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RESEARCH ARTICLE

Regional study on investment for transmission infrastructure in China based on the State Grid data

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Abstract Transmission infrastructure is an integral component of safeguarding the stability of electricity delivery. However, existing studies of transmission infrastructure mostly rely on a simple review of the network, while the analysis of investments remains rudimentary. This study conducted the first regionally focused analysis of investments in transmission infrastructure in China to help optimize its structure and reduce investment costs. Using State Grid data, the investment costs, under various voltages, for transmission lines and transformer substations are calculated. By analyzing the regional profile of cumulative investment in transmission infrastructure, we assess correlations between investment, population, and economic development across the regions. The recent development of ultra-high-voltage transmission networks will provide policy-makers new options for policy development.

Keywords regional study, energy geography, investment analysis, transmission lines, transformer substation

1 Introduction

Energy security is a commonly acknowledged concern for economic development at regional (Han et al., 2013a; Li et al., 2014, 2016; Xia et al., 2014), national (Chen et al., 2007; Ji et al., 2009; Xia et al., 2011), and global scales (Chen and Chen, 2011b, c). According to British Petroleum, global primary energy consumption reached 12,928 million tons of equivalent oil use in 2014 (BP, 2015). Associated environmental emissions have gained attention due to the current battle against climate change (Chen et al., 2011b; Li et al., 2013; Han et al., 2016; Li et al., 2015a; Xia et al., 2015). Serving as the backbone for electricity delivery, transmission infrastructure plays a significant role in promoting regional economic growth, and optimizing the allocation of energy resources. Since the middle of the twentieth century, China's transmission network has progressed greatly. By the end of 2013, transmission lines with a voltage class of over 220 kV reached an approximate total length of 2.2×10^6 km, and the gross substation capacity was approximately 12 billion kVA (Liu, 2015). To strengthen the development of a transnational interconnected network, it is critical that the distribution of energy resources be optimized on a greater scale. A number of transnational interconnected networks exist internationally, including the European network of transmission system operators, the North America interconnection system, the Russia-Baltic Sea electrical transmission network, the South Africa power grid, the Arabian Gulf interconnection system, the Central American electrical interconnection system, and the South America power grid (SGERI, 2014).

At present, the European power system is the most advanced interconnected continental transmission network, consisting of five synchronized power grids, namely continental Europe, Northern Europe, the Baltic Sea, the UK, and Ireland electric systems, plus two independent power systems. By the end of 2013, the installed capacity and electricity consumption amounted to approximately one billion kW and 3.55 trillion kWh, respectively, with a length of 300,000 km of transmission lines at or above 220 kV. The Asian power grid covers 48 countries and regions and is comprised of the Russia-Baltic Sea electrical transmission network, the Gulf interconnection system, and other national power grids (i.e., China, Japan, Korea, India, and a few Southeast Asian countries). Its cumulative installed capacity and total electricity consumption is 2.4

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billion kW and 10 trillion kWh, respectively. The maximum voltage class is 1000 kV, and the transmission lines with a voltage of over 220 kV stretch 1.5×10^6 km.

China, the largest developing country, has experienced dramatic economic growth in recent decades. Chen and Chen (2007c) have conducted several studies on resource analysis of the Chinese society (Chen and Chen, 2007a, b). To support the vigorous economy, large quantities of fossil fuels are being consumed to maintain a sufficient supply of electricity. The distribution of primary energy resources in China is geographically unbalanced. Coal resources are mainly found in the northwest and northern provincial regions, such as Shanxi, Shaanxi, and Inner Mongolia. The southwest provincial regions, including Sichuan, Yunnan, and Tibet, are rich in hydroelectric resources. However, energy demand is concentrated in the economically robust central and eastern regions. This geographic imbalance between resource distribution and energy requirements has led to the long-term need for long distance electricity transmission.

China is now a leader in the development of large-scale transmission networks. As illustrated in Fig. 1 and Fig. 2, by the end of 2012, the length of domestic transmission lines with a voltage over 220 kV totalled 543,000 km, and the substation capacity was 2.7 billion kVA, 18.1 and 77.7 times larger, respectively, than in 1980. Table 1 provides the lengths of the transmission lines under different voltages from 1995 to 2012. Currently, provinces within north-central China, east China, northeast China, northwest China, and south China power systems, have developed AC/DC interconnected systems. The northeast China and north-central China power systems are asynchronously interconnected by the Gaoling back-to-back (BTB) high voltage direct current (HVDC) power transmission demonstration project. The northeast China and east China power systems are linked by Gezhou Dam-Nanqiao, Longquan-Zhengping, Yidu-Huaxin HVDC (all ±500 kV) projects, and also the ±800 kV Jia Dam-Shanghai HVDC. The southwest China power system is asynchronously connected with the north-central China power system by Lingbao BTB HVDC power project, Deyang-Baoji HVDC (±500 kV), and Ningdong-Shandong HVDC (±660 kV); while the north-central China and south China power systems are connected by the Three Gorges Dam-Guangdong HVDC. With regard to cross-border electricity transmission, China imports electricity from Russia via the HVDC (±500 kV) BTB project, and transmits power to Vietnam and northern Laos.

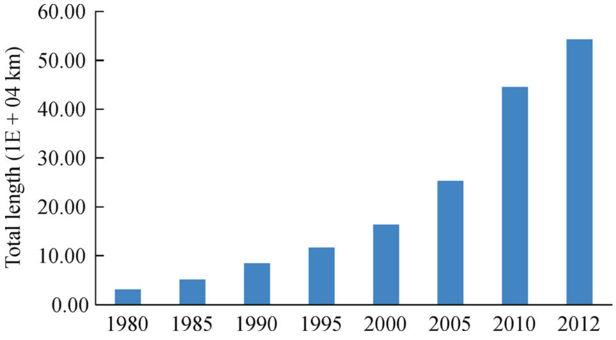

Fig. 1 Total length of transmission lines over 220 kV in China

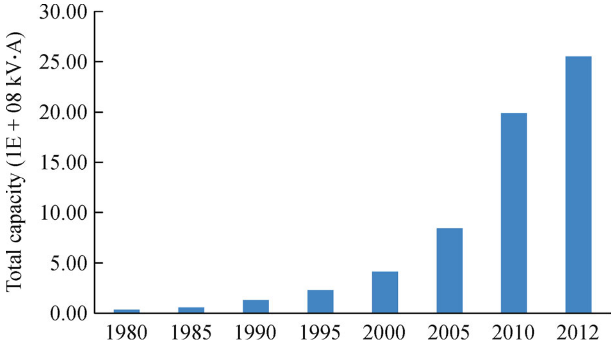

Fig. 2 Total capacity of transformer substations over 220 kV in China

Table 1 Total length of transmission lines over 220 kV in China

Year	Ultra-high	750 kV	660 kV	500 kV	330 kV	220 kV	Total
1995	0	0	0	13,052	5609	96,913	115,574
2000	0	0	0	26,837	8669	128,114	163,620
2005	0	141	0	62,866	13,059	177,617	253,683
2010	3972	6685	1400	135,180	20,338	277,988	445,563
2012	8840	12,666	1400	156,818	24,065	339,075	542,864

There have been major achievements in the conservation of natural resources and the mitigation of carbon emissions, through ecological engineering (Chen et al., 2011a; Han et al., 2013a; Han et al., 2015), waste disposal (Zhou et al., 2009; Chen et al., 2011b; Shao et al., 2013), and biomass utilization (Chen and Chen, 2011a; Wu et al., 2014b, 2015a, b). With government support, power generation technologies have achieved remarkable progress. While numerous studies have concentrated on technical (de Castro et al., 2013; Han et al., 2014; Ma et al., 2014; Wu et al., 2016a), economic (Rubin et al., 2007; Li et al., 2015b; Qadir et al., 2015; Kim and Kim, 2016; Wu et al., 2016b), policy (Han et al., 2013b; Meng et al., 2014; Wu et al., 2014a; Hua et al., 2016) and environmental assessments (Chen et al., 2011c, d; Yang et al., 2013) of power generation technologies; there remains a lack of useful studies of transmission networks themselves. Some research projects focus on the current situation of electric systems in China. Zhou et al. (2010) provided a comprehensive overview of power transmission systems in China, as well as a detailed introduction to their current status and future development. However, in-depth academic studies that provide further analysis of power transmission systems were not found.

The increased development of ultra-high voltage direct current and ultra-high voltage alternating current transmission networks is critical to the advancement of China's energy infrastructure. In the *Twelfth Five-Year Plan* released by the Chinese government, targets were established to accelerate the progress of the current electric system, expand the scale of the west-east electricity transmission project, improve transmission techniques, advocate for the construction of a smart grid, consolidate upgrades of the urban and rural electric systems, and ensure the flexibility and reliability of the power grids. Additionally, the State Grid Corporation of China has raised the "one ultra, four large" strategy. It seeks to encourage further development of power generation, including large scale hydro, thermal, nuclear, and renewable power. In the coming decade, extensive capital is expected to become available for the construction of transmission infrastructure.

As previously mentioned, China is characterized by unbalanced resource distribution and geological conditions. Various voltages and types of terrain will be considered when examining how to optimize the structure and reduce the costs of investments in transmission infrastructure. This is the first study to conduct an investment analysis of transmission infrastructure in China. Additionally, by investigating the spatial properties of the cumulative investment in transmission infrastructure, we seek to determine correlations between investment, population, and economic development across the regions. The results will help policymakers enact related development plans.

2 Methodology

2.1 Investment of transmission infrastructure

Using the *Guidebook for the General Investment Cost for Power Transmission and Transformation Project of SGCC* (SGCC, 2010, 2013), this paper investigates the investment costs of transmission lines and transformer substations under different voltage classes. To allow for the comparison of investments in building transmission lines of the same distance for different construction schemes, the unit distance investment cost of transmission lines $CI_{D,j}$ is used and expressed as

$$CI_{D,j} = CI_j / D_j, \tag{1}$$

where CI_j represents the total investment cost of transmission lines in the j^{th} construction scheme, and D_j is the construction distance of the j^{th} construction scheme. The j^{th} construction scheme includes relevant information including the voltage v, terrain t, type of circuit (single or double), etc.

To compare the investments for building transformer substations of the same nameplate capacity for different construction schemes, the unit capacity investment cost of transformer substations $CI_{C,i}$ is used and formulated as

$$CI_{C,i} = CI_i / (C_i \times n_i), \tag{2}$$

where CI_i represents the total construction investment cost of transformer substation in the i^{th} construction scheme, C_i reflects the nameplate capacity of the main transformer in the i^{th} construction scheme, and n_i manifests the number of main transformers in the i^{th} construction scheme. The i^{th} construction scheme contains relevant information, including the voltage v, the nameplate capacity M, and the grouping (single or double).

In this paper, the construction distances for the single-circuit and two-circuit transmission lines other than 330 kV and ±800 kV are assumed to be equivalent. Applying a weighted average, the unit distance investment cost of transmission lines under a certain voltage class $CI_{AEV,D,v,t}$ is generated as

$$CI_{AEV,D,v,t} = \frac{1}{2}\sum\nolimits_{n} CI_{Single,D,v,t}/n + \frac{1}{2}\sum\nolimits_{m} CI_{Double,D,v,t}/m, \tag{3}$$

where n and m indicate the number of single-circuit and two-circuit construction schemes, respectively, under the voltage v and the geological condition t.

The construction schemes for the transmission lines ranging from 110 kV – 1000 kV are comprised of six geological conditions that cover flatlands, hills, mountain lands, plateaus, river swamps, and deserts. After obtaining the unit distance investment cost, the construction schemes with the same voltage class and circuits are weighted using averages that correspond to the proportional area of the different types of terrain. According to the *China Statistical Yearbook 2011*, the terrain is categorized into five types, namely flatlands, hills, mountain lands, basins, and plateaus, excluding deserts and river swamps. Considering that desert only apply to voltage classes of 330 kV and 750 kV, and river swamps only occupy 1.82% of the geological territory, they are excluded from further analysis in this paper. Additionally, given the features of this type of terrain, basins are included within flatlands for the calculations. After weighting, the unit distance investment cost of transmission lines for a given voltage class $CI_{AEV,D,v}$ is simplified as

$$CI_{AEV,D,v} = \sum\nolimits_{m} CI_{AEV,D,v,t} \times PTA_m, \tag{4}$$

where PTA_m is the weight set according to the share of terrain t across the entire national territorial area, and m stands for the type of terrain.

Furthermore, based on the average nameplate capacity of transformers in various voltage classes, using 1000 kV transmission lines as the benchmark, the unit distance investment cost of transmission lines in delivering the equivalent capacity of electricity $CI_{EQU,D,v}$ could be formulated as

$$CI_{EQU,D,v} = CI_{AEV,D,v} \times ANC_{1000}/ANC_v, \tag{5}$$

where ANC_v represents the average nameplate capacity of transformers under the voltage class v, and ANC_{1000} is the average nameplate capacity of 1000 kV transformers.

Similarly, the unit capacity investment cost for transformer substations $CI_{AEV,C,M,v}$ is elaborated as

$$CI_{AEV,C,M,v} = \sum\nolimits_n CI_{C,M,v}/n, \tag{6}$$

where M reflects the nameplate capacity of the main transformer, and n reflects the number of the construction scheme i.

The number and nameplate capacities of the transformers in each voltage class were obtained from the *China Electric Power Yearbook*, and used to determine the average nameplate capacities per voltage class. Assuming that the nameplate capacity of the main transformers under various voltage classes is as reported in the *Guidebook for the General Investment Cost for Power Transmission and Transformation Project of SGCC*, the utilization rate could be inversely derived. Using the utilization rate to weight each voltage class, the average unit capacity investment cost of transformer substations $CI_{AEV,C,v}$ is expressed as

$$CI_{AEV,C,v} = \sum\nolimits_m CI_{AEV,C,M,v} \times P_{M,v}, \tag{7}$$

where m clarifies the type of nameplate capacity for main transformers in the construction schemes for transformer substations, and $P_{M,v}$ represents the utilization rate of the main transformer with a nameplate capacity of M under the voltage v.

2.2 Cumulative investment of transmission infrastructure in each province

For each voltage class, the capital cost of the transmission lines could be calculated by multiplying the circuit length of the lines by the specific weighted unit distance investment cost. The cumulative investment within a province is the summation of the capital cost of transmission lines under different voltage classes, which is expressed as

$$Inv_{T,d} = \sum\nolimits_v CI_{AEV,D,v} \times L_v, \tag{8}$$

where L_v demonstrates the circuit length under the voltage v in the province d.

Similarly, for each voltage class, the cumulative capital cost of transformer substations could be calculated by multiplying the transformers' cumulative nameplate capacity by the specific weighted unit capacity investment cost. The cumulative investment within a province is calculated by summing the capital cost of transformer substations under different voltage classes, which is formulated as

$$Inv_{S,d} = \sum\nolimits_v CI_{AEV,C,v} \times C_v, \tag{9}$$

where C_v represents the total nameplate capacity of main transformers under the voltage v in the transformer substations in the province d.

The per capita construction investments of transmission lines and transmission substations are respectively expressed as

$$Inv_{T,d,per} = Inv_{T,d}/P_d, \tag{10}$$

$$Inv_{S,d,per} = Inv_{S,d}/P_d, \tag{11}$$

where P_d represents the population in the province d.

2.3 Analysis of correlated influence factors in transmission infrastructure investment

Based on the calculated results obtained from the above equations, a regression analysis is performed for each province to determine the factors that contribute to the cumulative investment in the construction of transmission lines and transformer substations. A measurement model that is based on Ordinary Least Squares (OLS) is used. The variables that could affect the transmission infrastructure are selected as explanatory variables. The formulas are expressed as

$$\begin{aligned}\ln Inv_t = {} & \beta_0 \ln Inv_s + \beta_1 \ln pop + \beta_2 land \\ & + \beta_3 \ln elec + \beta_4 \ln GDP + \beta_5 \ln Inv_i \\ & + C + \varepsilon,\end{aligned} \tag{12}$$

$$\begin{aligned}\ln Inv_s = {} & \beta_0 \ln Inv_t + \beta_1 \ln pop + \beta_2 land \\ & + \beta_3 \ln elec + \beta_4 \ln GDP + \beta_5 \ln Inv_i \\ & + C + \varepsilon,\end{aligned} \tag{13}$$

where Inv_t stands for the cumulative capital investment of transmissions lines, ln Inv_s is the gross capital investment in transformer substations, pop is the permanent resident population, $land$ reflects the land area, $elec$ is electricity consumption, GDP is the gross regional domestic product, Inv_i is the fixed assets of the energy industry in that year, C is the intercept term, and ε is the stochastic error term.

3 Data sources

As previously mentioned, the investment costs for transmission infrastructure under various voltages were obtained from the *Guidebook for the General Investment Cost for Power Transmission and Transformation Project of SGCC (2010 and 2013 editions)* (SGCC, 2010, 2013).

There are 193 sets of construction schemes for transmission lines, which incorporate seven voltage classes and six types of terrain. For transformer substations, there are 45 construction schemes, which incorporate six voltage classes and twelve nameplate capacities, for the main transformers. Detailed inventories of the construction schemes of transmission infrastructure under different voltages are listed in Appendices A – M.

The area of various types of terrain is based on data reported in the *China Statistical Yearbook 2011* (NBS, 2011). The circuit length of transmission lines, nameplate capacities of transformers, and the energy consumption are all obtained from the *China Electric Yearbook 1993* (EBCEPY, 1995) and *China Electric Yearbook 2013* (EBCEPY, 2013). Population data for each province was obtained from the *China Statistical Yearbook 1994* (NBS, 1994) and the *China Statistical Yearbook 2013* (NBS, 2013). The area in each province was obtained from the *Guidebook for Administrative Division of the People's Republic of China 2012* (MOCA, 2012). The gross regional domestic product and the fixed-asset investments of the energy industry are based on data from the *China Statistical Yearbook 2013*. According to the State Statistics Bureau, the economic regions in China are categorized into eastern, central, western, and northeastern regions. The eastern regions include Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The central regions include Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan. The western regions include Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang; and the northeastern regions include Liaoning, Jilin, and Heilongjiang. Because Chongqing belongs to Sichuan before 1997, in this study Chongqing municipality incorporated into the Sichuan province.

4 Results and Discussion

4.1 Investment analysis of transmission infrastructure

4.1.1 Investment analysis of transmission lines

The unit distance investment costs of transmission lines vary by the type of terrain, even when the voltage and circuits are the same. The transmission lines across the plateaus and river swamps are estimated to be the most costly, followed by those situated in the mountains and desert areas. The transmission lines located in hilly and flat land areas are estimated to have the lowest unit distance investment cost. The unit distance investment cost of single-circuit 110 kV transmission lines for river swamps is 7.16E + 05 CNY/km (Fig. 3), which is notably higher than that for flat land (5.45E + 05 CNY/km) and hilly areas (5.94E + 05 CNY/km). The per unit costs of single-circuit 220 kV transmission lines in the plateaus and river swamps, at 40% and 33%, respectively (Fig. 4), were proven to be the two highest; again higher than that for the flat lands (7.70E + 05 CNY/km). Under the two-circuit scenario, the calculated unit costs of transmission lines across the plateau and river swamps are approximately equal, at 1.90E + 06 CNY/km and 1.88E + 02 CNY/km, respectively. The unit cost of single-circuit 330 kV transmission lines across the plateau (Fig. 5), which are dominant (1.10E + 06 CNY/km), are followed by that for deserts (9.89E + 05 CNY/km) and mountain lands (9.71E + 06 CNY/km). The unit cost of single-circuit transmission lines on the flatlands ranks as the lowest. For the cases under 500 kV, 750 kV, ±800 kV, and 1000 kV, the situation is similar, as shown in Figs. 6, 7, 8, and 9. The unit distance cost of transmission lines in the plateau is the highest; while that for the river swamps, deserts, and mountain lands is intermediate; and the cost for hills and flat land areas is lowest.

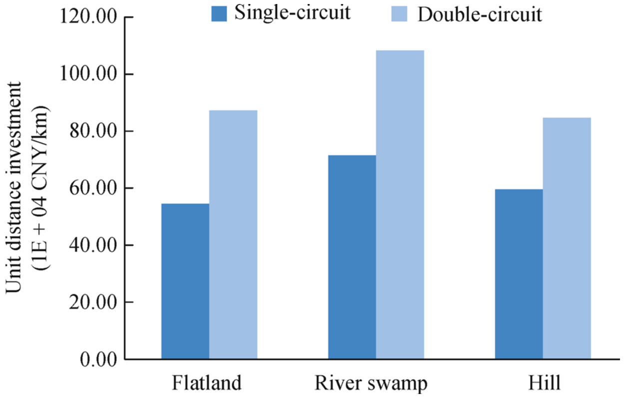

Fig. 3 Transmission lines under 110 kV

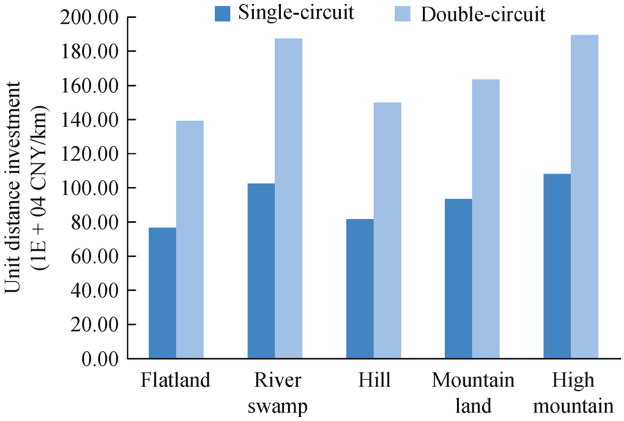

Fig. 4 Transmission lines under 220 kV

The variation in unit distance investment cost for different types of terrain can be explained by the impact of different geological conditions on the complexity of construction. The high altitude and vast expanse of land on

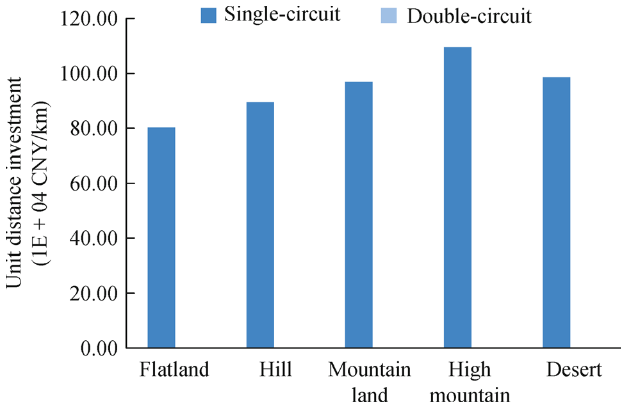

Fig. 5 Transmission lines under 330 kV

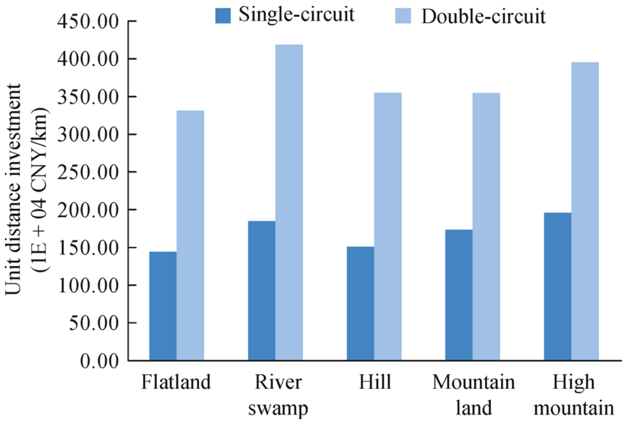

Fig. 6 Transmission lines under 500 kV

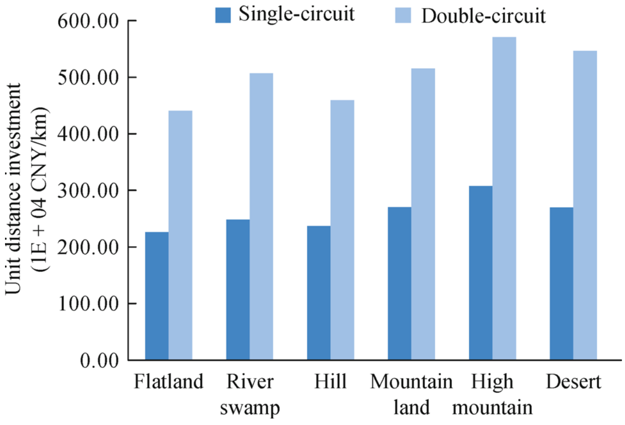

Fig. 7 Transmission lines under 750 kV

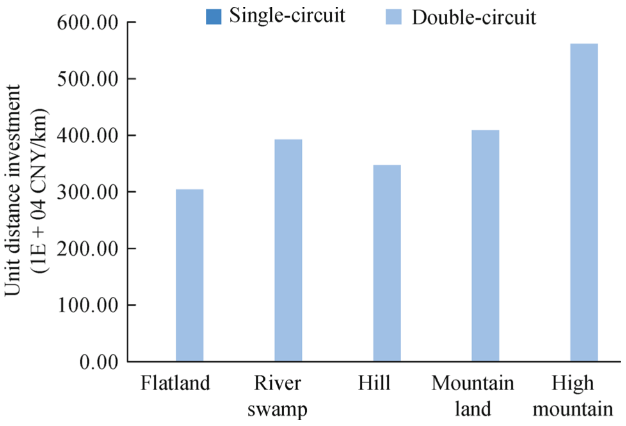

Fig. 8 Transmission lines under ±800 kV

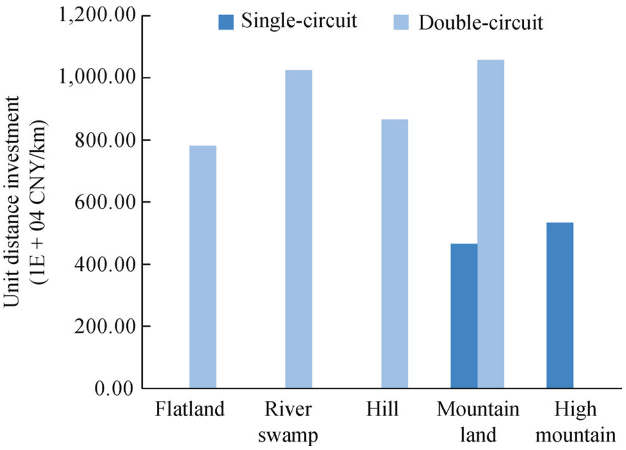

Fig. 9 Transmission lines under 1000 kV

the plateau greatly increases the costs of transporting and laying the electric cables, resulting in higher labor costs than those required for the other types of terrain. With regard to the river and swamp areas, the wet and soft soil requires more steel towers per unit distance to support the transmission lines, increasing costs. The terrain for laying transmission lines is geologically more favorable in the desert and mountainous areas than in the plateau and river swamps. Because desert and mountain areas have rougher terrain than flatlands and hilly areas, the unit investment cost of transmission lines across the desert and mountainous areas fit within the middle range of costs.

The average unit distance investment cost of two-circuit transmission lines with voltages of 110 kV, 220 kV, 750 kV, and 1000 kV exceeds that of single-circuit transmission lines by 56%, 77%, 94%, and 83%, respectively, i.e., by less than 100%. The average unit distance cost of two-circuit 500kV transmission lines appears to be 120% higher than that of single-circuit transmission lines. The ratio of the average unit cost of two-circuit lines to that of single-circuit lines can be plotted as an inverted “U-shape” distribution with increases in voltage class. All other conditions being equal, the two-circuit transmission lines deliver double the quantity of electricity of the single-circuit transmission lines. However, it should be noted that the cost of the transmission lines under different voltages varies greatly. Except for 550 kV, the two-circuit design lowers the construction investment for all voltage classes.

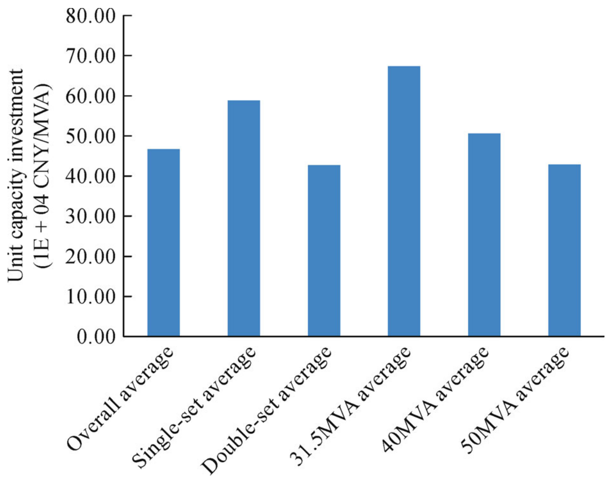

Fig. 10 Transformer substation under 110 kV

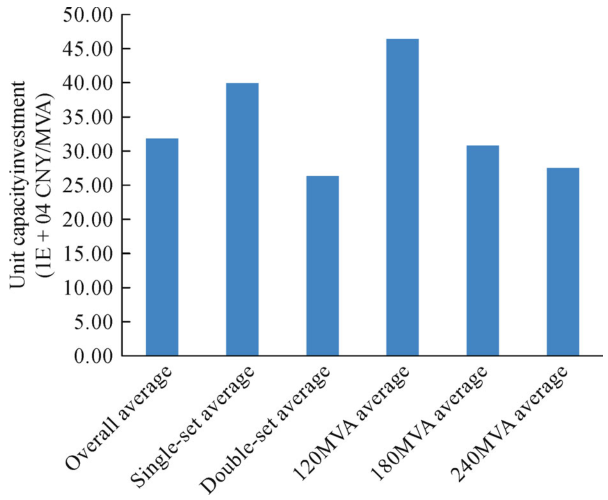

Fig. 11 Transformer substation under 220 kV

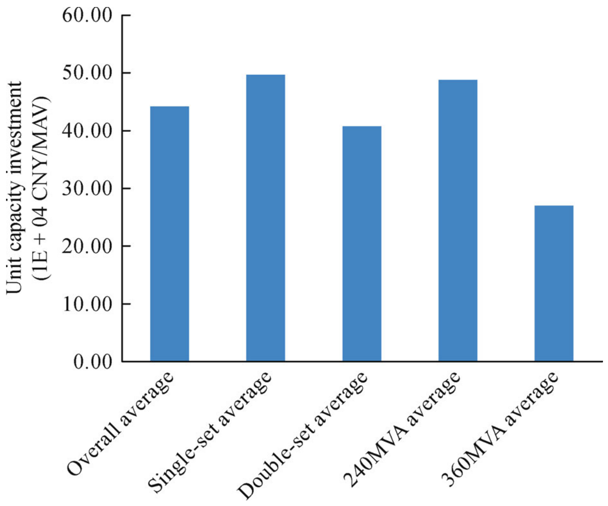

Fig. 12 Transformer substation under 330 kV

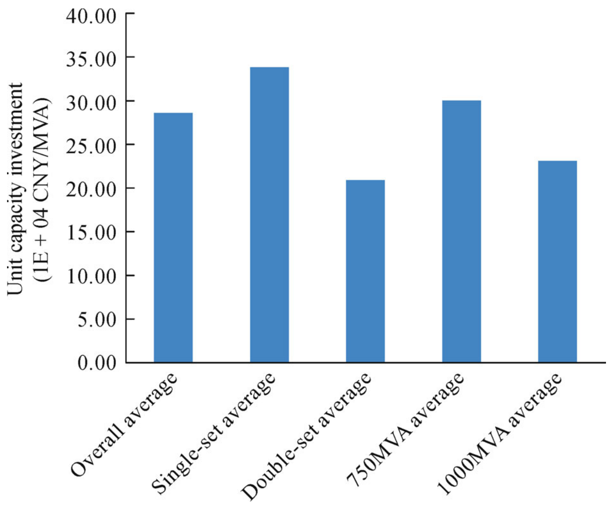

Fig. 13 Transformer substation under 500 kV

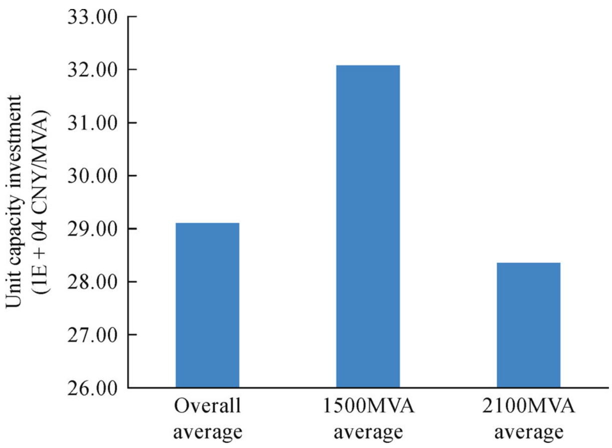

Fig. 14 Transformer substation under 750 kV

4.1.2 Investment analysis for construction of transformer substation

As illustrated in Figs. 10, 11, 12, 13, and 14, for substations of the same voltage class equipped with a single transformer, the average unit capacity investment cost for a transformer of lower nameplate capacity is 7% to 33% higher than that of a transformer with a higher nameplate capacity. Similarly, for substations equipped with two transformers with a voltage of 330 kV and 500 kV, the average unit capacity costs of transformer substations with a lower nameplate capacity are 77% and 17% higher, respectively, than for those with a higher nameplate capacity.

In most cases, when the voltage class and number of sets of the main transformer are equal, the unit investment cost for a substation with a transformer of higher nameplate capacity appears to be lower than that of lower nameplate capacity. This is because construction, design, and expropriation fees for transformer substations of the same voltage are generally equal. As a result, by using a transformer of higher nameplate capacity, the investment per unit capacity is lower.

It has been shown that, even with the same nameplate capacity, the average per unit construction cost of a single transformer substation can exceed that with two transformers by as much as 4% to 70%. When a substation with a single transformer adds a second unit, the only costs accrued are for the construction, material, and equipment fees, associated with the purchase of the new transformer. However, the expropriation, infrastructure, and additional design fees are shared by the two transformers. As a result, the average construction investment per unit capacity of the transformer substation with two transformers is comparatively lower than that with a single transformer.

4.1.3 Investment analysis for transmission infrastructure

Using weighted calculation, the overall unit distance investment costs of transmission lines under various voltage classes are obtained. As illustrated in Fig. 15, the overall unit cost increases constantly with the voltage class, from 8.07 E + 05 CNY/km for 110 kV to 8.58 E + 06 CNY/km for 1000 kV. Based on a benchmark of 1000 kV transmission lines, the unit distance investment cost of transmission lines under different voltages delivering the equivalent capacity of electricity is calculated. As shown in Fig. 16, these costs gradually decrease as the voltage class increases. The per unit cost is highest when the voltage is less than 110 kV and is lowest when the voltage is less than 750 kV. The unit cost for a voltage of 1000 kV is approximately 15% higher than that for 750 kV. Typically, the transmission capacity under various voltage classes is directly proportional to the square of the voltage class. Therefore, by comparison, low voltage transmission lines delivering the equivalent electricity through 750 kV and 1000 kV transmission lines require less total line length and lower investment costs. This finding implies that in regions with a great demand for electricity, high voltage transmission lines are more economical.

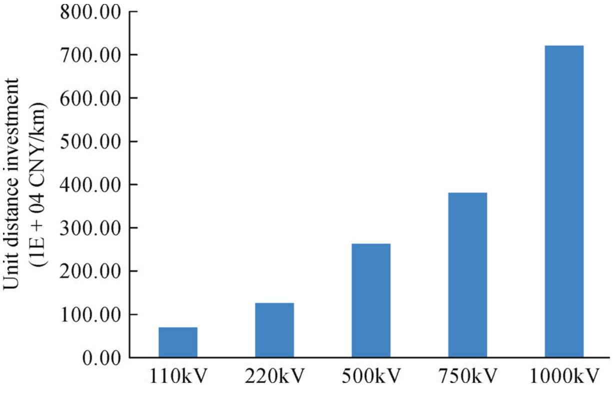

Fig. 15 Unit distance investment cost of transmission lines

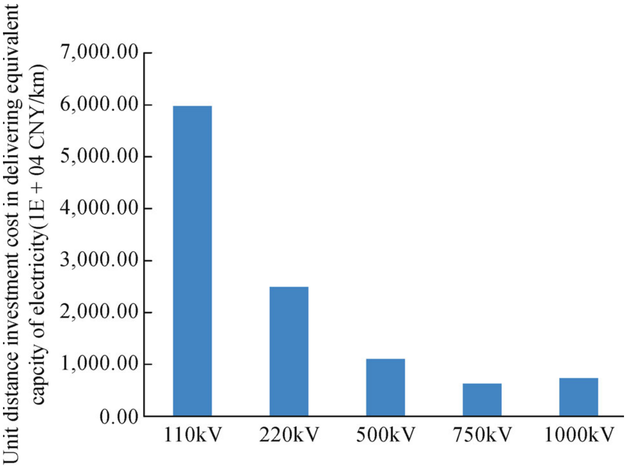

Fig. 16 Unit distance investment cost of transmission lines in delivering equivalent capacity of electricity

As shown in Fig. 17, a similar but smoother trend can be observed for transformer substations. Using a weighted calculation, the unit capacity construction cost of a main transformer reduces as voltage class and average nameplate capacity increases. At 750 kV, a breakpoint occurs, after which the unit cost increases. The unit cost for 1000 kV is approximately 10% higher than that for 750 kV.

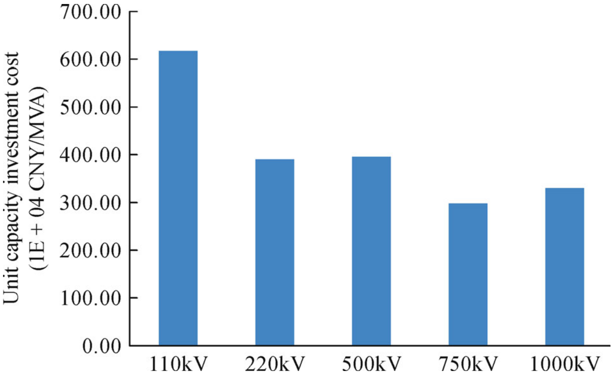

Fig. 17 Unit capacity investment cost of transformer substation

4.2 Spatial properties of the cumulative investment in transmission infrastructure

4.2.1 Spatial properties of the construction investment in transmission lines

As shown in Fig. 18, the cumulative construction investment in transmission lines across the different provinces has been uneven. In 2012, the provinces with a higher share of investment in transmission lines included Sichuan, Jiangsu, Guangdong, Hebei, Inner Mongolia, and Hubei, each representing over 5% of the national

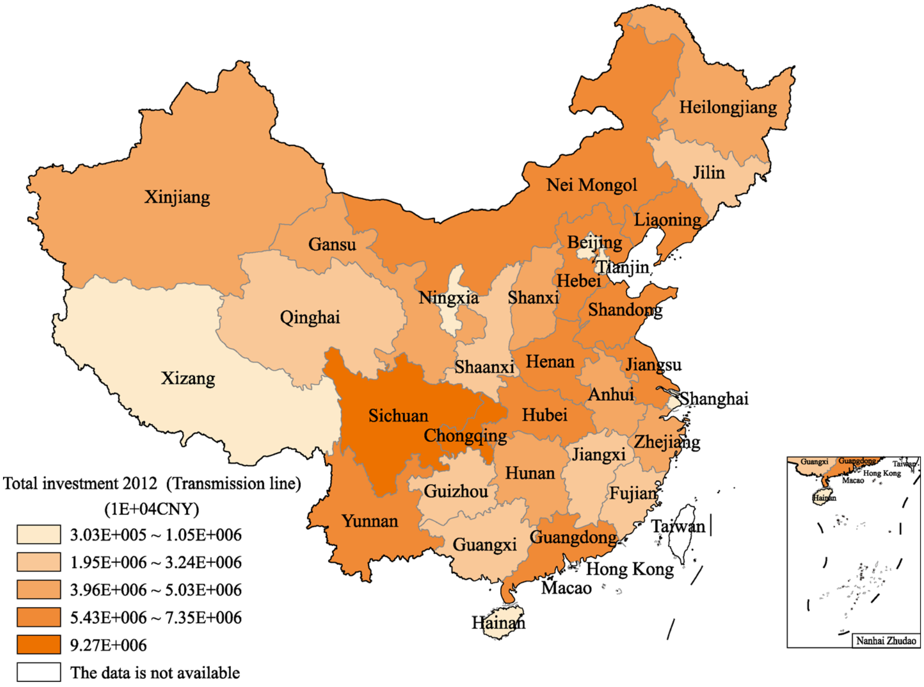

Fig. 18 Cumulative capital investment for transmission lines for different provinces in 2012

cumulative investment. Liaoning, Shandong, Yunnan, Henan and Zhejiang, are next with a share of over 4% each. With the exception of Inner Mongolia and Yunnan, all the above-mentioned provinces are in the top nine provincial economies for domestic GDP. The provinces of Tibet, Hainan, Tianjin, Shanghai, Beijing, and Ningxia each reflect less than 1% of the total investment and are among the lowest. Among these provinces, Shanghai, Tianjin, Beijing, Hainan and Ningxia are the smallest in area.

Since reforms were initiated, the spatial distribution of cumulative investment in transmission lines changed greatly (Fig. 19). The investment in transmission lines in the western regions increased, while that in the central, eastern, and northeastern regions, decreased. From 1993 to 2012, there was an increase of 9.4% in the western regions, while the central, eastern and northeastern regions decreased by 3.95%, 3.88%, and 1.63%, respectively. The results also suggest a large increase from 1993 to 2012 in the total capital investment for transmission lines in Inner Mongolia, Sichuan, Yunnan, Xinjiang, Qinghai and Guizhou. The provinces of Shandong, Hubei, Hunan, Guangdong, Guangxi, and Heilongjiang experienced a decrease in investment.

There were clear differences in the per capita investment in transmission lines between the provinces. Shanghai was observed to have the lowest per capita investment at 362.66 CNY, while Qinghai had the highest at 3,402.05 CNY. As seen in Fig. 20, the provinces with higher per capita investment in transmission lines are Qinghai, Inner Mongolia, Xinjiang, Ningxia and Gansu compared to more developed regional economies (namely Beijing, Shanghai, Tianjin) or more populous provinces (Shandong, Henan). The western provinces with low population density received lower per capita investment.

4.2.2 Spatial properties for capital investment in transformer substations

The domestic capital investment in transformer substations reached a total amount of 1.88E + 08 CNY, with Guangdong having the highest cumulative investment of 2.01E + 07 CNY and Tibet with the lowest at 1.29 E + 05 CNY. Guangdong and Jiangsu far outpace other provinces, with a value of 10.69% and 9.67%, respectively, followed by Zhejiang, Shandong, Sichuan, Hebei, Liaoning, and Henan, each over 5% (Fig. 21). Tibet, Hainan, Qinghai, Ningxia, Xinjiang, and Tianjin are among the provinces with lower cumulative investment in transmission substations, each below 1.5%.

Since reforms were initiated, investments in transformer substations increased in the western and eastern provincial regions by 3.13% and 2.13%, respectively, while those in the central and northeastern areas, decreased by 4.95% and 0.30%, respectively (Fig. 22). Because transformer substations not only transform voltage but also transmit and distribute electricity, the increase in investment in the western regions could be due to the expansion of electricity consumption and the advancement of infrastructure construction. There is also a direct correlation to the west-east electricity transmission project.

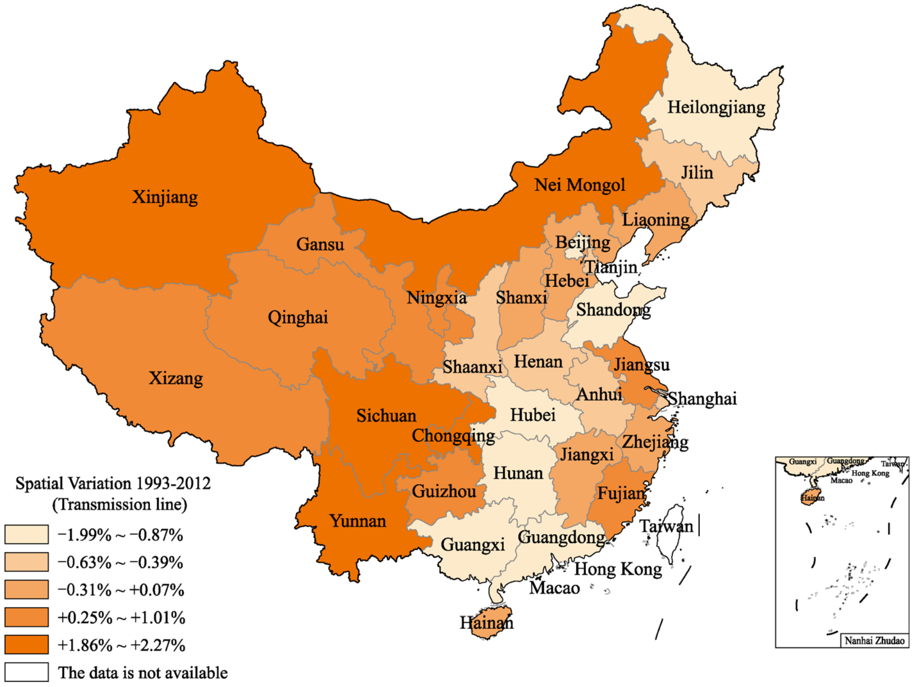

Fig. 19 Change in the share of cumulative capital investment for transmission lines in different provinces from 1993 to 2012

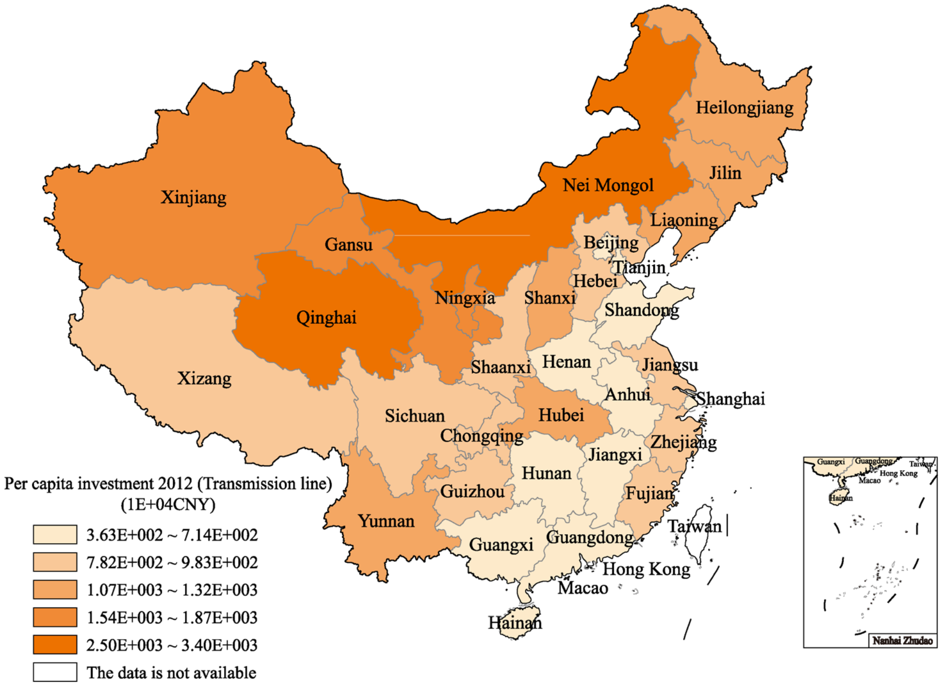

Fig. 20 Per capita investment of transmission lines in different provinces in 2012

With regard to the provincial per capita investment in transformer substations, as shown in Fig. 23, Ningxia, Qinghai, Inner Mongolia, Zhejiang, and Jiangsu, have received more investment, in agreement with their high per capita electricity consumption. Tibet, Jiangxi, Hainan, Hunan, and Heilongjiang have lower investment and considerably lower per capita electricity consumption than the other provinces.

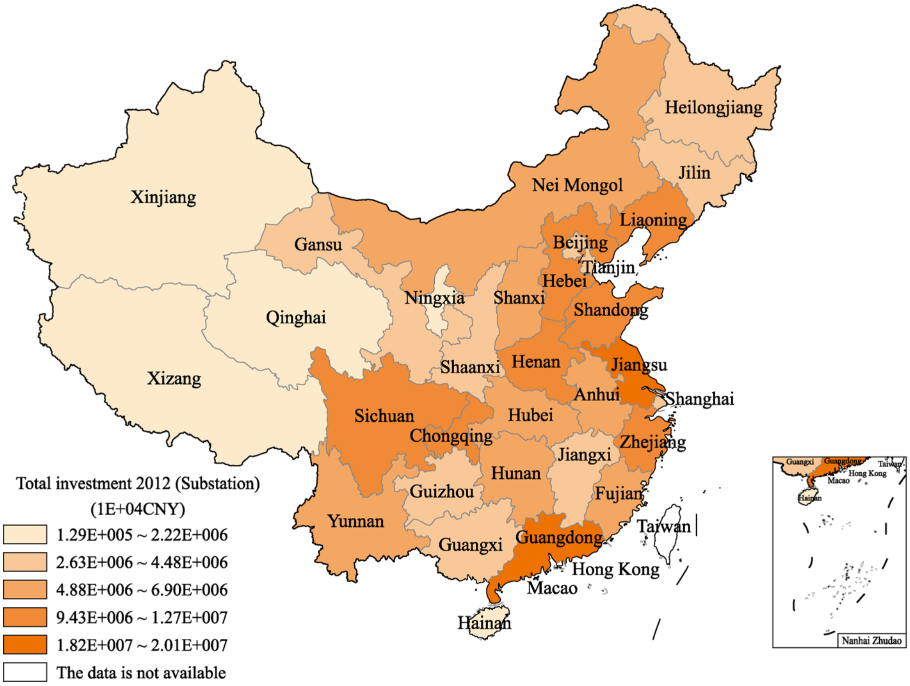

Fig. 21 Cumulative capital investment for transformer substation in different provinces in 2012

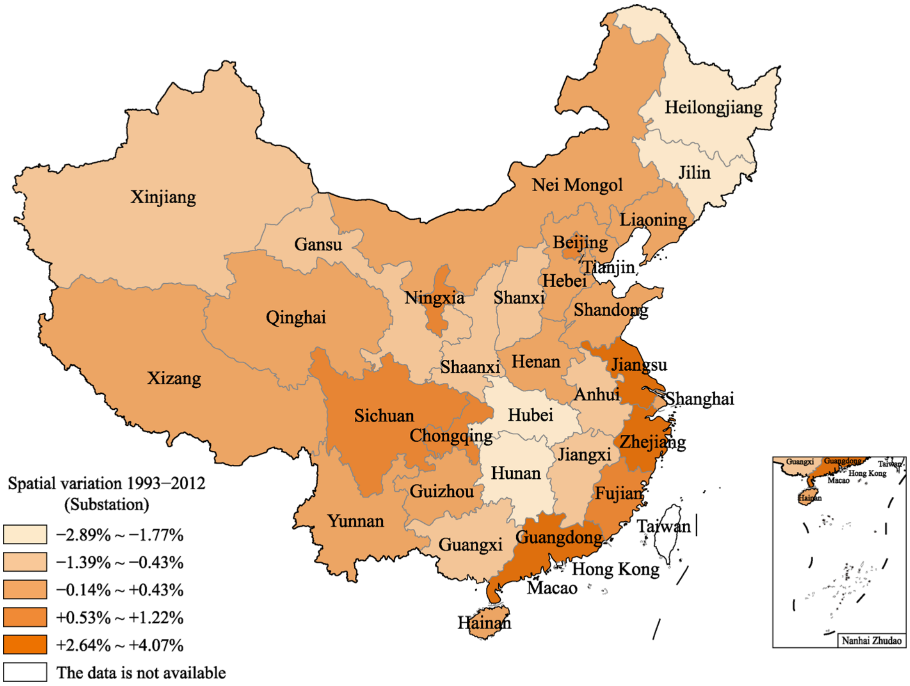

Fig. 22 Change in the share of cumulative capital investment for transformer substation in different provinces from 1993 to 2012

4.3 Analysis of correlated factors influencing transmission infrastructure investment

Based on the above spatial properties of cumulative investment for transmission infrastructure, we have selected the following explanatory variables: 1) permanent resident population, 2) land area, 3) total electricity consumption, 4) gross regional domestic product and 5)

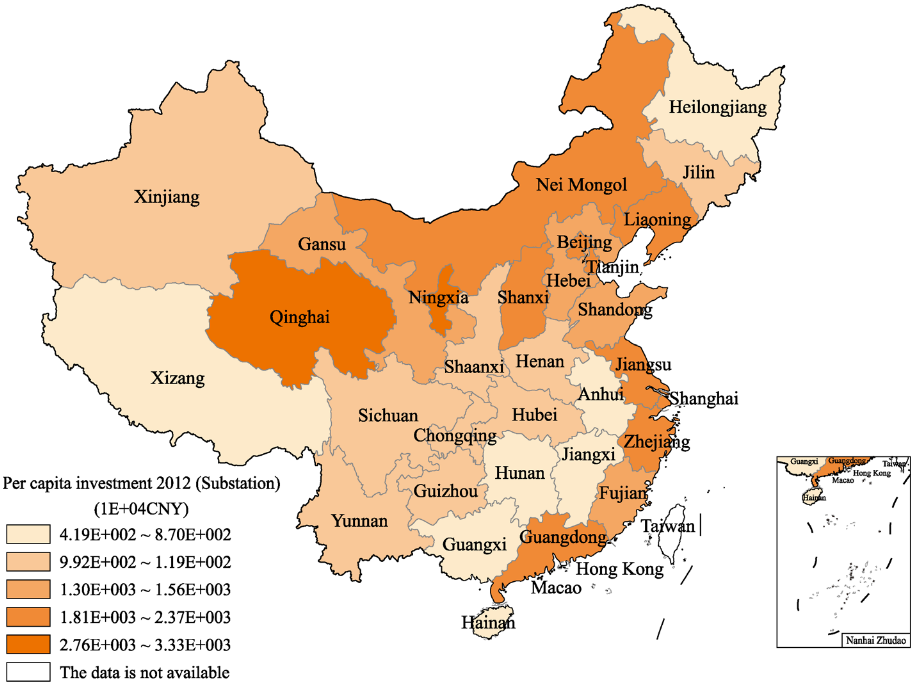

Fig. 23 Per capita investment of transformer substation in different provinces in 2012

fixed assets of the energy industry. We use these to analyze the factors that influenced the cumulative capital investment in transmission lines and transformer substations in 2012. Table 2 lists the estimated coefficient values of the explanatory variables based on OLS regression analysis for the 31 provinces.

As shown in Table 2, investment costs are closely correlated with the construction of transmission lines and transformer substations. The reason is simple. The process for the delivery of electricity starts with an increase in voltage at the transformer substation, after which the electricity flows long distances over transmission lines, finally ending with a reduction in voltage in the transformer substation near users.

Table 2 suggests that the regional permanent resident population and land area are both directly related to investment. Longer transmission lines or a higher voltage class are required for highly populated regions, which notably increases the required investment in construction. As the developed land area is expanded, more investment in transmission lines is needed to cover the larger area. The fixed assets of the energy industry mainly involve the mining and washing of coal, the extraction of petroleum and natural gas, the production and distribution of gas, and the production and distribution of water, which, to some degree, reflect the scale of investments in the power sector. As a result, these activities positively impact the investments in transmission lines. The gross regional domestic product is negatively correlated with the capital investment in transmission lines. This finding may be attributed to the high percentage of extra-high and ultra-high voltage power

Table 2 OLS regression for the influence factors of transmission infrastructure

Variables	(1) ln Inv_S	(2) ln Inv_S
ln Inv_S		0.299***
		(0.103)
ln Inv_S	0.873***	
	(0.300)	
ln pop	0.737***	−0.181
	(0.129)	(0.110)
	(0.00155)	(0.000904)
ln $elec$	−0.256	0.618***
	(0.245)	(0.0751)
ln GDP	−0.585***	0.312***
	(0.139)	(0.0865)
ln Inv_i	0.253**	−0.0369
	(0.0942)	(0.0624)
Constant	0.00193	−1.161***
	(0.688)	(0.326)
Observations	31	31
R^2	0.938	0.985

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

transmission lines in more developed regions due to their advanced technical levels, which reduces the needed per unit distance capital inputs.

Electric power consumption and the gross regional domestic product have a notably positive effect on cumulative investment in transformer substations. High electricity consumption requires more transformer substations to guarantee the supply of power. Land area can be negatively correlated with the capital input, i.e., transformer substations in smaller areas have a higher electricity supply burden. Therefore, for transformers with a higher voltage class, higher nameplate capacity is essential to decrease the capital input per unit capacity.

5 Conclusions

This study is the first conducted to analyze the investment costs of transmission infrastructure in China. The capital investment costs for transmission lines and transformer substations under different scenarios are calculated and compared. The results suggest that for transmission lines of the same voltage, construction in plateau and river swamp areas have the highest investment cost per unit distance. It has also been demonstrated that the unit capacity investment cost of transformer substations with a higher nameplate capacity is lower than those of lower nameplate capacity.

Additionally, the spatial distribution of capital investment for transmission lines and transformer substations are discussed at provincial level. With the constant improvement of infrastructure in the western regions, their share of cumulative capital investment has clearly increased, while that in the central, eastern, and northeastern regions has decreased. With regard to transformer substations, the share of cumulative capital investment in transformer substations in the western and eastern regions has increased, while that in the central and northeastern regions has decreased. Additionally, OLS regression for several explanatory variables was carried out to determine the factors that affect investment in transmission infrastructure.

China has exhibited great enthusiasm for the future by launching the “One Belt and One Road” strategy. As part of the program, China will vigorously encourage cross-border electricity transmission and the construction of transmission networks. It is anticipated that large sums of capital will be invested in the construction of an ultra-high voltage grid and other forms of transmission infrastructure. The Asian Infrastructure Investment Bank, sponsored by China, will assist Asian-Pacific countries in the construction of an electric network. For these reasons, the goal of this work is to determine the spatial properties of transmission infrastructure investment in China, which could, in turn, offer valuable guidance for multilateral cooperation.

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Appendix A

Inventory for construction schemes of transmission lines under 110 kV

Number	Scheme number	Terrain	Distance (km)	Total investment (1E + 04 CNY)	Unit distance investment (1E + 04 CNY/km)
1	1AP	Flatland	5.04E + 01	2.11E + 03	4.19E + 01
2	1AH	River swamp	3.25E + 01	1.91E + 03	5.88E + 01
3	1AQ	Hill	5.00E + 01	2.24E + 03	4.47E + 01
4	1BP	Flatland	5.04E + 01	2.36E + 03	4.68E + 01
5	1BH	River swamp	3.25E + 01	2.18E + 03	6.70E + 01
6	1BQ	Hill	5.00E + 01	2.48E + 03	4.96E + 01
7	1CP	Flatland	5.04E + 01	2.84E + 03	5.64E + 01
8	1CQ	Hill	5.00E + 01	3.11E + 03	6.21E + 01
9	1DP	Flatland	5.04E + 01	2.94E + 03	5.83E + 01
10	1DQ	Hill	5.00E + 01	3.20E + 03	6.40E + 01
11	1EP	Flatland	5.04E + 01	3.07E + 03	6.09E + 01
12	1EH	River swamp	3.25E + 01	2.90E + 03	8.91E + 01
13	1EQ	Hill	5.00E + 01	3.36E + 03	6.71E + 01
14	1FP	Flatland	5.04E + 01	3.14E + 03	6.24E + 01
15	1FQ	Hill	5.00E + 01	3.43E + 03	6.86E + 01
16	1GP	Flatland	5.04E + 01	3.11E + 03	6.17E + 01
17	1GH	River swamp	3.25E + 01	2.68E + 03	8.25E + 01
18	1GQ	Hill	5.00E + 01	3.21E + 03	6.41E + 01
19	1HP	Flatland	5.04E + 01	3.47E + 03	6.89E + 01
20	1HH	River swamp	3.25E + 01	2.90E + 03	8.92E + 01
21	1HQ	Hill	5.00E + 01	3.55E + 03	7.10E + 01
22	1IP	Flatland	5.04E + 01	4.50E + 03	8.93E + 01
23	1IH	River swamp	3.25E + 01	3.69E + 03	1.13E + 02
24	1IQ	Hill	5.00E + 01	4.44E + 03	8.88E + 01
25	1JP	Flatland	5.04E + 01	4.62E + 03	9.17E + 01
26	1JH	River swamp	3.25E + 01	3.89E + 03	1.20E + 02
27	1JQ	Hill	5.00E + 01	4.62E + 03	9.23E + 01
28	1KP	Flatland	5.04E + 01	4.94E + 03	9.81E + 01
29	1KH	River swamp	3.25E + 01	4.11E + 03	1.26E + 02
30	1KQ	Hill	5.00E + 01	5.04E + 03	1.01E + 02
31	1LP	Flatland	5.04E + 01	5.16E + 03	1.02E + 02
32	1LH	River swamp	3.25E + 01	4.40E + 03	1.35E + 02
33	1LQ	Hill	5.00E + 01	5.22E + 03	1.04E + 02
34	1MP	Flatland	8.47E + 00	9.95E + 02	1.18E + 02
35	1RP	Flatland	5.04E + 01	3.76E + 03	7.47E + 01
36	1RH	River swamp	3.25E + 01	3.15E + 03	9.68E + 01
37	1RQ	Hill	5.00E + 01	3.76E + 03	7.51E + 01
38	1TP	Flatland	5.04E + 01	4.05E + 03	8.04E + 01
39	1TH	River swamp	3.25E + 01	3.39E + 03	1.04E + 02
40	1TQ	Hill	5.00E + 01	4.04E + 03	8.08E + 01

Appendix B

Inventory for construction schemes of transmission lines under 220 kV

Number	Scheme number	Terrain	Distance (km)	Total investment (1E + 04 CNY)	Unit distance investment (1E + 04 CNY/km)
1	2AP	Flatland	5.00E + 01	3.72E + 03	7.45E + 01
2	2AH	River swamp	5.69E + 01	5.71E + 03	1.00E + 02
3	2AQ	Hill	5.00E + 01	4.00E + 03	8.00E + 01
4	2AS	Mountain land	5.42E + 01	4.93E + 03	9.10E + 01
5	2AG	Plateau	5.28E + 01	5.56E + 03	1.05E + 02
6	2BP	Flatland	5.00E + 01	4.14E + 03	8.27E + 01
7	2BH	River swamp	5.69E + 01	6.25E + 03	1.10E + 02
8	2BQ	Hill	5.00E + 01	4.49E + 03	8.98E + 01
9	2BS	Mountain land	5.42E + 01	5.46E + 03	1.01E + 02
10	2BG	Plateau	5.28E + 01	6.04E + 03	1.14E + 02
11	2CP	Flatland	5.00E + 01	3.62E + 03	7.24E + 01
12	2CH	River swamp	5.69E + 01	5.58E + 03	9.81E + 01
13	2CQ	Hill	5.00E + 01	3.91E + 03	7.82E + 01
14	2CS	Mountain land	5.42E + 01	4.89E + 03	9.03E + 01
15	2CG	Plateau	5.28E + 01	5.55E + 03	1.05E + 02
16	2DP	Flatland	5.00E + 01	3.93E + 03	7.86E + 01
17	2DH	River swamp	5.69E + 01	5.82E + 03	1.02E + 02
18	2DQ	Hill	5.00E + 01	4.07E + 03	8.13E + 01
19	2DS	Mountain land	5.42E + 01	5.01E + 03	9.25E + 01
20	2DG	Plateau	5.28E + 01	5.66E + 03	1.07E + 02
21	2EP	Flatland	5.00E + 01	8.03E + 03	1.61E + 02
22	2EH	River swamp	5.69E + 01	1.14E + 04	2.01E + 02
23	2EQ	Hill	5.00E + 01	8.45E + 03	1.69E + 02
24	2FP	Flatland	5.00E + 01	5.90E + 03	1.18E + 02
25	2FH	River swamp	5.69E + 01	9.18E + 03	1.61E + 02
26	2FQ	Hill	5.00E + 01	6.39E + 03	1.28E + 02
27	2FS	Mountain land	5.42E + 01	7.96E + 03	1.47E + 02
28	2FG	Plateau	5.28E + 01	9.02E + 03	1.71E + 02
29	2GP	Flatland	5.00E + 01	6.85E + 03	1.37E + 02
30	2GH	River swamp	5.69E + 01	1.07E + 04	1.87E + 02
31	2GQ	Hill	5.00E + 01	7.47E + 03	1.49E + 02
32	2GS	Mountain land	5.42E + 01	8.88E + 03	1.64E + 02
33	2GG	Plateau	5.28E + 01	1.02E + 04	1.92E + 02
34	2HP	Flatland	5.00E + 01	7.54E + 03	1.51E + 02
35	2HH	River swamp	5.69E + 01	1.25E + 04	2.19E + 02
36	2HQ	Hill	5.00E + 01	8.06E + 03	1.61E + 02
37	2HS	Mountain land	5.42E + 01	9.71E + 03	1.79E + 02
38	2HG	Plateau	5.28E + 01	1.09E + 04	2.07E + 02
39	2IP	Flatland	5.00E + 01	6.51E + 03	1.30E + 02
40	2IH	River swamp	5.69E + 01	9.74E + 03	1.71E + 02
41	2IQ	Hill	5.00E + 01	7.14E + 03	1.43E + 02

Appendix C

Inventory for construction schemes of transmission lines under 330 kV

Number	Scheme number	Terrain	Distance (km)	Total investment (1E + 04 CNY)	Unit distance investment (1E + 04 CNY/km)
1	3AP	Flatland	8.30E + 01	6.52E + 03	7.86E + 01
2	3BP	Flatland	8.30E + 01	6.82E + 03	8.21E + 01
3	3BM	Desert	4.20E + 01	4.01E + 03	9.55E + 01
4	3BS	Mountain land	5.30E + 01	5.00E + 03	9.44E + 01
5	3BG	Plateau	5.10E + 01	5.44E + 03	1.07E + 02
6	3CQ	Hill	6.70E + 01	5.96E + 03	8.89E + 01
7	3CM	Desert	4.20E + 01	4.20E + 03	1.00E + 02
8	3CS	Mountain land	5.30E + 01	5.12E + 03	9.67E + 01
9	3CG	Plateau	5.10E + 01	5.64E + 03	1.11E + 02
10	3DQ	Hill	6.70E + 01	6.05E + 03	9.02E + 01
11	3DM	Desert	4.20E + 01	4.25E + 03	1.01E + 02
12	3DS	Mountain land	5.30E + 01	5.30E + 03	1.00E + 02
13	3DG	Plateau	5.10E + 01	5.72E + 03	1.12E + 02

Appendix D

Inventory for construction schemes of transmission lines under 500 kV

Number	Scheme number	Terrain	Distance (km)	Total investment (1E + 04 CNY)	Unit distance investment (1E + 04 CNY/km)
1	5AP	Flatland	5.00E + 01	6.66E + 03	1.33E + 02
2	5AQ	Hill	5.00E + 01	7.00E + 03	1.40E + 02
3	5AH	River swamp	5.00E + 01	8.36E + 03	1.67E + 02
4	5AS	Mountain land	5.00E + 01	8.09E + 03	1.62E + 02
5	5AG	Plateau	5.00E + 01	9.06E + 03	1.81E + 02
6	5BP	Flatland	4.99E + 01	6.76E + 03	1.35E + 02
7	5BQ	Hill	4.99E + 01	7.09E + 03	1.42E + 02
8	5BH	River swamp	5.08E + 01	8.67E + 03	1.71E + 02
9	5BS	Mountain land	5.00E + 01	8.30E + 03	1.66E + 02
10	5BG	Plateau	4.70E + 01	8.78E + 03	1.87E + 02
11	5CP	Flatland	5.00E + 01	8.06E + 03	1.61E + 02
12	5CQ	Hill	5.00E + 01	8.41E + 03	1.68E + 02
13	5CH	River swamp	5.00E + 01	1.08E + 04	2.16E + 02
14	5CS	Mountain land	5.00E + 01	9.56E + 03	1.91E + 02
15	5CG	Plateau	5.00E + 01	1.09E + 04	2.18E + 02
16	5DP	Flatland	4.99E + 01	1.28E + 04	2.57E + 02
17	5DQ	Hill	4.99E + 01	1.34E + 04	2.68E + 02
18	5DH	River swamp	5.08E + 01	1.63E + 04	3.20E + 02
19	5DS	Mountain land	5.00E + 01	1.57E + 04	3.14E + 02
20	5DG	Plateau	4.70E + 01	1.62E + 04	3.46E + 02
21	5EP	Flatland	4.99E + 01	1.30E + 04	2.61E + 02

(*Continued*)

Number	Scheme number	Terrain	Distance (km)	Total investment (1E + 04 CNY)	Unit distance investment (1E + 04 CNY/km)
22	5EQ	Hill	4.99E + 01	1.36E + 04	2.72E + 02
23	5EH	River swamp	5.08E + 01	1.69E + 04	3.33E + 02
24	5ES	Mountain land	5.00E + 01	1.59E + 04	3.17E + 02
25	5EG	Plateau	4.70E + 01	1.67E + 04	3.56E + 02
26	5FP	Flatland	4.99E + 01	1.36E + 04	2.72E + 02
27	5FH	River swamp	5.06E + 01	1.81E + 04	3.59E + 02
28	5FS	Mountain land	5.00E + 01	1.71E + 04	3.43E + 02
29	5FG	Plateau	4.70E + 01	1.81E + 04	3.86E + 02
30	5GP	Flatland	5.00E + 01	1.59E + 04	3.17E + 02
31	5GQ	Hill	5.00E + 01	1.64E + 04	3.28E + 02
32	5GH	River swamp	5.00E + 01	2.03E + 04	4.07E + 02
33	5GS	Mountain land	5.00E + 01	1.91E + 04	3.82E + 02
34	5GG	Plateau	5.00E + 01	2.14E + 04	4.28E + 02
35	5HP	Flatland	4.99E + 01	1.67E + 04	3.34E + 02
36	5HQ	Hill	4.89E + 01	1.69E + 04	3.45E + 02
37	5HH	River swamp	5.06E + 01	2.26E + 04	4.47E + 02
38	5HS	Mountain land	5.00E + 01	2.10E + 04	4.19E + 02
39	5HG	Plateau	4.70E + 01	2.17E + 04	4.62E + 02
40	5IP	Flatland	4.99E + 01	2.73E + 04	5.47E + 02
41	5IQ	Hill	4.89E + 01	2.77E + 04	5.65E + 02
42	5IH	River swamp	5.06E + 01	3.29E + 04	6.51E + 02

Appendix E

Inventory for construction schemes of transmission lines under 750 kV

Number	Scheme number	Terrain	Distance (km)	Total investment (1E + 04 CNY)	Unit distance investment (1E + 04 CNY/km)
1	7A1P	Flatland	5.00E + 01	1.04E + 04	2.08E + 02
2	7A1Q	Hill	5.00E + 01	1.09E + 04	2.17E + 02
3	7A1H	River swamp	5.00E + 01	1.24E + 04	2.47E + 02
4	7A1S	Mountain land	5.00E + 01	1.23E + 04	2.45E + 02
5	7A1G	Plateau	5.00E + 01	1.40E + 04	2.81E + 02
6	7A1M	Desert	3.00E + 01	7.80E + 03	2.60E + 02
7	7A3P	Flatland	5.00E + 01	1.08E + 04	2.16E + 02
8	7A3Q	Hill	5.00E + 01	1.13E + 04	2.26E + 02
9	7A3S	Mountain land	5.00E + 01	1.28E + 04	2.56E + 02
10	7A3G	Plateau	5.00E + 01	1.47E + 04	2.94E + 02
11	7A3M	Desert	3.00E + 01	8.16E + 03	2.72E + 02
12	7A5P	Flatland	5.00E + 01	1.09E + 04	2.18E + 02
13	7A5Q	Hill	5.00E + 01	1.15E + 04	2.29E + 02
14	7A5S	Mountain land	5.00E + 01	1.30E + 04	2.60E + 02
15	7A5G	Plateau	5.00E + 01	1.50E + 04	2.99E + 02
16	7A5M	Desert	3.00E + 01	8.28E + 03	2.76E + 02

(*Continued*)

Number	Scheme number	Terrain	Distance (km)	Total investment (1E + 04 CNY)	Unit distance investment (1E + 04 CNY/km)
17	7B1P	Flatland	5.00E + 01	1.15E + 04	2.30E + 02
18	7B1Q	Hill	5.00E + 01	1.19E + 04	2.39E + 02
19	7B1S	Mountain land	5.00E + 01	1.35E + 04	2.71E + 02
20	7B1G	Plateau	5.00E + 01	1.55E + 04	3.11E + 02
21	7B2P	Flatland	5.00E + 01	1.30E + 04	2.61E + 02
22	7B2Q	Hill	5.00E + 01	1.36E + 04	2.73E + 02
23	7B2S	Mountain land	5.00E + 01	1.56E + 04	3.13E + 02
24	7B2G	Plateau	5.00E + 01	1.79E + 04	3.57E + 02
25	7C2P	Flatland	5.00E + 01	2.13E + 04	4.27E + 02
26	7C2Q	Hill	5.00E + 01	2.22E + 04	4.45E + 02
27	7C2H	River swamp	5.00E + 01	2.54E + 04	5.07E + 02
28	7C2S	Mountain land	5.00E + 01	2.53E + 04	5.06E + 02
29	7C2G	Plateau	5.00E + 01	2.78E + 04	5.57E + 02
30	7C2M	Desert	3.00E + 01	1.60E + 04	5.33E + 02
31	7D1P	Flatland	5.00E + 01	2.27E + 04	4.55E + 02
32	7D1Q	Hill	5.00E + 01	2.37E + 04	4.74E + 02
33	7D1S	Mountain land	5.00E + 01	2.64E + 04	5.27E + 02
34	7D1G	Plateau	5.00E + 01	2.92E + 04	5.84E + 02
35	7D1M	Desert	3.00E + 01	1.68E + 04	5.58E + 02

Appendix F

Inventory for construction schemes of transmission lines under ±800 kV

Number	Scheme number	Terrain	Distance (km)	Total investment (1E + 04 CNY)	Unit distance investment (1E + 04 CNY/km)
1	8B1P	Flatland	5.00E + 01	1.52E + 04	3.04E + 02
2	8B1Q	Hill	5.00E + 01	1.59E + 04	3.18E + 02
3	8B1H	River swamp	5.00E + 01	1.96E + 04	3.93E + 02
4	8B1S	Mountain land	5.00E + 01	1.92E + 04	3.83E + 02
5	8B1G	Plateau	5.00E + 01	2.15E + 04	4.30E + 02
6	8B3Q	Hill	5.00E + 01	1.89E + 04	3.79E + 02
7	8B3S	Mountain land	5.00E + 01	2.17E + 04	4.34E + 02
8	8B6G	Plateau	3.00E + 01	2.08E + 04	6.92E + 02

Appendix G

Inventory for construction schemes of transmission lines under 1000 kV

Number	Scheme number	Terrain	Distance (km)	Total investment (1E + 04 CNY)	Unit distance investment (1E + 04 CNY/km)
1	10A2S	Mountain land	5.00E + 01	2.33E + 04	4.66E + 02
2	10A2G	Plateau	5.00E + 01	2.67E + 04	5.35E + 02

(*Continued*)

Number	Scheme number	Terrain	Distance (km)	Total investment (1E + 04 CNY)	Unit distance investment (1E + 04 CNY/km)
3	10GB1P	Flatland	5.00E + 01	3.80E + 04	7.61E + 02
4	10GB1Q	Hill	5.00E + 01	4.04E + 04	8.09E + 02
5	10GB1H	River swamp	5.00E + 01	4.82E + 04	9.63E + 02
6	10GB2P	Flatland	5.00E + 01	3.86E + 04	7.73E + 02
7	10GB2H	River swamp	5.00E + 01	5.09E + 04	1.02E + 03
8	10GB2Q	Hill	5.00E + 01	4.09E + 04	8.18E + 02
9	10GB2S	Mountain land	5.00E + 01	4.85E + 04	9.70E + 02
10	10GB3P	Flatland	5.00E + 01	4.07E + 04	8.14E + 02
11	10GB3Q	Hill	5.00E + 01	4.36E + 04	8.71E + 02
12	10GB3H	River swamp	5.00E + 01	5.44E + 04	1.09E + 03
13	10GB4Q	Hill	5.00E + 01	4.86E + 04	9.72E + 02
14	10GB4S	Mountain land	5.00E + 01	5.76E + 04	1.15E + 03

Appendix H

Inventory for construction schemes of transformer substation under 110 kV

Scheme number	Number of groups	Nameplate capacity (MVA)	Total investment (1E + 04 CNY)	Unit capacity investment (1E + 04 CNY/MVA)
1A1	1	31.5	2.12E + 03	6.72E + 01
1A2	1	40	2.02E + 03	5.04E + 01
1A3	2	50	2.86E + 03	2.86E + 01
1B2	2	50	3.18E + 03	3.18E + 01
1B3	2	50	4.09E + 03	4.09E + 01
1B5	2	50	4.08E + 03	4.08E + 01
1C1	2	50	4.98E + 03	4.98E + 01
1C2	2	50	6.38E + 03	6.38E + 01

Appendix I

Inventory for construction schemes of transformer substation under 220 kV

Scheme number	Number of groups	Nameplate capacity (MVA)	Total investment (1E + 04 CNY)	Unit capacity investment (1E + 04 CNY/MVA)
2A1	1	120	5.56E + 03	4.63E + 01
2A3	1	180	6.52E + 03	3.62E + 01
2A5	2	180	9.69E + 03	2.69E + 01
2A7	1	180	8.27E + 03	4.59E + 01
2A8	1	180	5.57E + 03	3.09E + 01
2B1	2	180	9.20E + 03	2.56E + 01
2B2	2	180	9.51E + 03	2.64E + 01
2B3	2	240	1.21E + 04	2.52E + 01
2B4	2	240	1.44E + 04	3.00E + 01
2B5	2	180	8.60E + 03	2.39E + 01

Appendix J

Inventory for construction schemes of transformer substation under 330 kV

Scheme number	Number of groups	Nameplate capacity (MVA)	Total investment (1E + 04 CNY)	Unit capacity investment (1E + 04 CNY/MVA)
3A1	2	360	1.94E + 04	2.70E + 01
3C1	1	240	1.20E + 04	5.00E + 01
3C2	2	240	1.54E + 04	3.21E + 01
3D1	1	240	1.18E + 04	4.93E + 01
3D2	1	240	1.52E + 04	6.34E + 01

Appendix K

Inventory for construction schemes of transformer substation under 500 kV

Scheme number	Number of groups	Nameplate capacity (MVA)	Total investment (1E + 04 CNY)	Unit capacity investment (1E + 04 CNY/MVA)
5A1	1	750	3.11E + 04	4.15E + 01
5A1	1	1000	3.19E + 04	3.19E + 01
5A2	1	750	3.07E + 04	4.09E + 01
5A3	2	750	3.89E + 04	2.59E + 01
5A3	2	1000	4.01E + 04	2.01E + 01
5A4	1	750	3.11E + 04	4.14E + 01
5B1	1	750	2.50E + 04	3.34E + 01
5B2	2	750	3.38E + 04	2.25E + 01
5B3	2	1000	3.50E + 04	1.75E + 01
5C1	1	750	1.98E + 04	2.63E + 01
5C2	1	750	2.02E + 04	2.69E + 01
5C3	2	750	2.76E + 04	1.84E + 01
5D1	1	750	2.30E + 04	3.07E + 01
5D2	1	750	2.35E + 04	3.13E + 01
5D3	2	750	3.16E + 04	2.11E + 01

Appendix L

Inventory for construction schemes of transformer substation under 750 kV

Scheme number	Number of groups	Nameplate capacity (MVA)	Total investment (1E + 04 CNY)	Unit capacity investment (1E + 04 CNY/MVA)
7A1	1	2100	7.29E + 04	3.47E + 01
7C1	1	2100	6.10E + 04	2.90E + 01
7C2	1	2100	4.91E + 04	2.34E + 01
7C3	1	2100	5.52E + 04	2.63E + 01
7C4	1	1500	4.81E + 04	3.21E + 01

Appendix M

Inventory for construction schemes of transformer substation under 1000 kV

Scheme number	Number of groups	Nameplate capacity (MVA)	Total investment (1E + 04 CNY)	Unit capacity investment (1E + 04 CNY/MVA)
10A2	2	3000	2.04E + 05	3.40E + 01
10B1	2	3000	1.93E + 05	3.22E + 01