

The Spatiotemporal Changes of China's Inter-provincial Power Transmission Network from 2005 to 2020

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Abstract: This study integrates the downscaling model of electricity production consumption, the balance equation of electricity inflow and outflow, and the actual connectivity between provincial power grids into a research framework, and develops a downscaling method for inter-regional power transmission data, thereby obtaining a complete inter provincial power transmission dataset. It was found that from 2005 to 2020, the source of power supply gradually shifted from the Central China Power Grid to the Southwest Power Grid. Sichuan, Yunnan, and some provinces in the southwest region have become important sources of electricity supply. The scale of power transfer from the source point and the scale of power transfer from the sink point are both showing an increasing trend, and the scale of inter provincial and inter regional power transmission is constantly expanding, resulting in a strengthening trend of the close density of network connections.

Keywords: Power Transmission; Temporal and Spatial Changes; Downscaling.

1. Introduction

A significant spatial mismatch exists between power production and consumption in different provinces across China, which requires interprovincial and interregional power transmission to balance power supply and demand [1]. Extensive interprovincial and interregional power transmission optimizes energy resource allocation, improves the utilization rate of power generation equipment, and lowers the costs of power supply, ultimately promoting overall societal development [2, 3]. Recently, interprovincial and interregional power transmission in China has exhibited a consistent trend, with stable growth in transmission volume. During 2020, interprovincial power transmission in China amounted to 1533.56 billion kilowatt hours, of which 647.382 billion kilowatt hours were transmitted between different regional power grids, accounting for 20.11% and 8.49% of China's total electricity generation in that year. The transmission of electricity between provinces and regions is continuously increasing, and the regional power grids are also closely connected. Analyzing the spatiotemporal dynamics of power transmission networks facilitates identification of the importance of regional power grids, thereby providing support for decision-making to enhance the reliability and robustness of power networks.

Complex network analysis methods have been extensively employed to unveil the structural characteristics of complex systems [4-10]. Ji et al. (2016) utilized complex network theory to examine the evolutionary structure and attributes of the international power trade network from 1990 to 2010. The findings indicated that international power trade demonstrates regional characteristics and can be subdivided into multiple regional sub-networks. However, the current international power trade has not yet yielded positive carbon reduction effects despite optimizing power supply and demand [11]. Ma Li et al. (2022) constructed interprovincial power transmission tables for 2006 and 2015 and employed network

analysis metrics such as influence, extroversion, cohesion, and dependence to scrutinize the source and sink points, as well as the flow field characteristics of interprovincial power flow in China. They compared the changes in power flow patterns between 2006 and 2015 [12]. Nevertheless, this study solely encompasses two years of power transmission data and solely analyzes the overall characteristics of the transmission network, without examining the spatial and structural attributes of the provincial power grid within the network [12]. Pu et al. (2021) applied the more advanced Exponential Random Graph Models (ERGM) analysis method to explore the structural characteristics and evolution laws of cross-border power trading networks, as well as identify the factors influencing the formation of such networks. The research findings indicate a shift in the central position of the network from the West to the East, and that cross-border electricity trade can contribute to carbon dioxide emissions reduction, facilitate the transition to renewable energy, and mitigate the mismatch between electricity supply and demand [13].

The absence of comprehensive inter-provincial power transmission data has resulted in a dearth of empirical studies on the power transmission network in China and its structural characteristics within the existing body of research. Therefore, this study devised a downscaling technique to address the scarcity of inter-regional power transmission data. Subsequently, a dataset encompassing provincial power transmission data spanning from 2005 to 2020 was constructed, allowing for an analysis of the spatiotemporal dynamics in power transmission.

2. Methodology

2.1. Division of China's Regional and Provincial Power Grids

The division of China's regional and provincial power grids is classified into three scales in space: the National Grid (NG), Subnational Grids (SNGs), and Provincial Grids (PGs) [14,

15]. As shown in Table 1, the North China Grid (NCG) comprises Beijing (BJ), Tianjin (TJ), Hebei (HEB), Shanxi (SX), Shandong (SD), and Inner Mongolia (IM); the Northeast China Grid (NEG) comprises Liaoning (LN), Jilin (JL), and Heilongjiang (HLJ); the East China Grid (ECG) comprises Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ), Anhui (AH), and Fujian (FJ); and the Central China Grid (CCG) comprises Jiangxi (JX), Henan (HEN), Hubei (HUB), and Hunan (HUN). The Northwest Power Grid (NWG) comprises Shaanxi (SAX), Gansu (GS), Qinghai (QH), Ningxia (NX), and Xinjiang (XJ); the Southwest Power Grid (SWG) comprises Chongqing (CQ), Sichuan (SC), and Xizang (TIB); and the Southern Power Grid (CSG) comprises Guangdong (GD), Guangxi (GX), Hainan (HN), Guizhou (GZ), and Yunnan (YN) [12].

Table 1. Division of China's regional power grids

Subnational grids	Symbol	Provincial grids
North China Grid	NCG	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Shandong
Northeast China grid	NEG	Liaoning, Jilin, Heilongjiang
East China Grid	ECG	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian
Central China Grid	CCG	Jiangxi, Henan, Hubei, Hunan
Northwest China grid	NWG	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang
Southwest China grid	SWG	Chongqing, Sichuan, Tibet
China Southern Power Grid	CSG	Guangdong, Guangxi, Hainan, Guizhou, Yunnan

2.2. Downscaling of Inter-regional Power Transmission Data

Based on the electricity generation of the power output provinces and the electricity consumption of the power input provinces, establish a downscaling coefficient vector (λ_A) on the supply side and a downscaling coefficient vector (λ_B) on the demand side, as shown in formula (1) [16, 17].

$$\left\{ \begin{array}{l} \lambda_A = \left[\frac{EG_1^A}{\sum_{i=1}^m EG_i^A} \quad \frac{EG_2^A}{\sum_{i=1}^m EG_i^A} \quad \dots \quad \frac{EG_m^A}{\sum_{i=1}^m EG_i^A} \right] = [\lambda_1^A \quad \lambda_2^A \quad \dots \quad \lambda_m^A] \\ \lambda_B = \left[\frac{EC_1^B}{\sum_{j=1}^n EC_j^B} \quad \frac{EC_2^B}{\sum_{j=1}^n EC_j^B} \quad \dots \quad \frac{EC_n^B}{\sum_{j=1}^n EC_j^B} \right] = [\lambda_1^B \quad \lambda_2^B \quad \dots \quad \lambda_n^B] \end{array} \right. \quad (1)$$

Based on λ_i^A and λ_j^B , regional scale power transmission data can be downscaled to the interprovincial power transmission matrix, as shown in formula (2) [16].

Among them, t_{ij}^{AB} represents the amount of electricity transmitted from province i in regional grid A to province j in regional grid B . \mathbf{T}^{AB} represents the downscale power transmission matrix between m provinces in regional grid A and n provinces in regional grid B .

$$\begin{aligned} \mathbf{T}^{AB} &= E^{AB} \times \lambda_A^T \times \lambda_B \\ &= E^{AB} \times \begin{bmatrix} \lambda_1^A \\ \lambda_2^A \\ \vdots \\ \lambda_m^A \end{bmatrix} \times [\lambda_1^B \quad \lambda_2^B \quad \dots \quad \lambda_n^B] \\ &= \begin{bmatrix} t_{12}^{AB} & t_{12}^{AB} & \dots & t_{1m}^{AB} \\ t_{21}^{AB} & t_{22}^{AB} & \dots & t_{2m}^{AB} \\ \vdots & \vdots & \ddots & \vdots \\ t_{n1}^{AB} & t_{n2}^{AB} & \dots & t_{nm}^{AB} \end{bmatrix} \end{aligned} \quad (2)$$

For each node, there is the following balance equation for energy transfer in and out [17]:

$$X_i = EG_i + \sum_{j=1}^n T_{ji} = EC_i + \sum_{j=1}^n T_{ij} \quad (3)$$

In the formula, X_i is the total electricity flow of provincial power grid i , EG_i is the total electricity generation of power grid i , EC_i is the total electricity consumption of power grid i , and T_{ij} is the total electricity transmitted from the power grid and the power grid. Ultimately, by amalgamating all interprovincial transmission data within a given region with the aforementioned downscaled data, a comprehensive dataset on interprovincial power transmission can be created.

3. Results Analysis

By downscaling interregional power transmission data to provincial levels, this study obtained a comprehensive dataset of interprovincial power transmission from 2005 to 2020. Figures 1 to 4 illustrate the temporal and spatial changes in interprovincial power transmission in China during this period. The chord diagram reveals that interprovincial power transmission primarily flows from provinces with abundant power and energy resources, such as Hubei, Sichuan, Inner Mongolia, and Yunnan, to provinces with developed coastal economies and high electricity demand, such as Guangdong, Zhejiang, Shanghai, and Jiangsu. Additionally, as interregional and interprovincial power transmission channels increase in China, the volume of electricity transferred between provinces and regions also rises annually. The figure includes an abbreviation for the provincial power grid, and "ABR" indicates that the provincial power grid imports or exports electricity, which accounts for a small proportion of the total cross-provincial and cross-regional electricity transmission. Specifically, Heilongjiang, Liaoning, and Yunnan provinces import electricity, while Inner Mongolia, Jilin, Liaoning, Guangdong, Guangxi, and Yunnan provinces export electricity.

Research conducted in 2005 revealed that China's power sources were primarily concentrated in the central regions of Inner Mongolia, Shanxi, and Hubei. However, by 2020, there was a gradual westward shift in power sources, with Sichuan, Yunnan, and several provinces in the northwest region emerging as significant power output provinces. This shift can be attributed to several factors. Firstly, China experienced rapid economic growth and the expansion of high-energy-consuming industries such as steel, petrochemicals, non-ferrous metals, and building materials after 2005. As a result,

the original sources of electricity production became

insufficient to meet the growing demand.

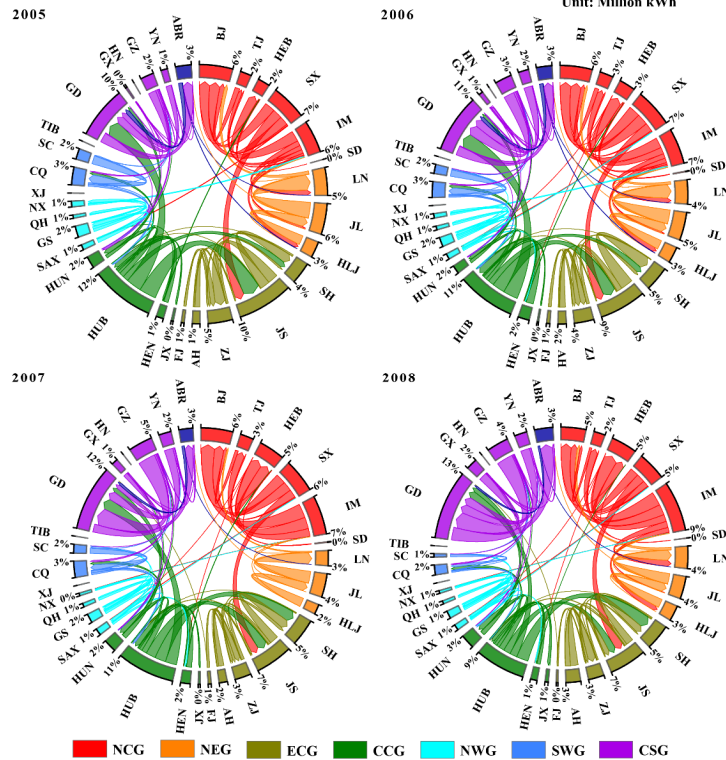


Fig 1. China's inter-provincial electricity transmission flows from 2005 to 2008

However, provinces like Shanxi, Inner Mongolia, Anhui, and Guizhou, which heavily rely on coal-fired power, faced increasing ecological pressure and constraints due to the exploitation of numerous coal resources. Consequently, the expansion of coal-fired power was relatively limited. Secondly, the development of the western region has

propelled the resource advantage economy in that area, enabling large-scale development of hydropower and coal resources. Lastly, advancements in long-distance transmission technology in China have facilitated the transmission of electricity from the southern region to the eastern coastal areas.

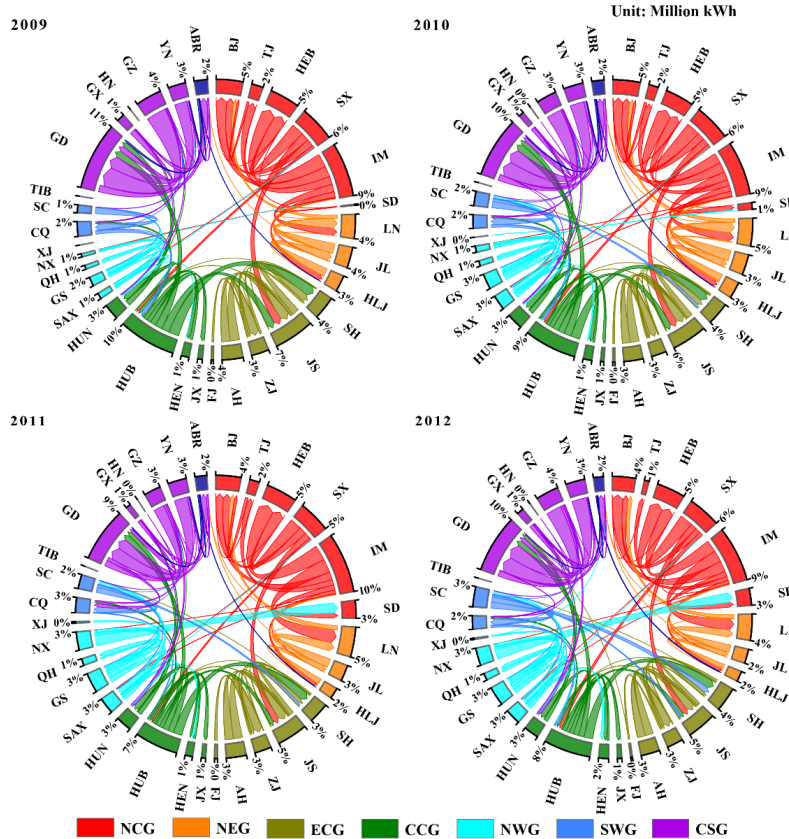


Fig 2. China's inter-provincial electricity transmission flows from 2009 to 2012

The transmission network pattern of China's electricity underwent significant changes between 2005 and 2020, with an expanding difference observed in the electricity transmission. This difference is evident in both the increasing electricity output at the source point and the growing scale of electricity input at the sink point. Additionally, there is a gradual increase in the outward degree of the source point and

the outward dependence of the sink point. The interprovincial power flow also exhibits a strengthening trend in terms of scale and network connection density. These changes indicate the emergence of a more pronounced regional division of labor in China's electricity production and consumption, further reinforcing the interprovincial dependence on electricity.

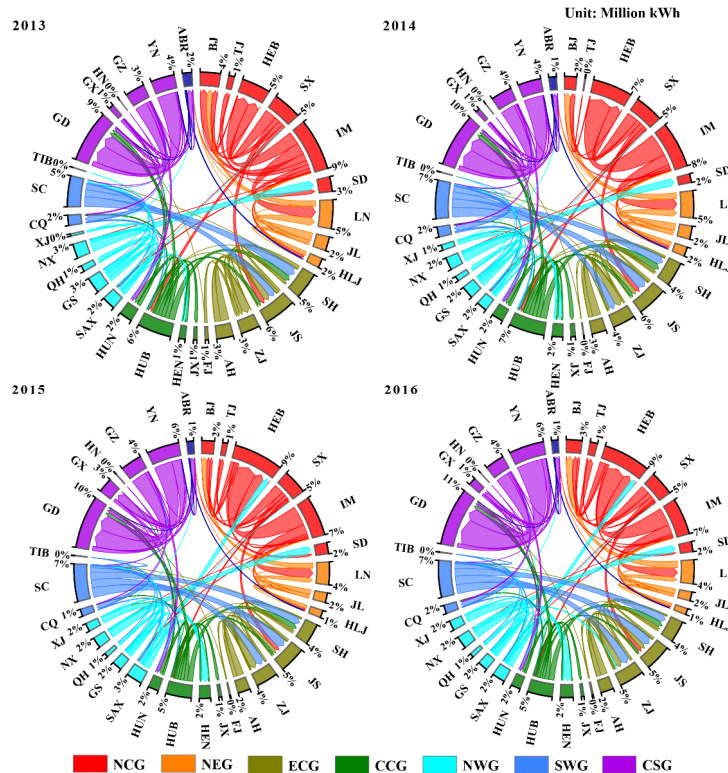


Fig 3. China's inter-provincial electricity transmission flows from 2013 to 2016

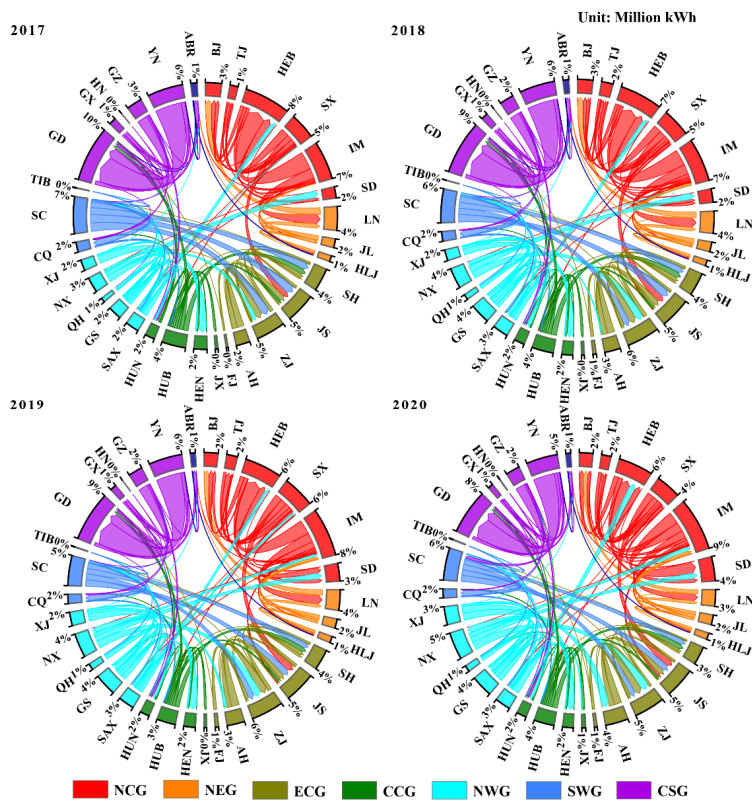


Fig 4. China's inter-provincial electricity transmission flows from 2017 to 2020

Based on a comprehensive analysis of the relationship between power flow from the source and sink fields, three major patterns have emerged from north to south: Inner Mongolia and Shanxi supply power to the three northeastern provinces and the Beijing-Tianjin-Hebei region, central Hubei, Anhui, and Sichuan supply power to the Jiangsu-Zhejiang-Shanghai region, and southern Yunnan and Guizhou supply power to Guangdong province. The fundamental pattern of China's west-to-east power transmission remains unbroken and shows a strengthening trend. However, from 2005 to 2020, with the progress and adoption of ultra-high voltage technology, China's interprovincial power transmission gradually shifted from a focus on regional power grids to cross-regional power transmission. Provinces and regions such as Xinjiang, Ningxia, Sichuan, and Shaanxi can now directly transmit electricity to the eastern region. The reduced dominance of the power connection network indicates a more balanced power distribution between provinces. Some large power consumers no longer depend solely on a single source point, but instead adopt multiple sources for their supply. Therefore, in the future, China's interprovincial power network will be more comprehensive and balanced.

In 2020, China's interprovincial transmission of electricity accounted for 19.80% of the total electricity generation, with a total transmission amount of approximately 1511.42 terawatt-hours. Inner Mongolia had the largest outward transmission of electricity, transporting around 229.69 terawatt-hours in 2020. Guangdong Province received the highest amount of direct electricity in 2020, receiving 222.21 terawatt-hours transmitted from other provinces. The main source of cross-provincial imported electricity in Guangdong Province was Yunnan Province, which transmitted 130.88 terawatt-hours, accounting for 8.66% of the national interprovincial electricity exchange. This made it the largest interprovincial electricity transmission with the highest flow rate. As the country's economy grows, so does electricity consumption, resulting in an increase in the number and capacity of transmission lines. Consequently, the total number of cross-provincial and cross-regional transmission networks and electricity consumption will continue to rise.

Inner Mongolia, Shanxi, Sichuan, Yunnan, Ningxia, and Xinjiang are the major electricity-producing provinces, while Beijing, Shanghai, Tianjin, Hebei, and Zhejiang are the major electricity-consuming provinces. If a province's electricity consumption represents a relatively small proportion of the total incoming electricity, it indicates a high potential for electricity export from that province. For instance, Inner Mongolia Autonomous Region, Ningxia Autonomous Region, and Yunnan Province, all of which account for less than 60% of the total electricity consumption, serve as the primary electricity-exporting provinces in the national power transmission system. These provinces, primarily located in western China, possess abundant water, coal, oil, natural gas, wind, and solar resources, enabling them to act as power hubs in China's power exchange system. Conversely, provinces with low power generation as a proportion of total electricity inflow heavily rely on electricity import from other provinces. Beijing and Shanghai, both accounting for less than 50% of the total electricity consumption, exemplify this situation. These two cities have a high proportion of tertiary industry, a highly developed economy, and limited energy resources. Consequently, they heavily depend on external power supply

in the power grid system, making them the leading consumers of electricity in China. If a province has a low proportion of power generation and electricity consumption relative to the total inflow, it is highly likely that this province plays a "transmission" role in the power trading network, as seen in Shaanxi and Gansu provinces.

4. Conclusion

This study developed a downscaling method for inter-regional power transmission data, constructed a provincial power transmission dataset from 2005 to 2020, and analyzed the dynamic changes in time and space of interprovincial power transmission. The analysis revealed that between 2005 and 2020, there was a gradual shift in the power supply source from the Central China Power Grid to the Southwest Power Grid. Provinces such as Sichuan, Yunnan, and several in the southwest region emerged as significant electricity suppliers. The scale of power transfer from the source point and sink point exhibited an increasing trend, while the interprovincial and interregional power transmission expanded, resulting in a strengthening network connection density.

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