Energy 322 (2025) 135555

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# The impact of trans-regional power transmission on urban energy system resilience in China

Jingna Yang [a,b], Kaile Zhou [a,b,c,*]

[a] School of Management, Hefei University of Technology, Hefei, 230009, China
[b] Anhui Provincial Key Laboratory of Philosophy and Social Sciences for Smart Management of Energy & Environment and Green & Low Carbon Development, Hefei University of Technology, Hefei, 230009, China
[c] Key Laboratory of Process Optimization and Intelligent Decision-making, Ministry of Education, Hefei University of Technology, Hefei, 230009, China

ARTICLE INFO

Handling editor: X Zhang

*Keywords:*
trans-regional power transmission
urban energy system resilience
ultra-high voltage

ABSTRACT

Few studies have explored the impact of trans-regional power transmission on urban energy system resilience. In this study, a time-varying difference-in-differences (DID) model was used to evaluate the impacts of trans-regional power transmission on the urban energy system resilience. The results show that the impact of trans-regional transmission on the resilience of urban energy systems is heterogeneous. Specifically, for the northern region, which is dominated by thermal power generation and output, trans-regional power transmission contributes to enhance the urban energy systems resilience. However, for southwestern regions, trans-regional power transmission has damaged the urban energy systems resilience. This conclusion remains valid after a series of robustness tests. This suggests that trans-regional power transmission may bring inequalities in regional energy utilization. Therefore, the economic compensation to power exporting regions should be increased. In the context of rapid industrial development, the active development of renewable energy and the expansion of power input channels in the western region are recommended. In addition, all cities should be encouraged to develop microgrids to improve the ability of urban energy systems to absorb risks.

## 1. Introduction

The distribution of energy resources across various regions in China is highly uneven [1–3]. Specifically, over 80% of coal reserves in China are concentrated in the western and northern regions, and more than 80% of its hydroelectric resources are primarily concentrated in the southwestern region [4,5]. Nevertheless, 75% of the energy demand is concentrated in the primary energy resource-poor eastern and central regions [6,7]. The uneven distribution and unbalanced consumption of energy in China necessitate the optimization of resource allocation on a broader scale to meet regional energy demands [8–10]. In addition, China is confronted with significant environmental challenges, necessitating a prompt transition towards a cleaner energy mix [11–15]. Therefore, trans-regional power transmission is considered a crucial mode of energy transfer, particularly in nations and regions with uneven distribution of energy resources [16–19].

The West-to-East Power Transmission (WEPT) project represents a significant stride taken by China to optimize its power mix [12,20–22]. Specially, the WEPT project aims to transform energy from the western region with rich in coal and hydroelectric resources, into power resources and transmit them to the energy-deficient eastern region. The western provinces of Yunnan and Guizhou have been supplying electricity to the southeastern province of Guangdong since 1993 [23]. Sichuan is also constantly transmitting power to the eastern China. As of June 2022, the Sichuan power grid has supplied a total of 1.35 trillion kilowatt-hours (kWh) electricity to the east and other regions in China. The WEPT project not only leverages the resource advantages in the western region to create economic benefits, but also meets the power demand and mitigates air pollutant emissions caused by coal-fired power station in the eastern region [24]. Trans-regional power transmission projects have emerged as a crucial mechanism for enhancing the efficiency of power allocation and ensuring a reliable electricity supply in China [25]. However, transmitting electricity over excessively long distances can lead to heightened transmission losses occurring at the same voltage level. Ultra-high voltage (UHV) transmission systems offer superior power transmission efficiency, long-distance transmission, and lower line losses, thereby effectively facilitating large-scale power transmission [26–28]. Since the operation of the first UHV line in 2009,

* Corresponding author. School of Management, Hefei University of Technology, Hefei, 230009, China.
*E-mail address:* zhoukaile@hfut.edu.cn (K. Zhou).

https://doi.org/10.1016/j.energy.2025.135555
Received 21 January 2025; Received in revised form 8 March 2025; Accepted 10 March 2025
Available online 13 March 2025

UHV lines have emerged as the predominant mode of long-distance power transmission in China [29]. The cumulative electricity transmitted in 2022 is approximately 900 billion kWh, representing approximately 11 % of the overall annual electricity consumption in China.

Currently, there have been some research efforts that focused on the impact of trans-regional power transmission on the regional economy and environment [30,31]. For example, a study has demonstrated that the power grid has contributed to economic growth through its impact on power supply and investment [32]. Another study used a spatial analysis model and found that trans-regional power transmission plays a key role in achieving balanced regional development and common prosperity [33]. In addition, estimations of environmental impacts embodied in trans-regional power transmission have also attracted the attention of researchers [34–37]. Some existing studies have estimated the embodied greenhouse gas emissions associated with the construction of large-scale power transmission infrastructure in China [38]. The impact of trans-regional transmission on sulfur dioxide emissions in the power importing region also been examined by researchers. The results revealed that trans-regional transmission led to a 7% decrease in sulfur dioxide emissions in the power importing region [24]. Similarly, treating the operation of UHV lines as a quasi-natural experiment, some related works have investigated the impact of trans-regional power transmission on regional carbon emissions [39]. The findings indicated that trans-regional transmission has the potential to substantially mitigate regional carbon emissions The above studies fully demonstrate that trans-regional power transmission can promote both economic development and environmental protection [40].

Urban areas are the mainstay of energy consumption, with urban energy utilization accounting for about 80% of overall primary energy consumption in China [41]. Ensuring urban energy security is fundamental to sustainable development [42–44]. However, in recent years, extreme disasters have been occurring with increasing frequency along with climate warming, causing a greater impact on the energy systems of cities [45–48]. In July 2022, the persistent extreme high temperature and drought led to a severe shortage of electricity supply in Sichuan, where hydropower supply is dominant [49,50]. The power supply and demand situation changed from a shortage of power during the peak period to facing a persistent deficit in power supply throughout the day [51]. The government has had to implement measures to shut down the production of some key enterprises and make electricity available to the public [52]. Gradually, the fragility of the urban energy systems in the western China has received widespread attention. Many studies have used resilience to denote the ability of energy systems to absorb disasters [53–55]. Energy system resilience is defined as the capacity of an energy system to withstand damage and rapidly restore normal operations by absorbing, adapting to, and recovering from disturbances [56,57]. The level of resilience of urban energy systems is closely linked to urban energy supply, energy transportation, energy storage, energy consumption and urban infrastructure [58]. The high resilience of urban energy systems indicates their greater ability to withstand and recover from risks [59]. Although it has been demonstrated that trans-regional power transmission can convert the resource advantages of power exporting regions into economic benefits, it is also effective in ensuring energy supply in importing regions by enhancing the accessibility of energy. However, the impact of trans-regional transmission on the urban energy systems resilience in power-exporting regions has received relatively little attention, particularly in the southwestern region which is primarily characterized by hydroelectric power export [60].

In this study, we initially develop an indicator framework for evaluating the urban energy systems resilience. The indicator system considers the urban energy supply, transmission, storage, consumption, and urban infrastructure, providing a comprehensive reflection of the urban energy system resilience. Then, we divided the power output areas into two groups based on power transmission type. We treat the operation of UHV lines as a quasi-experimental and examine the impact of trans-regional power transmission on urban energy systems resilience in power output regions. The results show that trans-regional transmission has different impacts on urban energy system resilience in different regions. Several robustness checks are performed to evaluate the reliability of the findings. The contributions of this study can be summarized as follows. First, previous studies considered the impacts of trans-regional power transmission on the economy and environment, and this study explored the impacts of trans-regional power transmission on the urban energy systems resilience for the first time, which provides a new perspective to improve the urban energy systems resilience. Second, this study divides the power exporting regions into two groups based on the type of power transmission. One group is dominated by thermal power transmission and the other group is dominated by hydroelectric transmission, which contributes to grasping the heterogeneity of trans-regional transmission on the urban energy systems resilience.

## 2. Methods

### 2.1. CRITIC-TOPSIS

This study first uses criteria importance through intercriteria correlation (CRITIC) to calculate the values of weight for each indicator. It determines objective weights according to the contrasting and conflicting characteristics of the indicators [61]. Contrast intensity denotes the disparity of values among individuals under the same indicator, and is usually expressed by standard deviation. A larger standard deviation indicates greater fluctuation, that is, the greater the disparity among individual values, the higher the corresponding weight. Indicator conflict is typically assessed through the correlation coefficient. If a strong positive correlation is observed between two indicators it means that they are less conflicting and will be weighted lower [62].

First, the sample data is defined by Eq. (1). Using Eq. (2) and Eq. (3) to standardize the positive and negative indicators.

$$X = \begin{bmatrix} x_{11} \ x_{12} \cdots x_{1n} \\ \vdots \ \vdots \ \ddots \ \vdots \\ x_{m1} \ x_{m2} \cdots x_{mn} \end{bmatrix} \tag{1}$$

$$x_{ij} = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{2}$$

$$x_{ij} = \frac{\max(x) - x}{\max(x) - \min(x)} \tag{3}$$

The contrast intensity between indicators is calculated using Eq. (4).

$$S_j = \sqrt{\sum_{i=1}^{m} \left(x_{ij} - \bar{x}_j\right)^2 \Big/ (m-1)} \tag{4}$$

where $\bar{x}_j = \frac{1}{m}\sum_{i=1}^{m} x_{ij}$.

Use Eq. (5) and Eq. (6) to calculate indicator conflicts and informativeness.

$$R_j = \sum_{i=1}^{n} \left(1 - r_{ij}\right) \tag{5}$$

$$G_j = S_j \times R_j \tag{6}$$

where $r_{ij}$ denotes the correlation coefficient between indicator $i$ and $j$. $R_j$ denotes the conflict ability of indicator $j$ with other indicators. $G_j$ is the information volume represented by indicator $j$.

Finally, the weight of indicator $j$ is calculated using Eq. (7).

$$w_j = G_j \Big/ \sum_{i=1}^{n} G_j \tag{7}$$

where $w_j$ represents the weight of the $j$th indicator.

Following the determination of weights for each indicator, we used TOPSIS to calculate the energy system resilience score of each city. TOPSIS, a multi-criteria decision-making method introduced by Hwang and Yoon, utilizes multi-attribute metrics to determine the optimal solution or individual [63]. In this study, we employ this method to assess the city-level scores of energy system resilience for ranking purposes. The essence of this method is to rank each evaluation object according to its distance to the ideal positive and negative solutions [64]. The weighted normalized decision matrix is first determined by Eq. (8) and Eq. (9).

$$b_{ij} = x_{ij} \Big/ \sqrt{\sum_{i=1}^{m} x_{ij}^2} \tag{8}$$

$$Z = (z_{ij})_{m \times n} = w_{ij} \times b_{ij} \tag{9}$$

We used Eq. (10) and Eq. (11) to obtain ideal positive and negative solutions.

$$C^+ = \{\max(z_{ij}) | i \in (1, m);\ j \in (1, n)\} \tag{10}$$

$$C^- = \{\min(z_{ij}) | i \in (1, m);\ j \in (1, n)\} \tag{11}$$

Use Eq. (12) and Eq. (13) to obtain the distances of each evaluated individual to the positive and negative ideal solution, respectively.

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(x_{ij} - c_j^+\right)^2} \tag{12}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(x_{ij} - c_j^-\right)^2} \tag{13}$$

where the distance values of $i$th solution from the positive and negative ideal solutions are represented $d+$ and $d-$, respectively. $c_j^+$ and $c_j^-$ represent the indicator values corresponding to $C+$ and $C-$, respectively.

Eq. (14) represents the distance of each assessment metric from the positive and negative ideal solutions.

$$c_i = \frac{d_i^-}{d_i^+ + d_i^-}, i = 1, 2, 3, \cdots, m \tag{14}$$

The parameter $c_i$ ranges from 0 to 1, with a greater value indicating higher resilience of the urban energy system and vice versa.

### 2.2. DID model

The DID model effectively mitigates the issue of endogeneity, resulting in highly stable outcomes [65]. In this study, the operation of an ultra-high voltage transmission project is used as a quasi-experimental design. The time-varying DID model is employed to assess the impact of trans-regional transmission on the resilience of urban energy systems.

$$y_{it} = \alpha_0 + \beta did_{it} + \lambda Z_{it} + \eta_i + \mu_t + \varepsilon_{it} \tag{15}$$

This is a DID model considering the fixed effects of city and fixed effects of time. $y_{it}$ denotes the urban energy system resilience of the city $i$ in year $t$. $did$ denotes the dummy variable. If the first UHV line is commissioned in city $i$ in year $t$, it is considered as 1. Otherwise, it is equals to 0. Here, we divided the power output areas into two groups based on power transmission type. The WEPT project in China comprises three power transmission channels, specifically the northern, central, and southern channels. Among them, the northern channel transmission electricity from Shaanxi and Inner Mongolia to the North China power grid; the central channel transmission electricity from Sichuan and Chongqing to the Central China and East China power grids; and the southern channel transmission electricity from Yunnan, Guizhou and Guangxi to South China power grids. More importantly, the power grid in China is operated by provincial companies as the governing bodies, that is provincial power grids are organized and dispatched as an executor. Based on previous approaches, this study selects all cities of province of landing sites as treatment group. The first group is the northern channel, primarily responsible for transmitting thermal power, and the treatment group encompasses all cities within the five provinces of Inner Mongolia, Shanxi, Shaanxi, Gansu and Ningxia. The second group considers the central and southern channels, which are mainly for hydropower transmission. The treatment group includes all cities in Sichuan and Yunnan. At the same time, we select control group mainly based on geographical adjacency and similar socio-economic situation. The control group for the first treatment group encompasses all cities in Guizhou, Guangxi, Qinghai, and Jiangxi, and the control group for the second treatment group includes all cities in Jilin, Heilongjiang, and Hebei, which do not have UHV lines being opened from 2006 to 2020.

### 2.3. Variable description and data source

*Dependent variable.* Urban energy system resilience is the dependent variable in this study. It reflects the ability of cities to respond to disasters. Therefore, we firstly construed the energy system resilience assessment index system from the dimensions of energy supply, energy transmission, energy consumption, energy storage and urban infrastructure, as presented in Table 1. The indicator system can comprehensively reflect the situation of the urban energy system. We then used CRITIC to obtain the weights of each indicator, and finally calculated the energy system resilience scores of 287 Chinese cities from 2006 to 2020 using TOPSIS.

*Independent variable.* In this study, the independent variable is the dummy variable *did*, which is equal to one if the first UHV transmission line is commissioned in city $i$ in year $t$. Otherwise, it is equals to 0. For the northern channel, the Southeast Jindong-Nanyang-Jingmen 1000 kV AC, as the first UHV transmission line, was officially put into operation in 2009. Subsequently Inner Mongolia, Ningxia, Gansu, and Shaanxi also operated their first UHV lines in July 2016, September 2016, June 2017, and August 2017 respectively. For the central channel, Sichuan, as a major province for hydropower transmission, built three UHV lines between from 2010 to 2014. For the southern channel, Yunnan operated its first UHV line in June 2010, Yunnan-Guangdong ±800 kV DC line, continuously exporting hydropower from Yunnan to the Guangdong region. Table 2 shows the UHV lines in China from 2009 to 2020.

*Control variables.* The growth of urban populations is frequently associated with a rise in energy utilization due to the correlation

**Table 1**
Indicator system of urban energy system resilience.

| Dimensions | Indicators | Positive or negative |
|---|---|---|
| Energy supply | Gas supply per capita | Positive |
| | LPG supply per capita | Positive |
| | Energy supply diversity index | Positive |
| | Gas coverage rate | Positive |
| Energy transmission | Gas transmission losses rate | Negative |
| | LPG transmission losses rate | Negative |
| | Gas transmission pipeline density | Positive |
| Energy consumption | Electricity consumption per capita | Positive |
| | Energy intensity | Negative |
| Energy storage | Gas storage capacity | Positive |
| | LPG storage capacity | Positive |
| Urban infrastructure systems | Energy sector practitioners | Positive |
| | Per capita road surface area | Positive |
| | Per capita public recreational green space | Positive |
| | Information infrastructure construction | Positive |

**Table 2**
UHV lines information in China from 2009 to 2020.

| No. | Time | UHV lines | Type |
|---|---|---|---|
| 1 | January 2009 | Shanxi-Nanyang (Henan)-Jingmen (Hubei) | 1000 kV AC |
| 2 | June 2010 | Yunnan-Guangzhou (Guangzhou) | ±800 kV DC |
| 3 | July 2010 | Xiangjiaba (Sichuan)-Shanghai | ±800 kV DC |
| 4 | December 2012 | Jinping (Sichuan)-Jiangsu | ±800 kV DC |
| 5 | September 2013 | Anhui-Zhejiang-Shanghai | 1000 kV AC |
| 6 | September 2013 | Puer (Yunnan)-Jiangmen (Guangdong) | ±800 kV DC |
| 7 | January 2014 | Southern Hami (Xinjiang)-Zhengzhou | ±800 kV DC |
| 8 | July 2014 | Xiluodu (Sichuan)-West Zhejiang | ±800 kV DC |
| 9 | December 2014 | Northern Zhejiang-Fuzhou (Fujian) | 1000 kV AC |
| 10 | May 2015 | Nuozhadu (Yunnan)-Guangdong | ±800 kV DC |
| 11 | July 2016 | Ximeng (Inner Mongolia)-Shandong | 1000 kV AC |
| 12 | September 2016 | Eastern Ningxia-Zhejiang | ±800 kV DC |
| 13 | November 2016 | Southern Anhui-Nanjing (Jiangsu)-Shanghai | 1000 kV AC |
| 14 | November 2016 | Western Inner Mongolia-Southern Tianjin | 1000 kV AC |
| 15 | June 2017 | Jiuquan (Gansu)-Hunan | ±800 kV DC |
| 16 | June 2017 | Northern Shanxi-Nanjing (Jiangsu) | ±800 kV DC |
| 17 | August 2017 | Yuheng (Shaanxi)-Weifang (Shandong) | 1000 kV AC |
| 18 | August 2017 | Ximeng (Inner Mongolia)-Shengli (Inner Mongolia) | 1000 kV AC |
| 19 | October 2017 | Ximeng (Inner Mongolia)-Taizhou (Jiangsu) | ±800 kV DC |
| 20 | December 2017 | Zhalute (Inner Mongolia)-Qingzhou (Shandong) | ±800 kV DC |
| 21 | May 2018 | Dianxi North (Yunan)-Guangdong | ±800 kV DC |
| 22 | January 2019 | Shanghai Temple (Inner Mongolia)-Linyi (Shandong) | ±800 kV DC |
| 23 | June 2019 | Western Beijing-Shijiazhuang (Hebei) | 1000 kV AC |
| 24 | September 2019 | Suzhou (Jiangsu)-Nantong (Jiangsu) GIL Integrated Pipe Corridor | 1000 kV AC |
| 25 | September 2019 | Changji (Xinjiang)-Guquan (Anhui) | 1000 kV AC |
| 26 | January 2020 | Shandong-Hebei | 1000 kV AC |

between human activity and energy usage. The larger the urban population, the more complex the challenge to the urban energy supply system becomes. The level of urban economic development also has an impact on urban energy systems. On the one hand, an increase in the regional economy is often accompanied by more industrial activities, commercial services, and these activities will increase energy utilization. Besides, cities with a higher degree of economic development typically possess a greater capacity to invest in cleaner and renewable energy resources, thereby facilitating the optimization of the energy mix and enhancing energy efficiency. The development of the secondary industry, which is dominated by heavy industry, usually consumes more energy. Furthermore, although transportation, energy, and communications infrastructure may not have a direct impact on the urban energy systems resilience, well-developed infrastructure plays a vital role in enabling the swift recovery of the energy system during emergency situations. Therefore, this study introduces urban population (pop), regional gross domestic product (gdp), industrial structure (ind), and urban infrastructure investment (inv) as control variables.

The raw data used in this study are derived from China City Statistical Yearbook, China Urban Construction Statistical Yearbook, and China Energy Statistical Yearbook. The information pertaining to UHV lines primarily originates from the official websites of State Grid Corporation of China and China Southern Power Grid.

## 3. Results

### 3.1. Trans-regional power transmission project in China

Rapid economic growth is often accompanied by greater consumption of energy. In China, uneven distribution of resources and unbalanced economic development have resulted in the fact that regions are not able to achieve a balance in the generation and consumption of electricity. Fig. 1 illustrates the disparity between electricity generation and consumption across various provinces in China.

As can be seen in Fig. 1, with the exception of Beijing and Chongqing, all provinces in China generated more electricity than they consumed in 2000. Since then, electricity consumption has grown along with the rapid economic growth in China's eastern region. Electricity generation in the eastern region is no longer able to meet local electricity consumption. However, in the western region, characterized by its abundant energy resources but slow in economic development, the generation of electricity in the region is much higher than the consumption of electricity. In 2020, Inner Mongolia, Sichuan, and Yunnan are generating far more electricity than they consumption, with the gap exceeding 1.2 billion kWh. The electricity consumption of eastern regions including Zhejiang, Jiangsu, Shanghai Guangdong and Shandong, on the other hand, far exceeds their power generation capacity.

Fig. 2 illustrates the electricity generation and electricity consumption of each province in 2020. Jiangsu, Guangdong, and Shandong are the three provinces with the highest electricity consumption. Inner Mongolia, Sichuan, Yunnan and Xinjiang, conversely, consume far less electricity than they generate. This further suggests that trans-regional transmission is necessary to well balance energy generation and consumption in different regions of China.

The UHV power transmission system is defined as the network for transmitting alternating current (AC) at 1000 kV and direct current (DC) ± 800 kV. Compared to previous high-voltage transmission methods, UHV is distinguished by its superior transmission efficiency, extended transmission distance, lower transmission losses, and adaptable power allocation. In 2009, China commissioned its first UHV power transmission line, the 1000 kV Jindong-Nanyang-Jingmen UHV AC line. Fig. 3 shows the electricity transmission capacity of UHV lines in China in 2020.

In 2020, the 22 UHV lines transmit a total of 531.8 billion kWh of electricity, including 244.1 billion kWh of electricity generated by renewable energy sources. As can be seen from Fig. 3, Inner Mongolia, Sichuan, Xinjiang and Yunnan are the largest power transmission provinces in terms of UHV line electricity transmission, accounting for 69 % of the total electricity transmission. Of these 22 UHV lines, 74 % of the electricity is transmitted to Shandong, Zhejiang, Jiangsu, Guangdong and Shanghai. In addition, some provinces are both power-exporting and power-importing provinces, such as Anhui and Zhejiang.

### 3.2. DID model estimation results

The estimation results that were obtained for the different treatment groups are shown in Table 3. Among them, Columns (1) and (2) show the results of Group 1. Columns (3) and (4) show the results of Group 2. Columns (1) and (3) represent the results without control variables. Columns (2) and (4) are results with control variables.

As shown in Table 3, the *did* coefficients of columns (1) and (2) are significantly positive. The results show that trans-regional transmission can significantly enhance the resilience of urban energy systems of the cities in the northern region that are dominated by thermal power

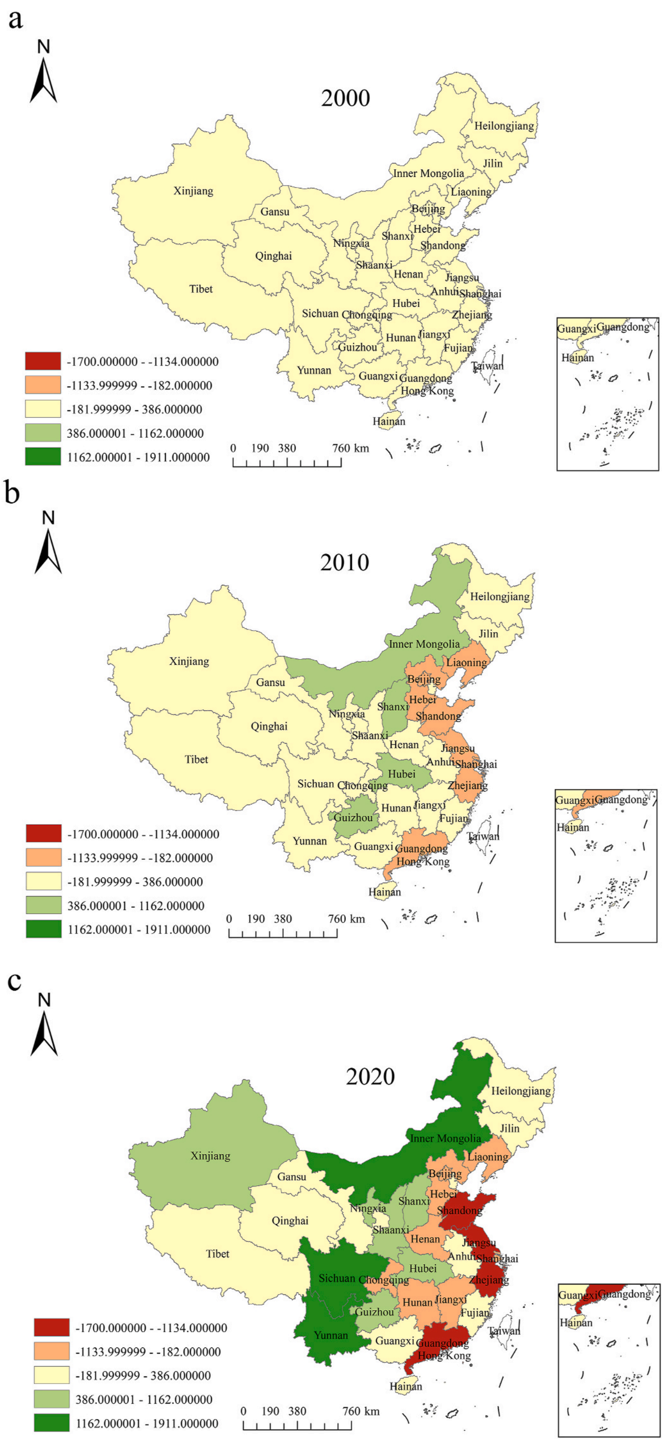


**Fig. 1.** The disparity between electricity generation and consumption of different provinces in China in 2000, 2010 and 2020. A value greater than zero indicates that more electricity is generated than consumed, while a value less than zero indicates that the local electricity supply is insufficient.

output. However, in columns (3) and (4), the coefficients of *did* are significantly negative, suggesting that trans-regional transmission has damaged the urban energy system resilience in southwest China, which is primarily characterized by hydropower generation. On the one hand, the advantageous policies in the Western Development Strategy have already attracted many industrial production transfers to the southwestern region, consequently leading to a significant surge in energy consumption in the southwestern region. On the other hand, along with global warming, the occurrence of extreme weather such as hurricanes and droughts are becoming more and more frequent. Hydropower is highly vulnerable to extreme weather, particularly during prolonged droughts, which can lead to a significant reduction in hydropower generation. In addition, in line with the national strategy of WEPT project, large-scale hydropower stations such as Xiangjiaba, Xiluodu, Jinping, and Baihetan in Sichuan are coordinated by national arrangements for development and consumption. The power generation is uniformly allocated across the China, with fixed distribution ratios both within and outside the province. It is not the case that Sichuan prioritizes consumption and only dispatches excess power [66]. Thus, trans-regional transmission can be more likely to damage the energy system resilience of the cities in the southwestern region, especially during extreme weather. In the northern region, power output is dominated by thermal power, making it less susceptible to the impacts of climate change. The economic benefits derived from electricity sales in this region play a crucial role in enhancing urban energy systems resilience by reinforcing their energy system infrastructure. Additionally, the increasing population in both the southwest and north regions will have a negative impact on the resilience of the urban energy system.

### *3.3. Parallel trend test*

The parallel trend assumption is a fundamental prerequisite for the application of the DID model. In other words, the trend of urban energy system resilience in both the treatment and control groups remained consistent before the first UHV line was operated. Referring to previous studies, we use Eq. (16) and Eq. (17) for parallel trend testing [67]. If the coefficients for the periods prior to the policy implementation lack statistical significance, it suggests that there is no significant discrepancy between the treatment and non-treatment groups regarding the trends of urban energy systems resilience. It indicates that the sample passes the parallel trend test. Fig. 4 shows the results of the parallel trend test for the first and second group cities.

For the first group, the northern region, we conducted a parallel trend test using Eq. (16).

$$y_{it} = \alpha_0 + \beta_t \sum_{t=-5}^{4} DID_{it} + \lambda Z_{it} + \eta_i + \mu_t + \varepsilon_{it} \tag{16}$$

For the second group, the southwestern region, we conducted a parallel trend test using Eq. (17).

$$y_{it} = \alpha_0 + \beta_t \sum_{t=-4}^{8} DID_{it} + \lambda Z_{it} + \eta_i + \mu_t + \varepsilon_{it} \tag{17}$$

As shown in Fig. 4a, after controlling for time and individual fixed effects, the *did* coefficients all include zero within the 95 % confidence interval. In the northern region, there is no statistically significant difference between the treatment and control groups of urban energy system resilience, thereby satisfying the assumption of parallel trend. Similarly, in the southwest region (Fig. 4b), the *did* coefficients contain 0 at the 95 % confidence interval before the first UHV line was operated, also satisfying the parallel trend assumption. In addition, it can be seen that for the southwestern region, the operation of the first UHV line has a delayed effect on the resilience of the urban energy system. It may be due to the fact that in the first few years of UHV line operation, the urban energy supply in southwest region was greater than the energy demand. As industrial development progresses in the region, energy consumption has been increasing, resulting in insufficient energy supply in the region.

### *3.4. Propensity score matching*

The combination of propensity score matching (PSM) and DID method can associate each treatment group sample with a corresponding control group sample, thus excluding the interference of sample selection bias [68]. It explains individual heterogeneity by identifying comparable individuals who are very similar to those in the treatment

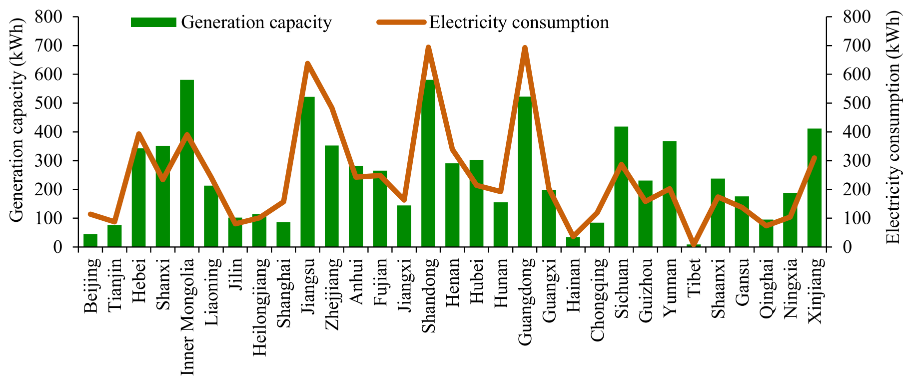


**Fig. 2.** Generation capacity and electricity consumption of different province or municipalities in 2020.

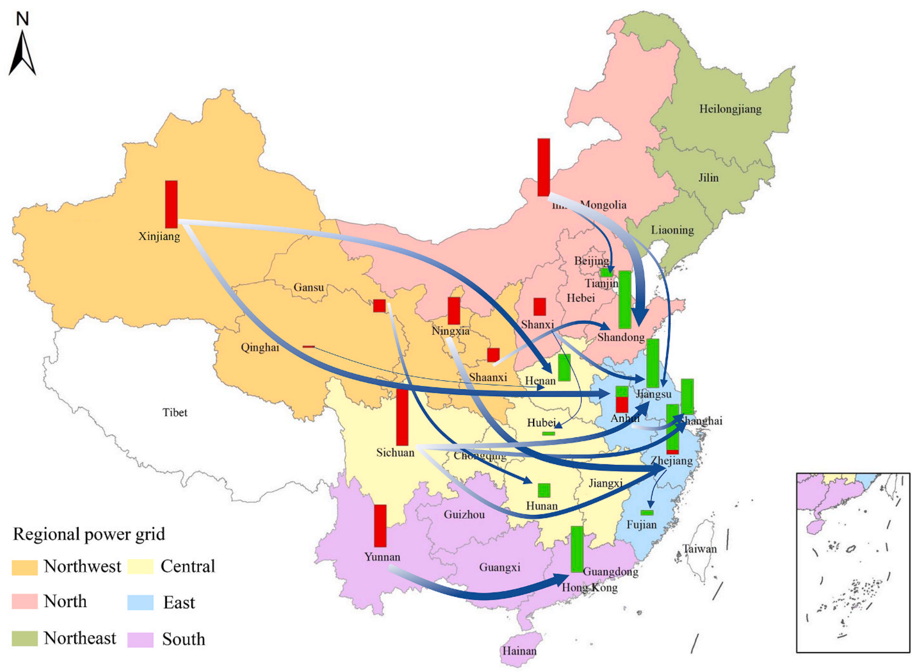


**Fig. 3.** Electricity transmission capacity of UHV lines in China in 2020. The red bar indicates the total output power capacity of UHV lines in a given region in 2020. The green bar indicates the total power input capacity of UHV lines in a given region in 2020. The blue line indicates a specific UHV line, the thicker the line, the more power is transmitted.

**Table 3**
Baseline results.

| Variables | Dependent variables: urban energy system resilience | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| did | 0.1480*** | 0.1330*** | −0.1367*** | −0.1381*** |
| | (0.0343) | (0.0370) | (0.0360) | (0.0362) |
| lnpop | | −0.2670*** | | −0.1686*** |
| | | (0.0645) | | (0.0449) |
| lngdp | | 0.0343 | | 0.1600** |
| | | (0.0435) | | (0.0536) |
| lninv | | 0.0075 | | 0.0381*** |
| | | (0.0105) | | (0.0115) |
| lnind | | 0.1100** | | −0.0415 |
| | | (0.0560) | | (0.0746) |
| Constant | 4.3414*** | 4.8237*** | 4.4190*** | 3.9627*** |
| | (0.0106) | (0.3192) | (0.0142) | (0.3764) |
| Observations | 960 | 955 | 927 | 920 |
| City effects | Yes | Yes | Yes | Yes |
| Year effects | Yes | Yes | Yes | Yes |
| Adj. R-squared | 0.7177 | 0.7254 | 0.7115 | 0.7206 |

group, enhancing the robustness of chance inference. In addition, by matching treatment and control groups, PSM-DID can ensure that covariates are balanced among groups before policy implementation, and reduces confounders from disrupting treatment effects [69]. Therefore, this study adopts the PSM-DID of nearest neighbor, radius matching and kernel matching to further evaluate the impact of trans-regional power transmission on urban energy system resilience. The results of the PSM-DID is presented in Table 4.

For cities in northern region, the *did* coefficients are significantly positive in all three regressions. And *did* coefficient values of the three columns are generally consistent with the baseline regression coefficient values. For cities in southwestern region, the *did* coefficients are significantly negative in all three regressions. That is, for the northern region, trans-regional power transmission facilitates urban energy system resilience, while the opposite for the southwest.

### 3.5. Robustness test

The Placebo test was used to mitigate the deviation of the results attributable to unobserved confounding factors. We perform a Placebo

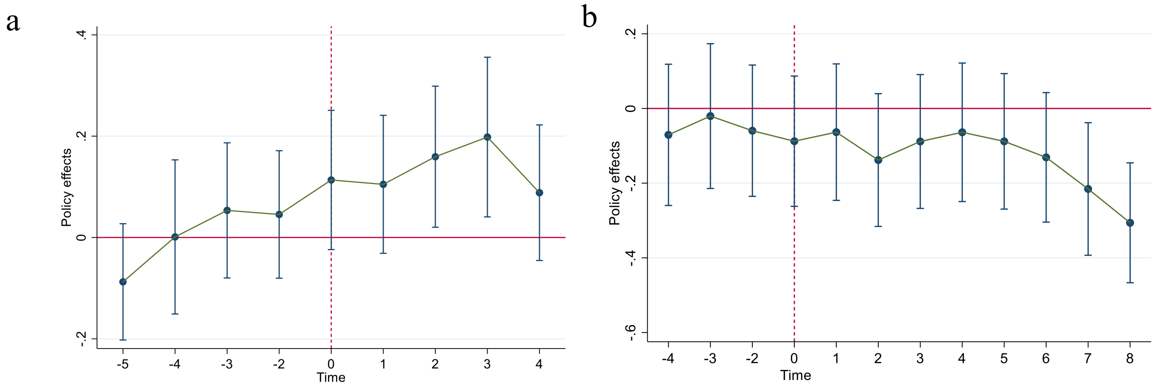


**Fig. 4.** Parallel trend test of group 1 (northern region) and group 2 (southwestern region), respectively.

**Table 4**
The results of propensity score matching.

| Variables | Dependent variables: urban energy system resilience | | | | | |
|---|---|---|---|---|---|---|
| | Northern region | | | Southwestern region | | |
| | Nearest neighbor | Radius matching | Kernel matching | Nearest neighbor | Radius matching | Kernel matching |
| did | 0.1219** | 0.1139** | 0.1115** | −0.0858* | −0.1256*** | −0.1256*** |
| | (0.0469) | (0.0368) | (0.0370) | (0.0497) | (0.0355) | (0.0355) |
| Constant | 4.3684*** | 4.8450*** | 4.8844*** | 3.5429*** | 3.9883*** | 3.9883*** |
| | (0.4201) | (0.3134) | (0.3163) | (0.5001) | (0.3858) | (0.3858) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes |
| City effect | Yes | Yes | Yes | Yes | Yes | Yes |
| Year effect | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 447 | 909 | 905 | 613 | 909 | 909 |
| Adj. R-squared | 0.7373 | 0.7302 | 0.7304 | 0.7422 | 0.7261 | 0.7261 |

test by randomly allocating samples to generate a virtual dummy variable. Specifically, we randomly assign the year of UHV lines operation to each city and subsequently perform DID estimation, repeating this process 500 times. Fig. 5 presents the probability density distributional characteristics of the estimated coefficients in the Placebo test of first group and second group, respectively.

In Fig. 5, the estimates follow a normal distribution with an average of 0, and most of the estimated values have $p$ values greater than 0.1, which suggests that the virtual time of the randomly assigned UHV lines exerts no significant effect on urban energy system resilience, which further demonstrates the stability of the baseline results.

Besides, during the operational phase of the UHV lines, numerous other energy policies aiming to reduce carbon emissions and restructuring the energy mix were implemented. These policies may influence urban energy system resilience, including smart city policies and low-carbon city pilot. The primary goal of the low-carbon pilot city policy is to promote the transformation and enhancement of the industrial structure, optimize the energy mix, and enhance energy use efficiency [70]. China implemented the initial cohort of low-carbon pilot projects, the second batch and the third batch of low-carbon pilots in July 2010, November 2012 and January 2017, respectively [71]. Smart city represents an innovative paradigm of urban development in the digital era, which can enhance intelligent and systematic operation of the city and improve urban energy efficiency [72]. China started exploring this new model of urban development in 2012 and established 90 pilot smart cities. In the subsequent years, in 2013 and 2015, a second and third round of pilot cities were announced [73]. Table 5 shows the results after excluding two policies. The results show that the *did* coefficient for the northern region remains significantly positive even after excluding two policies. For the southwestern region, the *did* coefficient continues

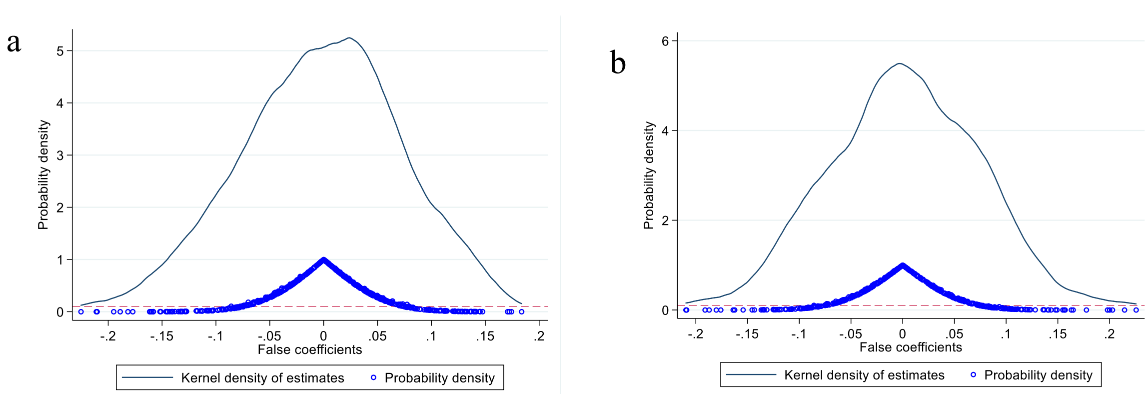


**Fig. 5.** Placebo test of northern region and southwestern region, separately.

**Table 5**
Regression results after excluding relevant policy.

| Variables | Dependent variables: urban energy system resilience | | | |
|---|---|---|---|---|
| | Northern region | | Southwestern region | |
| | Low-carbon city pilot policy | Smart city policy | Low-carbon city pilot policy | Smart city policy |
| did | 0.1533*** | 0.1124** | −0.1025** | −0.1532*** |
| | (0.0457) | (0.0459) | (0.0385) | (0.0391) |
| Constant | 4.7001*** | 4.2621*** | 4.2442*** | 4.1528*** |
| | (0.4115) | (0.4204) | (0.4406) | (0.4249) |
| Control variables | Yes | Yes | Yes | Yes |
| City effects | Yes | Yes | Yes | Yes |
| Year effects | Yes | Yes | Yes | Yes |
| Observations | 786 | 748 | 727 | 746 |
| Adj. R-squared | 0.7500 | 0.7633 | 0.6988 | 0.7263 |

to be negative, further demonstrating the reliability of the results.

In addition, this study further evaluates the reliability of the results by changing the dependent variables. When evaluating the resilience of the urban energy system, we further calculated the weights of each indicator for each year, which were then utilized to calculate the score of each city for each year with varying weights. The results are presented in Table 6. As illustrated in Table 6, for northern cities, the regression parameters of *did* is statistically significant and positive. For southwestern cities, the regression coefficients of *did* is opposite, which further proves the reliability of the results.

## 4. Discussion and conclusions

UHV lines play a crucial role in trans-regional power transmission. UHV represents not only an innovative transmission technology but also serves as a novel platform for resource allocation that can effectively promote low-carbon development. The construction of UHV in China is the most rapid and heavily invested among all countries. According to the 2020 Social Responsibility Report of State Grid, the company has constructed and commissioned 26 UHV projects, with a total length of 41,000 km of lines in operation and under construction, transmitting more than 1.6 trillion kWh of electricity in total. Currently, the total investment of 33 operated and 38 under-construction UHV lines in China is nearly 1.6 trillion yuan [74], which reflects the importance of trans-regional power transmission in energy systems in China. However, the impact of trans-regional power transmission on the urban energy systems resilience of power output regions requires further investigation. Here, an indicator system including urban energy supply, transmission, storage, consumption, and urban infrastructure is developed for evaluating urban energy systems resilience. We regard the operation of UHV lines in China as a quasi-natural experiment and assess the impact of trans-regional power transmission on the urban energy systems resilience in power output regions. This study found that trans-regional power transmission has a heterogeneous impact on urban energy systems resilience in the power output region. For the northern region, which is dominated by thermal power exports, trans-regional transmission is beneficial for improving the urban energy systems resilience. The trans-regional power transmission can convert the resource advantages of the northern region into economic advantages. By enhancing the energy infrastructure of the northern region, it contributes to the comprehensive and integrated development of the region. In addition, the northern region has a higher proportion of thermal power generation, which is less affected by extreme weather. Therefore, urban energy system is more flexible to respond to the effects of extreme weather. However, for the southwestern region, the distribution of hydropower under WEPT project in China has specific criteria, and is not prioritized for transmit to the local region. Thus, urban energy systems in the southwest are more vulnerable when extreme weather such as drought occur.

This conclusion remains robust following a series of robustness tests. This suggest that trans-regional power transmission may bring inequalities in regional energy utilization. In the context of energy transition, UHV will facilitate the large-scale advancement and deployment of clean energy in the western and northern regions, providing an important way to promote coordinated regional development. However, trans-regional power transmission may damage the resilience of the energy system in some of the power output regions, as demonstrated in this study. Therefore, it is essential to address and resolve certain issues related to the establishment and functioning of UHV infrastructure. For example, some UHV projects fail to conduct a precise assessment of the transmission capacity of power generation sources at the transmission origin before construction, leading to low utilization of UHV lines. Furthermore, the inadequate development of power grid infrastructure in the power input regions has led to a mismatch between transmitted power and consumption, resulting in underutilized and wasted UHV lines. Finally, trans-regional transmission may create regional energy consumption inequities.

Therefore, some key measures should be implemented to improve urban energy system resilience. First, differentiated development strategies are implemented for cities in different power exporting regions based on the resource endowment of the region. For example, in the southwestern region where hydropower is predominant, single power generation leads to greater challenges for the energy supply system during the extreme events. To fully leverage hydropower resources, these regions should actively advance the development of diversified and complementary multi-energy power supply system that integrate hydropower, wind, and solar energy, thereby enhancing the diversity and stability of the power supply. At the same time, it is crucial to accelerate the expansion of transmission infrastructure to facilitate trans-provincial power transmission, promoting resource complementarity and shared benefits. For example, during the wet season, surplus hydropower can be transmitted to other provinces through interregional power networks, while in the dry season, electricity can be imported from external sources via the same channels. This bidirectional coordination not only optimizes energy resource allocation but also enhances the resilience and sustainability of the power system. For cities in the northern region mainly focused on exporting thermal power, renewable energy should be vigorously developed to achieve energy transition in China towards clean energy as soon as possible. Further strengthen trans-regional grid connectivity and enhance the overall stability of the regional grid to maximize the positive impacts of trans-regional power transmission and promote the long-term sustainable advancement of trans-regional power transmission.

Secondly, the government should actively promote the development of local renewable energy sources, by implementing policy incentive including subsidies and tax benefits and providing technical support to encourage enterprises and residents to participate in distributed energy projects. This approach will reduce dependence on trans-regional power transmission while enhancing the diversity and resilience of the energy

**Table 6**
Regression results after changing the dependent variable.

| Variables | Dependent variables: urban energy system resilience | | | |
|---|---|---|---|---|
| | Northern region | | Southwestern region | |
| did | 0.1899*** | 0.1634*** | −0.1295** | −0.1368*** |
| | (0.0400) | (0.0428) | (0.0403) | (0.0405) |
| Constant | 4.3499*** | 5.2021*** | 4.4292*** | 3.8899*** |
| | (0.0120) | (0.3457) | (0.0163) | (0.5129) |
| Control variables | No | Yes | No | Yes |
| City effects | Yes | Yes | Yes | Yes |
| Year effects | Yes | Yes | Yes | Yes |
| Observations | 960 | 955 | 927 | 920 |
| Adj. R-squared | 0.7013 | 0.7134 | 0.6840 | 0.6949 |

supply. In addition, power system planning and design must fully consider the impacts of extreme weather. Comprehensive emergency response plans should be established, and the disaster resilience of critical infrastructure should be reinforced, such as strengthening transmission lines and enhancing the protection standards of substations, to ensure the stability and reliability of the power system under severe weather conditions. Furthermore, energy storage deployment should be strategically aligned with local resource availability and energy demands. Advanced energy storage technologies, such as battery storage, pumped hydro storage, and hydrogen energy storage, should be optimally integrated to support peak shaving, emergency backup, and the large-scale adoption of renewable energy. Expanding the application of diverse energy storage solutions will further enhance the flexibility, stability, and reliability of the power system.

Finally, compared to the eastern region of China, the western region exhibits a lower level of development. Therefore, it is imperative to increase economic support for cities in the western region, promote cooperation among cities in the east and west through investment and industrial transfer. In this way, balanced regional development is promoted to mitigate the effects of regional inequality caused by trans-regional power transmission. Furthermore, the western region should also develop specialized industries based on its inherent advantages to enhance its economic and social development. Trans-regional power transmission and exchange has become an important way to ensure power supply and optimize resource allocation in China. It is of great significance in guaranteeing energy security and promoting sustainable development. Therefore, it is necessary to further optimize the market trading system of trans-regional power transmission, and to pay attention to the energy security of the power exporting region while ensuring the adequate supply of energy in the eastern region. In addition, investment in trans-regional energy infrastructure should be further increased to improve trans-regional transmission capacity.

This study is subject to certain limitation, which point out possible directions and challenges for future research. First, the urban energy system resilience evaluation indicator system can be expanded with the energy mix transformation and urbanization processes. Second, in this study we did not consider all UHV transmission lines. Instead, the cities were categorized into two distinct categories based on power transmission type and filtered the control groups according to their geographic location and economic situation of cities. In future studies, the impacts of certain UHV lines on urban energy systems resilience can be explored through scenario analysis and other methodologies. Finally, the power grid in China is operated by provincial companies as the governing bodies, that is provincial power grids are organized and dispatched as an executor. Therefore, we are using all cities of a certain province as the treatment group. For other countries, it is necessary to choose the treatment group and non-treatment group with the actual situation of the region.

## CRediT authorship contribution statement

**Jingna Yang:** Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Kaile Zhou:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

## Declaration of competing interest

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

## Acknowledgments

This work is supported by the National Natural Science Foundation of China [grant No. 72242103].

## Data availability

Data will be made available on request.

## References

[1] Lyu W, Cui Z, Yuan M, Shan E. Cooperation for trans-regional electricity trading from the perspective of carbon quota: a cooperative game approach. Int J Electr Power Energy Syst 2024;156:109773. https://doi.org/10.1016/j.ijepes.2023.109773.
[2] Peng W, Wagner F, Ramana M, Zhai H, Small MJ, Dalin C, Zhang X, Mauzerall DL. Managing China's coal power plants to address multiple environmental objectives. Nat Sustain 2018;1:693–701. https://doi.org/10.1038/s41893-018-0174-1.
[3] Wang Y, Yan Q, Yang J, Komonpipat S, Zhang Q. Can inter-provincial transmission reduce regional carbon emissions? Evidence from China. Energy Policy 2024;184:113915. https://doi.org/10.1016/j.enpol.2023.113915.
[4] Wang Y, Chao Q, Zhao L, Chang R. Assessment of wind and photovoltaic power potential in China. Carbon Neutrality 2022;1:15. https://doi.org/10.1007/s43979-022-00020-w.
[5] Zhou X, Yi J, Song R, Yang X, Li Y, Tang H. An overview of power transmission systems in China. Energy 2010;35:4302–12. https://doi.org/10.1016/j.energy.2009.04.016.
[6] Wang Y, Wang R, Tanaka K, Ciais P, Penuelas J, Balkanski Y, Sardans J, Hauglustaine D, Liu W, Xing X. Accelerating the energy transition towards photovoltaic and wind in China. Nature 2023;619:761–7. https://doi.org/10.1038/s41586-023-06180-8.
[7] Zhou D, Zhao S, Ding H, Wang Q. Optimal transition pathways toward carbon neutrality in Chinese power sector: considering regional heterogeneity and technological change. Comput Ind Eng 2023;183:109553. https://doi.org/10.1016/j.cie.2023.109553.
[8] Hao N, Peng B, Tang K, Wu J. Does energy poverty trap exist in Chinese cities? Evidence from evaluating the co-evolution of energy consumption and income. Cities 2024;150:105082. https://doi.org/10.1016/j.cities.2024.105082.
[9] Tan X, Lin S, Xie B-C. The distributional effect of inter-regional transmission grid expansion on China's power industry. Climate Change Economics 2022;13:2240005. https://doi.org/10.1142/S201000782240005X.
[10] Yang Y-S, Xie B-C, Tan X. Impact of green power trading mechanism on power generation and interregional transmission in China. Energy Policy 2024;189:114088. https://doi.org/10.1016/j.enpol.2024.114088.
[11] Ge Z, Geng Y, Wei W, Jiang M, Chen B, Li J. Embodied carbon emissions induced by the construction of hydropower infrastructure in China. Energy Policy 2023;173:113404. https://doi.org/10.1016/j.enpol.2022.113404.
[12] Hu Y, Cheng H. Displacement efficiency of alternative energy and trans-provincial imported electricity in China. Nat Commun 2017;8:14590. https://doi.org/10.1038/ncomms14590.
[13] Li N, Chen W. Modeling China's interprovincial coal transportation under low carbon transition. Appl Energy 2018;222:267–79. https://doi.org/10.1016/j.apenergy.2018.03.103.
[14] Li Y, Lukszo Z, Weijnen M. The impact of inter-regional transmission grid expansion on China's power sector decarbonization. Appl Energy 2016;183:853–73. https://doi.org/10.1016/j.apenergy.2016.09.006.
[15] Qiu S, Lei T, Wu J, Bi S. Energy demand and supply planning of China through 2060. Energy 2021;234:121193. https://doi.org/10.1016/j.energy.2021.121193.
[16] Brown PR, Botterud A. The value of inter-regional coordination and transmission in decarbonizing the US electricity system. Joule 2021;5:115–34. https://doi.org/10.1016/j.joule.2020.11.013.
[17] Yang F, Zhang S, Sun C. Energy infrastructure investment and regional inequality: evidence from China's power grid. Sci Total Environ 2020;749:142384. https://doi.org/10.1016/j.scitotenv.2020.142384.
[18] Yang H, Deshmukh R, Suh S. Global transcontinental power pools for low-carbon electricity. Nat Commun 2023;14:8350. https://doi.org/10.1038/s41467-023-43723-z.
[19] Yi B, Zhang S, Fan Y. Economics of planning electricity transmission considering environmental and health externalities. iScience 2022;25:104815. https://doi.org/10.1016/j.isci.2022.104815.
[20] Han G, Chen L, Wei W, Zhang P, Xu Z, Liang S, Yang Y. Impacts of trans-provincial thermal power transmission on air-quality recovery and related health outcomes in China. Environmental Science & Technology 2023;57:8289–300. https://doi.org/10.1021/acs.est.2c08925.
[21] Ming Z, Lilin P, Qiannan F, Yingjie Z. Trans-regional electricity transmission in China: Status, issues and strategies. Renew Sustain Energy Rev 2016;66:572–83. https://doi.org/10.1016/j.rser.2016.08.023.
[22] Wang Y, Li M, Wang L, Wang H, Zeng M, Zeng B, Qiu F, Sun C. Can remotely delivered electricity really alleviate smog? An assessment of China's use of ultra-high voltage transmission for air pollution prevention and control. J Clean Prod 2020;242:118430. https://doi.org/10.1016/j.jclepro.2019.118430.
[23] Chen R, Xu P, Yao H. Decarbonization of China's regional power grid by 2050 in the government development planning scenario. Environ Impact Assess Rev 2023;101:107129. https://doi.org/10.1016/j.eiar.2023.107129.
[24] Li J, Lin B. Environmental impact of electricity relocation: a quasi-natural experiment from interregional electricity transmission. Environ Impact Assess Rev 2017;66:151–61. https://doi.org/10.1016/j.eiar.2017.07.002.

[25] Zhang Q, Chen W. Modeling China's interprovincial electricity transmission under low carbon transition. Appl Energy 2020;279:115571. https://doi.org/10.1016/j.apenergy.2020.115571.
[26] Li J, Wang Z, Zhou S, Lu B, Dai W, Bao H. Optimal planning energy storage for promoting renewable power consumption in the urgent situation of UHV systems. Int J Electr Power Energy Syst 2022;143:108453. https://doi.org/10.1016/j.ijepes.2022.108453.
[27] Li Y, Yi B-W, Wang Y. Can ultra-high voltage power transmission bring environmental and health benefits? An assessment in China. J Clean Prod 2020;276:124296. https://doi.org/10.1016/j.jclepro.2020.124296.
[28] Tan X, Lin S, Liu Y-L, Xie B-C. Has the inter-regional transmission grid promoted clean power development? A quantitative assessment on China's electricity sector. J Clean Prod 2020;269:122370. https://doi.org/10.1016/j.jclepro.2020.122370.
[29] Zhang K, Zhang W, Shi Q, Zhang J, Yuan J. Coupling effects of cross-region power transmission and disruptive technologies on emission reduction in China. Resour Conserv Recycl 2023;189:106773. https://doi.org/10.1016/j.resconrec.2022.106773.
[30] Deng X, Lv T, Xu J, Hou X, Liu F. Assessing the integration effect of inter-regional transmission on variable power generation under renewable energy consumption policy in China. Energy Policy 2022;170:113219. https://doi.org/10.1016/j.enpol.2022.113219.
[31] Few S, Djapic P, Strbac G, Nelson J, Candelise C. A geographically disaggregated approach to integrate low-carbon technologies across local electricity networks. Nat Energy 2024:1–12. https://doi.org/10.1038/s41560-024-01542-6.
[32] Xu Z, Das DK, Guo W, Wei W. Does power grid infrastructure stimulate regional economic growth? Energy Policy 2021;155:112296. https://doi.org/10.1016/j.enpol.2021.112296.
[33] Jia Z, Wen S, Wang Y. Power coming from the sky: economic benefits of inter-regional power transmission in China. Energy Econ 2023;119:106544. https://doi.org/10.1016/j.eneco.2023.106544.
[34] Wei W, Hao S, Yao M, Chen W, Wang S, Wang Z, Wang Y, Zhang P. Unbalanced economic benefits and the electricity-related carbon emissions embodied in China's interprovincial trade. J Environ Manag 2020;263:110390. https://doi.org/10.1016/j.jenvman.2020.110390.
[35] Yi B-W, Xu J-H, Fan Y. Inter-regional power grid planning up to 2030 in China considering renewable energy development and regional pollutant control: a multi-region bottom-up optimization model. Appl Energy 2016;184:641–58. https://doi.org/10.1016/j.apenergy.2016.11.021.
[36] Yi B-W, Zhang S, Wang Y. Estimating air pollution and health loss embodied in electricity transfers: an inter-provincial analysis in China. Sci Total Environ 2020;702:134705. https://doi.org/10.1016/j.scitotenv.2019.134705.
[37] Zhang C, He G, Zhang Q, Liang S, Zipper SC, Guo R, Zhao X, Zhong L, Wang J. The evolution of virtual water flows in China's electricity transmission network and its driving forces. J Clean Prod 2020;242:118336. https://doi.org/10.1016/j.jclepro.2019.118336.
[38] Wei W, Li J, Chen B, Wang M, Zhang P, Guan D, Meng J, Qian H, Cheng Y, Kang C. Embodied greenhouse gas emissions from building China's large-scale power transmission infrastructure. Nat Sustain 2021;4:739–47. https://doi.org/10.1038/s41893-021-00704-8.
[39] Wang H, Zhang Y, Lin W, Wei W. Transregional electricity transmission and carbon emissions: evidence from ultra-high voltage transmission projects in China. Energy Econ 2023;123:106751. https://doi.org/10.1016/j.eneco.2023.106751.
[40] Yu S, Zhou S, Qin J. Layout optimization of China's power transmission lines for renewable power integration considering flexible resources and grid stability. Int J Electr Power Energy Syst 2022;135:107507. https://doi.org/10.1016/j.isci.2022.104815.
[41] Wang X, Tan Y, Zhou G, Jing G, Francis EJ. A framework for analyzing energy consumption in urban built-up areas based on single photonic radar and spatial big data. Energy 2024;290:130202. https://doi.org/10.1016/j.energy.2023.130202.
[42] Basu S, Bale CS, Wehnert T, Topp K. A complexity approach to defining urban energy systems. Cities 2019;95:102358. https://doi.org/10.1016/j.cities.2019.05.027.
[43] Jafar HT, Tavakoli O, Bidhendi GN, Alizadeh M. Sustainable electricity supply planning: a nexus-based optimization approach. Renew Sustain Energy Rev 2024;195:114316. https://doi.org/10.1016/j.rser.2024.114316.
[44] Shan Y, Fang S, Cai B, Zhou Y, Li D, Feng K, Hubacek K. Chinese cities exhibit varying degrees of decoupling of economic growth and CO2 emissions between 2005 and 2015. One Earth 2021;4:124–34. https://doi.org/10.1016/j.oneear.2020.12.004.
[45] Sridharan V, Broad O, Shivakumar A, Howells M, Boehlert B, Groves D, Rogner H, Taliotis C, Neumann J, Strzepek K. Resilience of the Eastern African electricity sector to climate driven changes in hydropower generation. Nat Commun 2019;10:302. https://doi.org/10.1038/s41467-018-08275-7.
[46] Stürmer J, Plietzsch A, Vogt T, Hellmann F, Kurths J, Otto C, Frieler K, Anvari M. Increasing the resilience of the Texas power grid against extreme storms by hardening critical lines. Nat Energy 2024:1–10. https://doi.org/10.1038/s41560-023-01434-1.
[47] Wu J, Zuidema C, de Roo G. Climate policy integration on energy transition: an analysis on Chinese cases at the local scale. Cities 2022;120:103469. https://doi.org/10.1016/j.cities.2021.103469.
[48] Yalew S, van Vliet M, Gernaat D, Ludwig F, Miara A, Park C, Byers E, De Cian E, Piontek F, Iyer G. Impacts of climate change on energy systems in global and regional scenarios. Nat Energy 2020;5:794–802. https://doi.org/10.1038/s41560-020-0664-z.
[49] Liu H, Brown T, Andresen GB, Schlachtberger DP, Greiner M. The role of hydro power, storage and transmission in the decarbonization of the Chinese power system. Appl Energy 2019;239:1308–21. https://doi.org/10.1016/j.apenergy.2019.02.009.
[50] Lv B, Hao Z, Ma Q, Chen Y, Zhang X, Fu Y, Hao F. Spatial compounding of droughts and hot extremes across southwest and east China resulting from energy linkages. J Hydrol 2024:130827. https://doi.org/10.1016/j.jhydrol.2024.130827.
[51] Ala A, Simic V, Pamucar D, Jana C. A novel neutrosophic-based multi-objective grey wolf optimizer for ensuring the security and resilience of sustainable energy: a case study of Belgium. Sustain Cities Soc 2023;96:104709. https://doi.org/10.1016/j.scs.2023.104709.
[52] Zhou S, Han Y, Zalhaf AS, Chen S, Zhou T, Yang P, Elboshy B. A novel multi-objective scheduling model for grid-connected hydro-wind-PV-battery complementary system under extreme weather: a case study of Sichuan, China. Renew Energy 2023;212:818–33. https://doi.org/10.1016/j.renene.2023.05.092.
[53] Büyüközkan G, Ilıcak Ö, Feyzioğlu O. A review of urban resilience literature. Sustain Cities Soc 2022;77:103579. https://doi.org/10.1016/j.scs.2021.103579.
[54] Kuang B, Shi Y, Hu Y, Zeng Z, Chen J. Household energy resilience in extreme weather events: an investigation of energy service importance, HVAC usage behaviors, and willingness to pay. Appl Energy 2024;363:123051. https://doi.org/10.1016/j.apenergy.2024.123051.
[55] Montoya-Rincon JP, Mejia-Manrique SA, Azad S, Ghandehari M, Harmsen EW, Khanbilvardi R, Gonzalez-Cruz JE. A socio-technical approach for the assessment of critical infrastructure system vulnerability in extreme weather events. Nat Energy 2023;8:1002–12. https://doi.org/10.1038/s41560-023-01315-7.
[56] Fan W, Lv W, Wang Z. How to measure and enhance the resilience of energy systems? Sustain Prod Consum 2023;39:191–202. https://doi.org/10.1016/j.spc.2023.05.015.
[57] Moslehi S, Reddy TA. Sustainability of integrated energy systems: a performance-based resilience assessment methodology. Appl Energy 2018;228:487–98. https://doi.org/10.1016/j.apenergy.2018.06.075.
[58] Peng C, Chen H, Lin C, Guo S, Yang Z, Chen K. A framework for evaluating energy security in China: Empirical analysis of forecasting and assessment based on energy consumption. Energy 2021;234:121314. https://doi.org/10.1016/j.energy.2021.121314.
[59] Zhang P, Wan J, Zhong W, Hu W. Toward governance, resilience, and economic outcomes in urban energy transition based on renewable energy allocation. Sustain Cities Soc 2024:105462. https://doi.org/10.1016/j.scs.2024.105462.
[60] Huang J, Zonghui W, Koroteev DD, Rynkovskaya M. Energy efficiency security in urban areas: challenges and implementation. Sustain Cities Soc 2024;107:105380. https://doi.org/10.1016/j.scs.2024.105380.
[61] Du X, Wang Y, Chen F. Evaluation of coal-resource-based cities transformation based on CRITIC-TOPSIS model. Sustain Cities Soc 2024:105271. https://doi.org/10.1016/j.scs.2024.105271.
[62] Diakoulaki D, Mavrotas G, Papayannakis L. Determining objective weights in multiple criteria problems: the critic method. Comput Oper Res 1995;22:763–70. https://doi.org/10.1016/0305-0548(94)00059-H.
[63] Liu E-n, Wang Y, Chen W, Chen W, Ning S. Evaluating the transformation of China's resource-based cities: an integrated sequential weight and TOPSIS approach. Soc Econ Plann Sci 2021;77:101022. https://doi.org/10.1016/j.seps.2021.101022.
[64] Chen W, Shen Y, Wang Y. Evaluation of economic transformation and upgrading of resource-based cities in Shaanxi province based on an improved TOPSIS method. Sustain Cities Soc 2018;37:232–40. https://doi.org/10.1016/j.scs.2017.11.019.
[65] Wang D, Chen S. The effect of pilot climate-resilient city policies on urban climate resilience: evidence from quasi-natural experiments. Cities 2024;153:105316. https://doi.org/10.1016/j.cities.2024.105316.
[66] China Network. Sichuan, mainly hydroelectric power generation, why the shortage of electricity? Sichuan power supply situation is serious. China Network; 2022. http://henan.china.com.cn/finance/2022-08/17/content_42073526.htm.
[67] Beck T, Levine R, Levkov A. Big bad banks? The winners and losers from bank deregulation in the United States. J Finance 2010;65:1637–67. https://doi.org/10.1111/j.1540-6261.2010.01589.x.
[68] Blundell R, Costa Dias M. Evaluation methods for non-experimental data. Fiscal Stud 2000;21:427–68. https://doi.org/10.1111/j.1475-5890.2000.tb00031.x.
[69] Ghimire A, Ali S, Long X, Chen L, Sun J. Effect of Digital Silk Road and innovation heterogeneity on digital economy growth across 29 countries: new evidence from PSM-DID. Technol Forecast Soc Change 2024;198:122987. https://doi.org/10.1016/j.techfore.2023.122987.
[70] Chen G, Wei B. Low-carbon city pilots and site selection for migrant employment: evidence from China. Energy Econ 2024:107417. https://doi.org/10.1016/j.eneco.2024.107417.
[71] Wang L, Shao J, Ma Y. Does China's low-carbon city pilot policy improve energy efficiency? Energy 2023;283:129048. https://doi.org/10.1016/j.energy.2023.129048.
[72] Wu M, Guo M, Xu J. The influence of smart city policy on urban green energy efficiency–A quasi-natural experiment based on 196 cities. J Clean Prod 2024;449:141818. https://doi.org/10.1016/j.jclepro.2024.141818.
[73] Chen C, Li S-E, Wang L. Can smart cities reduce labor misallocation? Evidence from China. Technol Forecast Soc Change 2024;201:123264. https://doi.org/10.1016/j.techfore.2024.123264.
[74] The Paper. From "to build or not to build" to "enough or not enough", the controversy over UHV has not ended for two decades 2023. The Paper, https://www.thepaper.cn/newsDetail_forward_24139091.