wholesale market. Energy. 2021;235.
[3] Williams JH, DeBenedictis A, Ghanadan R, Mahone A, Moore J, Morrow WR, et al. The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. Science. 2012;335:53-9.
[4] Zhou N, Zhang JJ, Khanna N, Fridley D, Jiang S, Liu X. Intertwined impacts of water, energy development, and carbon emissions in China. Appl Energ. 2019;238:78-91.
[5] Baherifard MA, Kazemzadeh R, Yazdankhah AS, Marzband M. Intelligent charging planning for electric vehicle commercial parking lots and its impact on distribution network's imbalance indices. Sustain Energy Grids. 2022;30.
[6] Kahrl F, Williams JH, Hu JF. The political economy of electricity dispatch reform in China. Energ Policy. 2013;53:361-9.
[7] Peng W, Yuan JH, Zhao Y, Lin MY, Zhang Q, Victor DG, et al. Air quality and climate benefits of long-distance electricity transmission in China. Environ Res Lett. 2017;12.
[8] Qin Y, Curmi E, Kopec GM, Allwood JM, Richards KS. China's energy-water nexus - assessment of the energy sector's compliance with the "3 Red Lines" industrial water policy. Energ Policy. 2015;82:131-43.
[9] Sadeghi D, Amiri N, Marzband M, Abusorrah A, Sedraoui K. Optimal sizing of hybrid renewable energy systems by considering power sharing and electric vehicles. Int J Energ Res. 2022;46:8288-312.
[10] Ahmad F, Iqbal A, Ashraf I, Marzband M, Khan I. Optimal location of electric vehicle charging station and its impact on distribution network: A review. Energy Rep. 2022;8:2314-33.
[11] Jin Y, Behrens P, Tukker A, Scherer L. The energy-water nexus of China's interprovincial and seasonal electric power transmission. Appl Energ. 2021;286.
[12] Zhang PF, Cai WQ, Yao MT, Wang ZY, Yang LZ, Wei WD. Urban carbon emissions associated with electricity consumption in Beijing and the driving factors. Appl Energ. 2020;275.

[13] Kazemi-Razi SM, Abyaneh HA, Nafisi H, Ali Z, Marzband M. Enhancement of flexibility in multi-energy microgrids considering voltage and congestion improvement: Robust thermal comfort against reserve calls. Sustain Cities Soc. 2021;74.

[14] Zhang YY, Fang JK, Wang SG, Yao HL. Energy-water nexus in electricity trade network: A case study of interprovincial electricity trade in China. Appl Energ. 2020;257.

[15] Qu S, Wang HX, Liang S, Shapiro AM, Suh SW, Sheldon S, et al. A Quasi-Input-Output model to improve the estimation of emission factors for purchased electricity from interconnected grids. Appl Energ. 2017;200:249-59.

[16] Holland RA, Scott K, Agnolucci P, Rapti C, Eigenbrod F, Taylor G. The influence of the global electric power system on terrestrial biodiversity. P Natl Acad Sci USA. 2019;116:26078-84.

[17] de Chalendar JA, Taggart J, Benson SM. Tracking emissions in the US electricity system. P Natl Acad Sci USA. 2019;116:25497-502.

[18] Yi BW, Zhang SH, Wang Y. Estimating air pollution and health loss embodied in electricity transfers: An inter-provincial analysis in China. Sci Total Environ. 2020;702.

[19] Chini CM, Djehdian LA, Lubega WN, Stillwell AS. Virtual water transfers of the US electric grid. Nat Energy. 2018;3:1115-23.

[20] Zhang W, Wang F, Hubacek K, Liu Y, Wang JN, Feng KS, et al. Unequal Exchange of Air Pollution and Economic Benefits Embodied in China's Exports. Environ Sci Technol. 2018;52:3888-98.

[21] Wiedmann T, Lenzen M. Environmental and social footprints of international trade. Nat Geosci. 2018;11:314-21.

[22] Dorninger C, Hornborg A, Abson DJ, von Wehrden H, Schaffartzik A, Giljum S, et al. Global patterns of ecologically unequal exchange: Implications for sustainability in the 21st century. Ecol Econ. 2021;179.

[23] Schaffartzik A, Pichler M. Extractive Economies in Material and Political Terms: Broadening the Analytical Scope. Sustainability-Basel. 2017;9.

[24] Zhang H, Da YB, Zhang X, Fan JL. The impacts of climate change on coal-fired power plants: evidence from China. Energ Environ Sci. 2021;14:4890-902.

[25] Li JS, Wei WD, Zhen W, Guo Y, Chen B. How Green Transition of Energy System Impacts China's Mercury Emissions. Earths Future. 2019;7:1407-16.

[26] Li JS, Peng K, Wang P, Zhang N, Feng K, Guan DB, et al. Critical Rare-Earth Elements Mismatch Global Wind- Power Ambitions. One Earth. 2020;3:116-25.

[27] Liao XW, Hall JW, Eyre N. Water use in China's thermoelectric power sector. Global Environ Chang. 2016;41:142-52.

[28] Liao XW, Hall JW. Drivers of water use in China's electric power sector from 2000 to 2015. Environ Res Lett. 2018;13.

[29] Wei WD, Li JS, Chen B, Wang M, Zhang PF, Guan DB, et al. Embodied greenhouse gas emissions from building China's large-scale power transmission infrastructure. Nat Sustain. 2021;4:739-47.

[30] Li FY, Ye ZY, Xiao XL, Xu JJ, Liu G. Material stocks and flows of power infrastructure development in China. Resour Conserv Recy. 2020;160.

[31] Ji L, Liang S, Qu S, Zhang YX, Xu M, Jia XP, et al. Greenhouse gas emission factors of purchased electricity from interconnected grids. Appl Energ. 2016;184:751-8.

[32] Song R, Zhu J, Hou P, Wang H. Getting every ton of emissions right: An analysis of emission factors for purchased electricity in China. World Resources Institute, Working Paper. 2013.

[33] Lindner S, Liu Z, Guan DB, Geng Y, Li X. CO2 emissions from China's power sector at the provincial level: Consumption versus production perspectives. Renew Sust Energ Rev. 2013;19:164-72.

[34] Zhu YN, Ke J, Wang JH, Liu H, Jiang S, Blum H, et al. Water transfer and losses embodied in the West-East electricity transmission project in China. Appl Energ. 2020;275.

[35] Qu S, Liang S, Xu M. CO2 Emissions Embodied in Interprovincial Electricity Transmissions in China. Environ Sci Technol. 2017;51:10893-902.

[36] Zhang C, Zhong LJ, Liang S, Sanders KT, Wang J, Xu M. Virtual scarce water embodied in inter-provincial electricity transmission in China. Appl Energ. 2017;187:438-48.

[37] Wang HX, Wang WC, Liang S, Zhang C, Qu S, Liang YH, et al. Determinants of Greenhouse Gas Emissions from Interconnected Grids in China. Environ Sci Technol. 2019;53:1432-40.

[38] Liao XW, Chai L, Jiang Y, Ji JP, Zhao X. Inter-provincial electricity transmissions' co-benefit of national water savings in China. J Clean Prod. 2019;229:350-7.

[39] Hornborg A. Ecological economics, Marxism, and technological progress: Some explorations of the conceptual foundations of theories of ecologically unequal exchange. Ecol Econ. 2014;105:11-8.

[40] Prell C, Sun LX, Feng KS, Myroniuk TW. Inequalities in Global Trade: A Cross-Country Comparison of Trade Network Position, Economic Wealth, Pollution and Mortality. Plos One. 2015;10.

[41] Prell C. Wealth and pollution inequalities of global trade: A network and input-output approach. Soc Sci J. 2016;53:111-21.

[42] Pinero P, Bruckner M, Wieland H, Pongracz E, Giljum S. The raw material basis of global value chains: allocating environmental responsibility based on value generation. Econ Syst Res. 2019;31:206-27.

[43] Dai F, Yang JJ, Guo H, Sun HP. Tracing CO2 emissions in China-US trade: A global value chain perspective. Sci Total Environ. 2021;775.

[44] Meng B, Peters GP, Wang Z, Li M. Tracing CO2 emissions in global value chains. Energ Econ. 2018;73:24-42.

[45] Meng B, Fang Y, Guo JM, Zhang YX. Measuring China's domestic production networks through Trade in Value-added perspectives. Econ Syst Res. 2017;29:48-65.

[46] Yu Y, Feng KS, Hubacek K. China's unequal ecological exchange. Ecol Indic. 2014;47:156-63.

[47] Zhao HY, Zhang Q, Huo H, Lin JT, Liu Z, Wang HK, et al. Environment-economy tradeoff for Beijing-Tianjin-Hebei's exports. Appl Energ. 2016;184:926-35.
[48] Zhang W, Liu Y, Feng KS, Hubacek K, Wang JN, Liu MM, et al. Revealing Environmental Inequality Hidden in China's Inter-regional Trade. Environ Sci Technol. 2018;52:7171-81.
[49] He G, Zhang HL, Xu Y, Lu X. China's clean power transition: Current status and future prospect. Resour Conserv Recy. 2017;121:3-10.
[50] Guo HY, Davidson MR, Chen QX, Zhang D, Jiang N, Xia Q, et al. Power market reform in China: Motivations, progress, and recommendations. Energ Policy. 2020;145.
[51] He G, Kammen DM. Where, when and how much solar is available? A provincial-scale solar resource assessment for China. Renewable Energy. 2016;85:74-82.
[52] Lu X, McElroy MB, Peng W, Liu SY, Nielsen CP, Wang HK. Challenges faced by China compared with the US in developing wind power. Nat Energy. 2016;1.
[53] Hejazi MI, Voisin N, Liu L, Bramer LM, Fortin DC, Hathaway JE, et al. 21st century United States emissions mitigation could increase water stress more than the climate change it is mitigating. P Natl Acad Sci USA. 2015;112:10635-40.
[54] Wang P, Chen LY, Ge JP, Cai WJ, Chen WQ. Incorporating critical material cycles into metal-energy nexus of China's 2050 renewable transition. Appl Energ. 2019;253.
[55] Fishman T, Graedel TE. Impact of the establishment of US offshore wind power on neodymium flows. Nat Sustain. 2019;2:332-8.
[56] Zhang C, Zhong LJ, Wang J. Decoupling between water use and thermoelectric power generation growth in China. Nat Energy. 2018;3:792-9.
[57] Macknick J, Newmark R, Heath G, Hallett KC. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ Res Lett. 2012;7.
[58] Zhang C, Zhong LJ, Fu XT, Wang J, Wu ZX. Revealing Water Stress by the Thermal Power Industry in China Based on a High Spatial Resolution Water Withdrawal and Consumption Inventory. Environ Sci Technol. 2016;50:1642-52.
[59] Bakken TH, Modahl IS, Raadal HL, Bustos AA, Arnoy S. Allocation of water consumption in multipurpose reservoirs. Water Policy. 2016;18:932-47.
[60] Wang CY, Wang RR, Hertwich E, Liu Y, Tong F. Water scarcity risks mitigated or aggravated by the inter-regional electricity transmission across China. Appl Energ. 2019;238:413-22.
[61] Zhang YY, Hou SR, Chen SQ, Long HH, lIU JF, Wang JQ. Tracking flows and network dynamics of virtual water in electricity transmission across China. Renewable and Sustainable Energy Reviews. 2020.
[62] Pfister S, Koehler A, Hellweg S. Assessing the Environmental Impacts of Freshwater Consumption in LCA. Environ Sci Technol. 2009;43:4098-104.
[63] Pfister S, Hellweg S. The water "shoesize" vs. footprint of bioenergy. P Natl Acad Sci USA. 2009;106:E93-E4.
[64] IPCC. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas

Inventories. 2019.
[65] Shan YL, Huang Q, Guan DB, Hubacek K. China CO2 emission accounts 2016-2017. Sci Data. 2020;7.
[66] Liu Z, Guan DB, Wei W, Davis SJ, Ciais P, Bai J, et al. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. Nature. 2015;524:335-+.
[67] Chen WM, Kang JN, Han MS. Global environmental inequality: Evidence from embodied land and virtual water trade. Sci Total Environ. 2021;783.
[68] CEC. Statistics for Electric Power Industry in China. Beijing: China Electricity Council; 2013-2017.
[69] Liu L, Yin ZH, Wang P, Gan YW, Liao XW. Water-carbon trade-off for inter-provincial electricity transmissions in China. J Environ Manage. 2020;268.
[70] Lin JT, Du MX, Chen LL, Feng KS, Liu Y, Martin RV, et al. Carbon and health implications of trade restrictions. Nat Commun. 2019;10.
[71] Liu Z, Davis SJ, Feng K, Hubacek K, Liang S, Anadon LD, et al. Targeted opportunities to address the climate-trade dilemma in China. Nat Clim Change. 2016;6:201-+.
[72] Nasiri N, Zeynali S, Ravadanegh SN, Marzband M. A tactical scheduling framework for wind farm-integrated multi-energy systems to take part in natural gas and wholesale electricity markets as a price setter. Iet Gener Transm Dis. 2022;16:1849-64.
[73] Guan DB, Meng J, Reiner DM, Zhang N, Shan YL, Mi ZF, et al. Structural decline in China's CO2 emissions through transitions in industry and energy systems. Nat Geosci. 2018;11:551-+.
[74] Zhang HR, Li RX, Chen B, Lin HM, Zhang QR, Liu MD, et al. Evolution of the life cycle primary PM2.5 emissions in globalized production systems. Environ Int. 2019;131.
[75] Acquaye A, Feng KS, Oppon E, Salhi S, Ibn-Mohammed T, Genovese A, et al. Measuring the environmental sustainability performance of global supply chains: A multi-regional input-output analysis for carbon, sulphur oxide and water footprints. J Environ Manage. 2017;187:571-85.

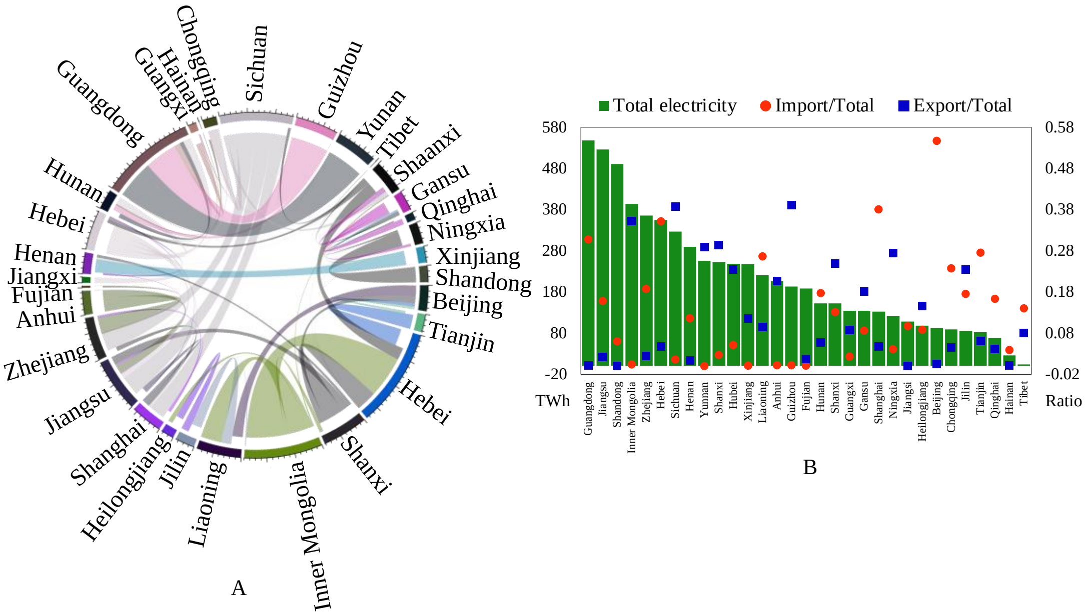

**Figure 1. China's interprovincial electricity flow structure in 2015:** A: Circular diagram of the electricity flow network; B: Electricity flow structure ratio of total electricity, imported electricity and exported electricity.

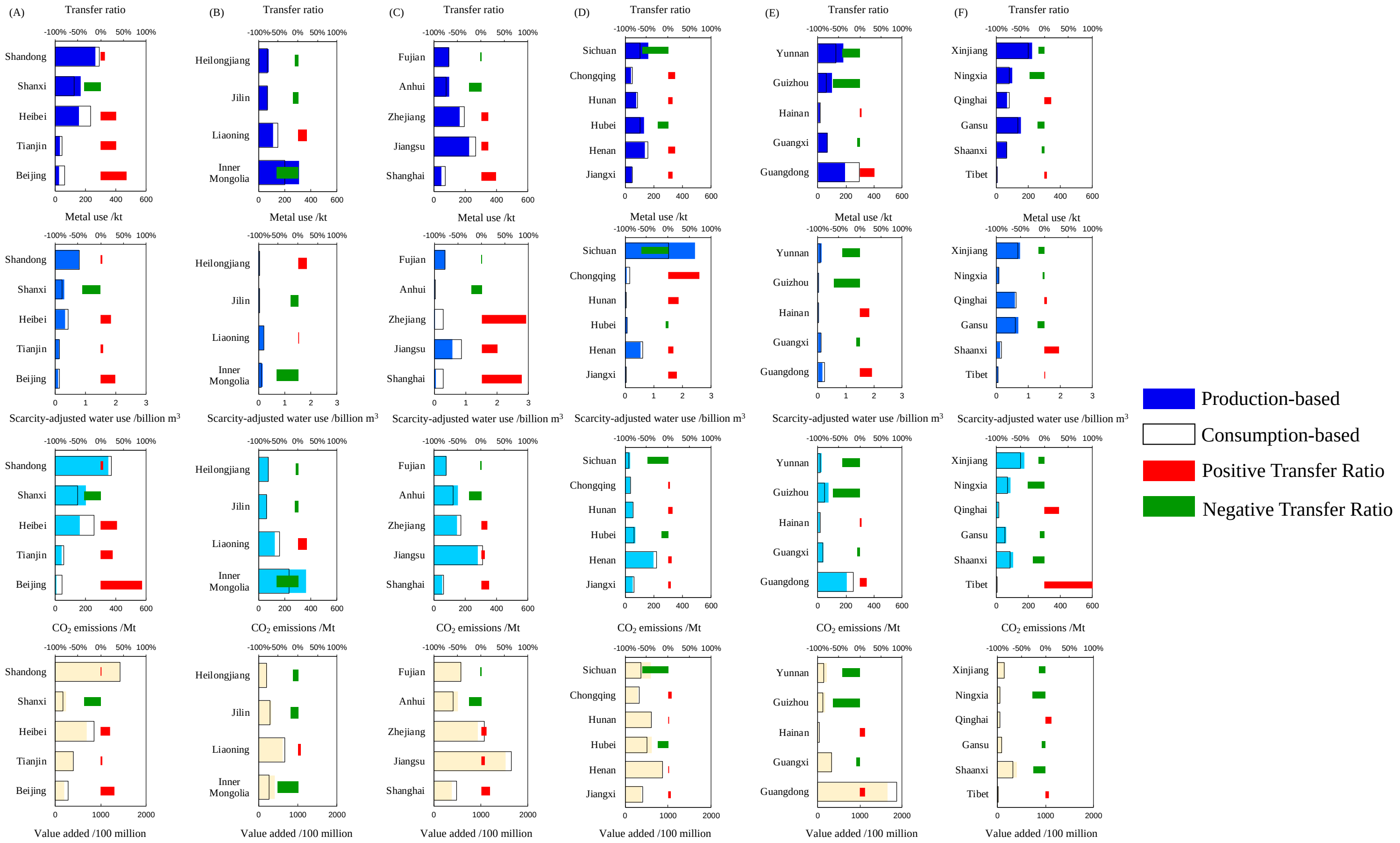

**Figure 2. Production-based and consumption-based electricity metal-water-carbon and electricity value added of the 31 provinces in six power grids in 2015:** A: North China Power Grid; B: Northeast Power Grid; C: East China Power Grid; D: Central China Power Grid; E: South China Power Grid; F: Northwest Power Grid. Black hollow bars represent the consumption-based perspective, and coloured solid bars represent the production-based perspective. The red and green bars represent the positive transfer ratio and negative transfer ratio, respectively.

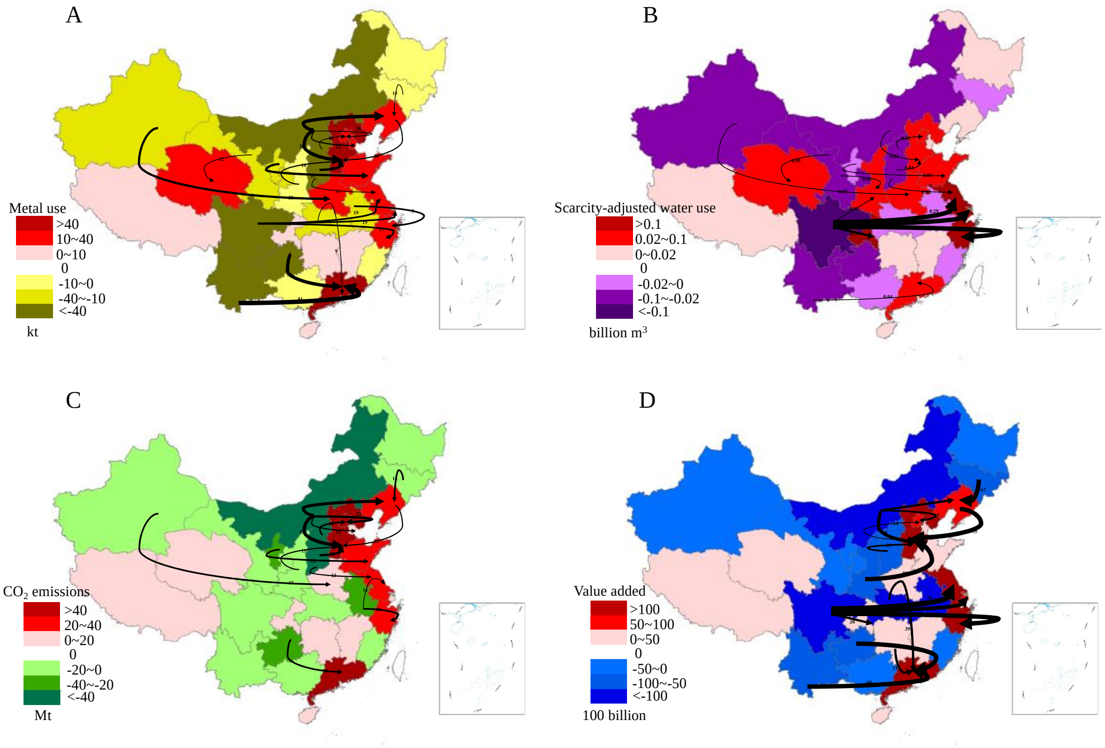

**Figure 3. The direction of transfers of electricity metal-water-carbon and valued added embodied in China's interprovincial electricity flows in 2015.** The arrows coloured in black represent the direction of electricity flows (from exported to imported).

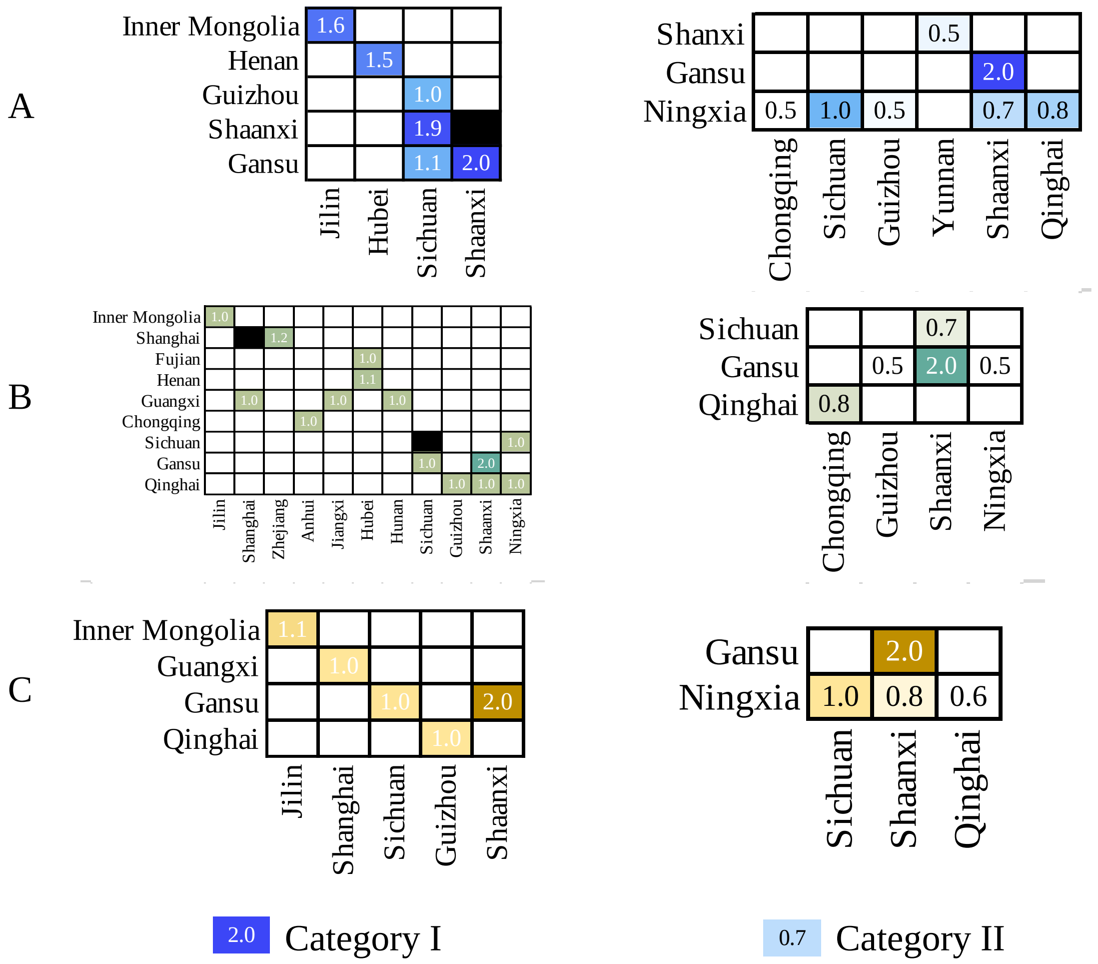

**Figure 4. REI of representative pairs of provinces in the two categories between electricity metal-water-carbon and value added.** A: CO$_2$ emissions-value added; B: Scarcity-adjusted water use-value added; C: Metal use-value added. The whole transfer matrix for REI among all provinces is shown in Figure S1.