

# Research on Power Supply-Demand Matching and Social Welfare from the Perspective of Regional Multi-energy Synergy

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## Article

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# Abstract

Serving as the "main artery" for China's interprovincial power allocation, Ultra-High Voltage (UHV) transmission provides critical infrastructure support for establishing a unified national electricity market. This study systematically evaluates the rationality of UHV network planning, aiming to address the spatial mismatch between energy resources and load centers while facilitating the transition to a new energy system, with corresponding theoretical frameworks and policy recommendations. This paper employs system dynamics methodology. Provincial electricity supply and demand models are constructed within the framework of a national unified electricity market. From the perspectives of multi-energy synergy and sectoral heterogeneity, the supply and demand situations across provincial administrative regions are projected. Based on these projections, an Improved Artificial Fish Swarm Algorithm model is applied. This model simulates electricity supply-demand matching mechanisms under different temporal scenarios. Finally, the impacts of these mechanisms are systematically evaluated. This evaluation covers different regions and stakeholders under various time scenarios. Four dimensions are considered: efficiency, equity and environment. The main conclusions are as follows: First, China's power supply and demand pattern is undergoing a structural evolution. The geographical separation between power generation and consumption is increasingly widening. Provincial roles are becoming progressively differentiated. Second, the evolution of supply-demand matching mechanisms highlights the urgent need to enhance the mutual support capacity of the national power market and to reduce transmission costs. Third, although the mechanisms have improved overall social welfare, they have also generated redistributive effects, resulting in a marked divergence in welfare across regions.

## 1. Introduction

Driven by the goals of achieving carbon peak and carbon neutrality, China's energy structure is accelerating its transition towards clean and low-carbon alternatives, with renewable energy installation capacity continuing to expand and the pressure for new energy integration becoming increasingly prominent<sup>[1, 2]</sup>. This transformation demands greater flexibility, interconnectivity, and resource allocation capabilities from the power system<sup>[3, 4]</sup>. The national unified electricity market is nearing its initial completion, with its framework design now largely established. Serving as the backbone for inter-provincial and cross-regional power transmission within this unified market, Ultra-High Voltage (UHV) transmission lines have not only effectively alleviated the spatial mismatch between energy resources and load centers but have also provided critical corridors for the large-scale cross-regional transmission of clean energy, thereby facilitating the formation of a "national grid" market allocation framework<sup>[5, 6]</sup>.

Against this backdrop, the spatial mismatch in regional power supply and demand remains a fundamental constraint on system efficiency and security<sup>[7]</sup>. As regional industrial structures, renewable energy deployment, and power demand patterns rapidly evolve, an important yet underexplored question arises: whether the existing and planned UHV transmission network remains structurally adequate to accommodate the medium-to long-term evolution of inter-provincial power supply and demand dynamics.

To address this gap, this study focuses on the following core research question: Given the projected evolution of inter-provincial power supply and demand, can China's existing UHV transmission network effectively support inter-provincial power balance, and what potential structural bottlenecks require further optimization?

To this end, this paper constructs a system dynamics model for China's power supply side. This model is built from the perspective of multi-energy synergy. A corresponding demand-side model is also developed. This demand-side model is based on industrial heterogeneity characteristics. These models are used to simulate and project the evolution of China's power supply-demand dynamics through 2035. Potential supply-demand gaps are identified through these simulations.

Based on the projected data, an Improved Artificial Fish Swarm Algorithm (IAFSA) is employed as the core optimization method. This algorithm aims to minimize both construction costs and transmission path lengths. The objective is to derive optimal solutions that meet the power demands of each province.

Finally, an in-depth validation is conducted from three dimensions: efficiency, equity, and environment. This validation systematically evaluates the social welfare effects caused by changes in power supply-demand matching pathways. It also analyzes the impacts of new power matching pathways on different regions and market participants. Through this approach, theoretical support is provided for the rationality of the power supply-demand matching pathways.

## 2. Literature Review

Current research primarily focuses on three key areas: price-based balancing mechanisms, inter-regional trading design, and source-grid-load-storage coordination. These research streams exhibit both intrinsic interconnections and relative independence in their thematic focus.

### 2.1. An electricity supply and demand balance mechanism based on price signal and multi-market coordination

Research on electricity supply-demand matching optimization has evolved from the early single energy market toward multi-market coordination with price signals as the core lever. Electricity prices are jointly shaped by fuel costs, carbon prices, renewable penetration, and extreme weather events, and their increased volatility in turn incentivizes the entry of energy storage and demand response resources into the system<sup>[8, 9]</sup>. At the policy level, ancillary services have been marketized, yet peak regulation compensation in some provinces still overlaps with spot prices, interfering with unit commitment and storage dispatch decisions<sup>[11, 12]</sup>. When the carbon price exceeds a certain threshold, it pre-activates the economic viability of gas-fired power replacing coal-fired power, thereby altering the reserve structure<sup>[13–15]</sup>. The green electricity trading rules decouple environmental value from electrical energy prices, affecting the bidding strategies of renewable generators<sup>[16–18]</sup>. Subsidy phase-out and green premiums have been incorporated into long-term planning; studies indicate that shifting subsidies toward inter-provincial green electricity premiums can improve transmission channel utilization by approximately 9%<sup>[19]</sup>, and when the carbon price rises from 80 CNY/ton to 120 CNY/ton, the marginal cost increase of coal-fired power exceeds that of gas-fired power, with the carbon–electricity linkage shifting the coal-fired output curve rightward<sup>[20]</sup>. Regarding the coordination between inter-provincial and intra-provincial markets, excessively low inter-provincial price caps suppress the peak-shaving willingness of sending-side peak-load units<sup>[21]</sup>. On the demand side, both price-based and incentive-based responses are incorporated; medium- and long-term trading refines deviation assessment, compelling retail power companies to balance day-ahead schedules with actual consumption<sup>[22, 23]</sup>.

## 2.2. Cross-regional electricity trading mechanism and market coordination

Cross-regional electricity trading expands the scope of resource allocation by breaking down inter-provincial barriers and improves transmission channel utilization<sup>[24]</sup>, while simultaneously promoting renewable energy accommodation through surplus spot trading, which enables the redistribution of zero-marginal-cost electricity<sup>[25]</sup>, thereby reducing electricity costs at the receiving end and increasing revenues for the sending end<sup>[26]</sup>. Comparisons among typical international markets reveal that: the UK's decentralized model emphasizes medium- and long-term physical contracts, offering low price risk but limited flexibility; the US centralized full-volume bidding enables rapid dispatch but experiences high price volatility; and the Nordic hybrid model balances risk management and efficiency through financial contracts combined with spot bidding. A consensus is that centralized clearing should incorporate transmission channel security constraints and rank bids by price differentials<sup>[27–30]</sup>. China's 2013 rules established a framework with centralized matching as the primary mechanism and bilateral negotiation as supplementary, where sell-side and buy-side bids are sequenced according to energy-saving and environmental protection criteria and resource optimization criteria, respectively, and are then subject to security verification before unified clearing<sup>[31]</sup>. For the northwest region, domestic studies have proposed introducing inter-provincial surplus renewable energy spot trading on top of existing medium- and long-term transactions, allowing curtailed wind and solar power to be sold at prices below the benchmark tariff, thereby achieving mutual benefits for multiple parties<sup>[32, 33]</sup>. The trading mechanism emphasizes that the transmission electricity price is uniquely determined by the optimal path, with buyers bearing line losses, and adopts block bidding with time-block clearing to smooth DC transmission fluctuations and reduce operational risks<sup>[34, 35]</sup>.

## 2.3. 'Source-Network-Load-Storage' collaborative optimization and system operation resilience

Electricity supply-demand matching has expanded from the earlier source-load bilateral framework to a coordinated "source-grid-load-storage" architecture. Mainstream methodological tools include bi-level programming (with the upper level minimizing total investment and operational costs, and the lower level enabling autonomous decision-making by multiple agents) and Stackelberg game models (where the grid dominates electricity prices and reserve capacity, while generation and storage adjust accordingly). Simulations indicate that distribution-side energy storage can reduce the peak-valley difference by approximately 12% and improve the local renewable energy consumption rate by nearly 80%<sup>[36, 37]</sup>, while the Stackelberg game approach can lower the annual comprehensive cost of the entire grid by about 10%<sup>[38, 39]</sup>. Energy storage is categorized into source-side, distribution-side, and user-side types<sup>[40, 41]</sup>; their coordinated deployment can increase the renewable energy consumption rate of distribution networks by 6 to 10 percentage points and reduce the need for line expansion by approximately 10%. However, when annual utilization hours fall below 600 hours, peak-shaving revenues are insufficient to cover capital costs, necessitating regulatory oversight<sup>[42, 43]</sup>. At the distribution network level, a multi-tiered "province-distribution-microgrid" coordination framework, combined with flexible interconnection and reactive power compensation, enhances feeder load transfer capability by 15%<sup>[44]</sup>. On the demand-side response front, when residential time-of-use tariffs reach a peak-to-valley ratio of 4:1 and smart meter penetration exceeds 80%, summer peak loads

can be reduced by 2.4%; with the addition of distributed photovoltaics and residential battery storage forming a virtual power plant, the peak-shaving potential exceeds 5%<sup>[45, 46]</sup>. For industrial interruptible loads, when compensation prices are 20% above the real-time spot average, the interruption completion rate can reach 90%, providing rapid reserve capacity during extreme weather events and thereby enhancing the resilience of the entire supply-demand matching chain<sup>[47]</sup>.

## 2.4. Comprehensive welfare evaluation and optimization of power system under multi-objective equilibrium

Research on the welfare implications of electricity supply-demand matching has expanded from the classical economic efficiency perspective to a composite value framework encompassing economic, social, and environmental dimensions. Early studies aimed at maximizing social welfare through marginal cost pricing to achieve Pareto optimality; however, due to market imperfections and bounded rationality among end-users, the theoretical gains are attenuated, prompting a shift toward mechanism design feasibility and distributional effects<sup>[45, 48, 49]</sup>. With the ongoing energy transition, the welfare dimensions have been substantially deepened: (1) In terms of social equity, attention is directed to the disproportionate burden of transition costs on low-income groups, necessitating the incorporation of lifeline tariffs, direct subsidies, or socialized cost allocation mechanisms to safeguard energy justice<sup>[50, 51]</sup>; (2) On the environmental and climate front, the internalization of carbon pricing and positive externalities of renewable energy is achieved through green premiums and environmental value trading, thereby incentivizing clean energy investment<sup>[52, 53]</sup>; (3) With respect to system resilience, reserve capacity, capacity mechanisms, and scarcity pricing are regarded as fundamental public goods that ensure long-term security, addressing extreme weather events and geopolitical risks<sup>[54–56]</sup>; (4) In the realm of digital technologies, smart meters and AI enhance demand response efficiency and user benefits, yet they also introduce new challenges such as data privacy, algorithmic fairness, and the digital divide. Collectively, these multidimensional investigations constitute a comprehensive analytical framework for welfare assessment<sup>[57, 58]</sup>.

### Remark

Existing research has established a three-dimensional analytical framework encompassing mechanisms, agents, and values, with the perspective shifting from single-market equilibrium to complex system coordination, and methodologies evolving from theoretical derivation to policy design and empirical testing. Nevertheless, three major gaps and challenges remain.

First, the characterization of coupling mechanisms among multi-dimensional complex systems remains insufficient—although separate models exist for prices, trading, source-grid-load-storage coordination, policy rules, and social welfare, there is a lack of a unified analytical framework that simultaneously accommodates cross-provincial physical constraints, multi-timescale markets, multi-agent game interactions, carbon–electricity policy linkages, and welfare distribution. Consequently, critical issues such as the real-time interaction between inter-provincial transmission capacities and intra-provincial clearing under the unified electricity market, as well as the impact of green electricity trading on spatial resource allocation and inter-temporal investment incentives, have yet to receive systematic quantitative explanations.

Second, the research paradigm needs to transition from deterministic optimization to uncertainty governance—most existing models seek optimal solutions based on deterministic or probabilistic assumptions; however, the essence of the new power system lies in the superposition of multiple uncertainties. Research on the interconnections among these uncertainties and their effects on system resilience remains insufficient, necessitating the integration of tools such as scenario planning and robust optimization for adaptive planning and resilience design.

Third, the value dimension must be expanded from efficiency priority to a multi-objective collaborative evaluation system—although welfare studies have incorporated equity, security, and environmental considerations, the social welfare functions in quantitative models are still largely simplified to minimizing total economic costs or maximizing total surplus, while objectives such as distributional effects, regional equity, and intergenerational justice are mostly treated as qualitative constraints or ex-post evaluations. As a result, theoretically efficient schemes may underperform in practice due to public opposition or implementation resistance. There is an urgent need for a design theory that embeds multi-objective trade-off mechanisms, and for the development of comprehensive evaluation models capable of quantifying and measuring the impacts of different policy portfolios on various provinces and market participants.

### 3. Electricity Supply and Demand Forecasting System Research and Design

This study constructs a system dynamics framework to model China's power supply side considering multi-energy synergy and demand side with industry heterogeneity, so as to fully simulate the evolution of China's power supply and demand by 2035.

#### 3.1. Electricity demand system

The structure and change trend of electricity demand are deeply influenced by socio-economic activities. Referring to the practice of Yu et al.<sup>[33]</sup>, the single consumption method is used to analyze electricity demand from four parts, namely electricity consumption of the primary industries, secondary industries and tertiary industries and residential life, which covers all fields of socio-economic activities and can comprehensively reflect the total amount, structure and change trend of electricity demand.

The sum of electricity consumption by primary industries, secondary industries and tertiary industries and residential electricity consumption is the total electricity demand.

$$W_{i,t} = W_{1,i,t} + W_{2,i,t} + W_{3,i,t} + W_{4,i,t}$$

3.1

Where  $W_{i,t}$  is the total power demand of province (city) in year ,  $W_{1,i,t}$  is the power demand of primary industry sector in province in year ,  $W_{2,i,t}$  is the power demand of secondary industry sector in province in year ,  $W_{3,i,t}$  is the power demand of tertiary industry sector in province in year , and  $W_{4,i,t}$  is the power demand of residents in province in year .

Analyze the relevant data of each province from 2013 to 2023 respectively, and obtain the weight value of each influencing factor by referring to the indexes of relevant literature as well as regressing the data accordingly, and the specific model is shown in Fig. 1. The model indicators are presented in Table 1.

Table 1  
System dynamics power demand forecasting model parameters

| industry             | dimensional                                    | index                                                                                                                          |
|----------------------|------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------|
| primary industries   | policy dimension                               | Industrial output value target, key agricultural industry development planning target                                          |
|                      | economic dimension                             | The output value of the primary industry, the employed population                                                              |
|                      | Power consumption energy consumption dimension | The unit output power consumption and electric energy substitution rate of the primary industry                                |
|                      | meteorological factor                          | The number of extreme weather, annual precipitation                                                                            |
|                      | Electric energy substitution dimension         | New electricity demand for agricultural production                                                                             |
|                      | development dimension                          | New installed capacity of distributed power supply                                                                             |
| secondary industries | policy dimension                               | The second industry strategic emerging industry development goals, double carbon constraint coefficient, structural adjustment |
|                      | economic dimension                             | Output value of light and heavy industry                                                                                       |
|                      | Power consumption energy consumption dimension | Power consumption of light and heavy industry                                                                                  |
|                      | social factor                                  | Influencing factors of the epidemic                                                                                            |
|                      | development dimension                          | The second industry of distributed generation                                                                                  |
| tertiary industries  | policy dimension                               | The development plan of the tertiary industry emerging industry                                                                |
|                      | economic dimension                             | The tertiary industry unit output value, fixed investment                                                                      |
|                      | Power consumption energy consumption dimension | Energy consumption per unit output value of tertiary industry                                                                  |
|                      | development dimension                          | Distributed power generation capacity                                                                                          |
|                      | Electric energy substitution dimension         | Proportion of public transport electric vehicles                                                                               |
| residential life     | economic dimension                             | Per capita disposable income, permanent resident population, household electric vehicle ownership                              |
|                      | Power consumption energy consumption dimension | The average power consumption of electric vehicles, the average power consumption of main household appliances                 |
|                      | Electric energy substitution dimension         | Coal to electricity clean heating ratio                                                                                        |

### 3.1.1. Electricity demand of the first, second and third industrial sectors

The unit consumption method is used to predict the power demand of the first, second and third industrial sectors,

$$W_{1,i,t,k} = GDP_{1,i,t,k} \times E_{1,i,t,k}$$

3.2

Where  $W_{1,i,t,k}$  is the power demand of industry sector  $k(= 1, 2, 3)$  in province (city) in year ,  $GDP_{1,i,t,k}$  represents the GDP of industry in province (city) in year , and  $E_{1,i,t,k}$  represents the power consumed by industry in province (city) in year per unit of output value.

Year GDP is expressed as the product of Year  $t - 1$  GDP and the sum of the growth rates of Year 1 plus Year GDP,

$$GDP_{1,i,t,k} = GDP_{1,i,t-1,k} \times (1 + \Delta G_{1,i,t,k})$$

3.3

where  $\Delta G_{1,i,t}$  represents the growth rate of gross productivity in sector in province (city) in year .

The power consumption per unit of output value changes with policy changes, industrial structure adjustment and technological level changes,

$$E_{1,i,t,k} = E_{1,i,t-1,k} \times (1 + \Delta E_{1,i,k})$$

3.4

$$\Delta E_{1,i,k} = a_1 \ln X_{1,i,k} + a_2 \ln Y_{1,i,k} + a_3 \ln Z_{1,i,k} + \cdots + \varphi_1$$

3.5

In the formula,  $E_{1,i,t-1}$  represents the power consumption per unit output value of the industrial unit in the  $t - 1$  year of province ( city ),  $\Delta E_{1,i}$  represents the change of the power consumption per unit output value of the department in province ( city ),  $X_{1,i}$ ,  $Y_{1,i}$  and  $Z_{1,i}$  represent the indicators that are significantly related to the change of the power consumption per unit output value of the department in the A province ( city ).  $a_1$ ,  $a_2$  and  $a_3$  are regression coefficients,  $\varphi_1$  is an error term, and some coefficients are adjusted in combination with policies and industrial structure changes.

### 3.1.2. Residential electricity demand

The residential electricity demand is forecasted,

$$W_{4,i,t} = P_{i,t} \times E_{4,i,t}$$

3.6

In the formula,  $W_{4,i,t}$  is the residential electricity demand of province ( city ) in the year,  $P_{i,t}$  represents the population of province ( city ) in the year, and  $E_{4,i,t}$  represents the per capita electricity consumption of province ( city ) in the year.

The year population is expressed as the product of the  $t - 1$  year GDP and 1 plus the year population growth rate,

$$P_{i,t} = P_{i,t-1} \times (1 + \Delta P_{i,t})$$

3.7

In the formula,  $P_{i,t-1}$  represents the  $t - 1$  year population of province ( city ), and  $\Delta P_{i,t}$  represents the year population growth rate of province ( city ).

Per capita electricity consumption changes with policy changes, industrial restructuring, technical level and other unnatural factors and natural factors.

$$E_{4,i,t} = E_{4,i,t-1} \times (1 + \Delta E_{4,i})$$

3.8

$$\Delta E_{4,i} = d_1 \ln X_{4,i} + d_2 \ln Y_{4,i} + d_3 \ln Z_{4,i} + \cdots + \varphi_4$$

3.9

In the formula,  $E_{4,i,t-1}$  represents the per capita power consumption of residents in province ( city ) in the year,  $\Delta E_{4,i}$  represents the change of per capita power consumption of residents in province ( city ),  $X_{4,i}$ ,  $Y_{4,i}$ ,  $Z_{4,i}$  represent the indicators significantly related to the change of per capita power consumption obtained by regression in A province ( city ),  $d_1$ ,  $d_2$ ,  $d_3$  are regression coefficients,  $\varphi_4$  is the error term, and some coefficients are adjusted in combination with policy and industrial structure changes.

## 3.2. Electricity supply system

In 2023, the total power generation in China reached 9.5 trillion kilowatt hours. Among them, thermal power, hydropower, wind power and photovoltaic power are the main power generation methods in China, accounting for 95.5% of the total power generation. At the same time, they cover two major categories of traditional energy and renewable energy, which can fully reflect the structure and change trend of power supply.

The sum of the power generation of the four power generation modes is the total power supply,

$$Q_{i,t} = \sum_{k=1}^{k=4} Q_{i,t,k}$$

3.10

In the formula,  $Q_{i,t}$  is the total power supply of province ( city ) in the year,  $Q_{i,t,1}$  is the thermal power supply of province ( city ) in the year,  $Q_{i,t,2}$  is the hydropower generation of province ( city ) in the year,  $Q_{i,t,3}$  is the wind power supply of province ( city ) in the year,  $Q_{i,t,4}$  is the photovoltaic power supply of province ( city ) in the year.

The relevant data of each province from 2013 to 2023 are analyzed respectively. By referring to the indicators of relevant literature and conducting corresponding regression on the data, the weight values of each influencing factor are obtained<sup>[23–26]</sup>. The specific model is shown in Fig. 2. The model indicators are presented in Table 2.

Table 2  
System dynamics power demand forecasting model parameters

| generating model               | dimensional                  | index                                                                                   |
|--------------------------------|------------------------------|-----------------------------------------------------------------------------------------|
| thermal power generation       | policy dimension             | Coal and electricity development policy incentives, ' double carbon ' policy incentives |
|                                | economic dimension           | Raw coal consumption, raw coal price                                                    |
|                                | Installed capacity dimension | Thermal power installed capacity                                                        |
| Hydropower generation          | policy dimension             | Hydropower development policy incentives, ' double carbon ' policy incentives           |
|                                | meteorological factor        | The number of extreme weather, annual precipitation                                     |
|                                | Installed capacity dimension | hydroelectric capacity                                                                  |
| Wind power generation          | policy dimension             | Wind power development policy incentives, ' double carbon ' policy incentives           |
|                                | meteorological factor        | The number of extreme weather, annual precipitation                                     |
|                                | Installed capacity dimension | installed wind power capacity                                                           |
|                                | technology dimension         | construction cost                                                                       |
| Photoelectric power generation | policy dimension             | Optoelectronics development policy incentives, ' double carbon ' policy incentives      |
|                                | meteorological factor        | The number of extreme weather, annual precipitation                                     |
|                                | Installed capacity dimension | Photoelectric installed capacity                                                        |
|                                | technology dimension         | construction cost                                                                       |

The power generation of each power generation mode is predicted,

$$Q_{i,t,k} = C_{i,t,k} \times A_{i,t,k}$$

### 3.11

In the formula,  $Q_{i,t,k}$  is the A-type power generation capacity of province ( city ) in the year,  $C_{i,t,k}$  represents the A-type power generation capacity of province ( city ) in the year, and  $A_{i,t,k}$  represents the power generation efficiency of type power generation mode of province ( city ) in the year.

Calculate power generation efficiency

$$A_{i,t,k} = e_1 \ln X_{5,i,k} + e_2 \ln Y_{5,i,k} + e_3 \ln Z_{5,i,k} + \cdots + \varphi_5$$

3.12

In the formula,  $X_{5,i,k}$ ,  $Y_{5,i,k}$ ,  $Z_{5,i,k}$  represent the indicators that are significantly related to the power generation of power generation methods obtained by regression in province ( city ).  $e_1$ ,  $e_2$ ,  $e_3$  are regression coefficients, and  $\varphi_5$  is the error term.

### 3.3. Estimation method of power supply and demand gap

In this paper, the demand and supply of the power system in each province are forecasted, and the power gap can be obtained by comparing the power demand and supply forecast data in each province and calculating the difference between the two,

$$\text{gap}_{i,t} = W_{i,t} - Q_{i,t}$$

3.13

In the formula,  $\text{gap}_{i,t}$  denotes the gap between supply and demand of electricity in province in year ,  $W_{i,t}$  denotes the demand of electricity in province in year , and  $Q_{i,t}$  denotes the supply of electricity in province in year . If the result is positive, it means that the province's electricity supply is insufficient; if it is negative, it means that the electricity supply is excessive.

### 3.4. Model test

In order to verify the accuracy and reliability of the established power demand and supply prediction model, the model is used to predict the power supply and demand data from 2019 to 2023, and the actual value is compared with the predicted value. If the error is relatively small, it shows that the established prediction model can accurately reflect the trend of power demand and supply, and has high prediction accuracy.

Comparing the actual values of electricity demand and supply from 2019 to 2023 with the predicted values, the absolute value of the deviation values are less than 10%, so it can be considered that the model has a high accuracy in predicting electricity demand, which is practically significant for the prediction of electricity demand in each province.

## 4. Power supply and demand forecasting and gap analysis of each province

### 4.1. Electricity demand and supply forecasts by province

Based on the constructed forecasting model and combining the historical power demand data of each province, the future power demand and supply are forecasted, and the results are shown in Table 3,

Table 3  
Electricity Demand and Supply Forecast Results by Province

|                | Electricity demand forecasting |       |       | Electricity supply forecast |       |       |
|----------------|--------------------------------|-------|-------|-----------------------------|-------|-------|
|                | 2023                           | 2030  | 2035  | 2023                        | 2030  | 2035  |
| Beijing        | 1358                           | 1829  | 2141  | 455                         | 608   | 614   |
| Tianjin        | 1051                           | 1351  | 1584  | 808                         | 1115  | 1393  |
| Hebei          | 4757                           | 6277  | 7493  | 3736                        | 6586  | 9057  |
| Shanxi         | 2885                           | 3905  | 4567  | 4376                        | 8294  | 11682 |
| Inner Mongolia | 4823                           | 6992  | 8560  | 7451                        | 13495 | 19471 |
| Liaoning       | 2663                           | 3745  | 4032  | 2203                        | 3015  | 3743  |
| Jilin          | 928                            | 1228  | 1402  | 1098                        | 2034  | 2805  |
| Heilongjiang   | 1184                           | 1643  | 1789  | 1234                        | 1900  | 2461  |
| Shanghai       | 1849                           | 2472  | 2736  | 955                         | 1076  | 1153  |
| Jiangsu        | 7833                           | 10505 | 12151 | 6106                        | 8533  | 10742 |
| Zhejiang       | 6192                           | 9359  | 10956 | 4353                        | 6784  | 8786  |
| Anhui          | 3214                           | 4790  | 6167  | 3336                        | 5729  | 7943  |
| Fujian         | 3090                           | 4406  | 5567  | 3074                        | 4548  | 6041  |
| Jiangxi        | 2026                           | 2955  | 3829  | 1669                        | 3191  | 4262  |
| Shandong       | 7966                           | 10452 | 11870 | 5916                        | 7812  | 8767  |
| Henan          | 4090                           | 5414  | 6537  | 3172                        | 5303  | 7253  |
| Hubei          | 2706                           | 4074  | 5079  | 3013                        | 3202  | 3148  |
| Hunan          | 2277                           | 3433  | 3835  | 1700                        | 2253  | 2712  |
| Guangdong      | 8502                           | 13394 | 15074 | 6719                        | 10971 | 14652 |
| Guangxi        | 2449                           | 3808  | 4363  | 2287                        | 3931  | 5421  |
| Hainan         | 482                            | 710   | 813   | 448                         | 904   | 1298  |
| Chongqing      | 1453                           | 2317  | 2669  | 1054                        | 1840  | 2482  |
| Sichuan        | 3711                           | 5147  | 5947  | 4713                        | 6191  | 6809  |
| Guizhou        | 1783                           | 2731  | 3103  | 2271                        | 2875  | 3430  |
| Yunnan         | 2513                           | 3821  | 4386  | 3905                        | 5207  | 5597  |
| Tibet          | 135                            | 218   | 268   | 137                         | 327   | 508   |
| Shaanxi        | 2450                           | 3836  | 4734  | 2946                        | 4918  | 6870  |
| Gansu          | 1645                           | 2118  | 2506  | 1925                        | 3220  | 4454  |

|          | Electricity demand forecasting |      |      | Electricity supply forecast |      |      |
|----------|--------------------------------|------|------|-----------------------------|------|------|
|          | 2023                           | 2030 | 2035 | 2023                        | 2030 | 2035 |
| Qinghai  | 1018                           | 1293 | 1514 | 874                         | 1161 | 1447 |
| Ningxia  | 1387                           | 1814 | 2165 | 2246                        | 3607 | 5133 |
| Xinjiang | 3821                           | 5132 | 5419 | 4912                        | 6982 | 9472 |

During the period from 2013 to 2023, electricity consumption across Chinese provinces exhibited differentiated development trajectories. Eastern coastal regions, leveraging their mature industrial foundations and highly concentrated urban clusters, have established a stable and substantial base of electricity consumption while maintaining sustained growth momentum. Meanwhile, central and western provinces, although starting from a relatively lower base, have demonstrated more robust growth momentum driven by the combined effects of ongoing policy support under the Western Development and Central Rise strategies and rapid regional economic expansion. This regional differentiation not only reflects the uneven development of China's regional economies but also reveals the intrinsic connection between electricity demand patterns and regional economic characteristics.

From the perspective of electricity supply, differences in resource endowments have similarly shaped distinct development pathways across provinces. Coal-rich regions such as Inner Mongolia and Shanxi have become crucial pillars of national electricity supply through large-scale thermal power development, while southwestern provinces like Yunnan and Sichuan have achieved significant increases in power generation by fully utilizing their abundant hydropower resources. The formation of this supply structure is both an objective outcome of the distribution of natural resources and closely related to the national energy strategic layout.

Looking ahead, electricity consumption growth in the eastern, central, and western regions is projected to exhibit notable divergence. In eastern coastal provinces, rising energy efficiency and industrial structure optimization will gradually moderate the growth of new electricity demand. These regions will increasingly rely on the development of clean energy and cross-regional power allocation to meet their needs. In contrast, western provinces, benefiting from abundant renewable energy resources and favorable national policies, are gradually emerging as new engines for national electricity consumption growth. Particularly with the deepening advancement of the "dual-carbon" strategy, the development potential of wind, solar, and other clean energy sources in western regions will be further unleashed, injecting sustained momentum into their electricity consumption growth.

In terms of power generation capacity development, provinces will continue to follow distinct pathways from 2023 to 2035. Eastern provinces, while maintaining moderate capacity growth, will shift their focus toward clean energy projects such as offshore wind and distributed photovoltaic power generation. Resource-rich provinces, on the other hand, will intensify efforts to advance energy structure transformation, achieving synergy between traditional and clean energy sources through integrated wind-solar-thermal-storage development. It is noteworthy that continuous advancements in Ultra-High Voltage transmission technology will provide stronger support for cross-regional electricity resource allocation, helping to alleviate the spatial mismatch between energy resources and load centers.

Western regions, capitalizing on their unique geographical advantages and resource conditions, are emerging as critical bases for China's clean energy development. The abundant hydropower, wind, and solar resources in provinces such as Yunnan, Sichuan, and Guizhou can not only meet local demand but also supply clean electricity to eastern regions through cross-regional transmission networks. This model of regional collaborative development not only contributes to optimizing the national energy structure but also provides a vital pathway for achieving carbon neutrality goals.

## 4.2. Electricity supply and demand gap by province

Based on electricity supply-demand projections, provincial power balance gaps have been identified. Analyzing these gaps provides critical insights into regional electricity market conditions and reveals imbalances in resource distribution, serving as an important foundation for formulating policies regarding power allocation, energy mix optimization, and infrastructure development. This indicator not only reflects regional disparities in economic development and energy resource distribution, but also offers valuable references for optimizing China's national power system and achieving sustainable energy development. The power supply and demand gaps of each province in 2023, 2030, and 2035 are shown in Table 4, Fig. 3, Fig. 4, and Fig. 5.

Table 4  
Electricity supply and demand gap by province

| Beijing        | Gap in 2023 | Gap in 2030 | Gap in 2035 |           | Gap in 2023 | Gap in 2030 | Gap in 2035 |
|----------------|-------------|-------------|-------------|-----------|-------------|-------------|-------------|
|                | 903         | 1221        | 1527        | Hubei     | -307        | 872         | 1931        |
| Tianjin        | 243         | 236         | 191         | Hunan     | 577         | 1180        | 1123        |
| Hebei          | 1021        | -309        | -1564       | Guangdong | 1783        | 2423        | 422         |
| Shanxi         | -1491       | -4389       | -7115       | Guangxi   | 162         | -123        | -1058       |
| Inner Mongolia | -2628       | -6503       | -10911      | Hainan    | 34          | -194        | -485        |
| Liaoning       | 460         | 730         | 289         | Chongqing | 399         | 477         | 187         |
| Jilin          | -170        | -806        | -1403       | Sichuan   | -1002       | -1044       | -862        |
| Heilongjiang   | -50         | -257        | -672        | Guizhou   | -488        | -144        | -327        |
| Shanghai       | 894         | 1396        | 1583        | Yunnan    | -1392       | -1386       | -1211       |
| Jiangsu        | 1727        | 1972        | 1409        | Tibet     | -2          | -109        | -240        |
| Zhejiang       | 1839        | 2575        | 2170        | Shaanxi   | -496        | -1082       | -2136       |
| Anhui          | -122        | -939        | -1776       | Gansu     | -280        | -1102       | -1948       |
| Fujian         | 16          | -142        | -474        | Qinghai   | 144         | 132         | 67          |
| Jiangxi        | 357         | -236        | -433        | Ningxia   | -859        | -1793       | -2968       |
| Shandong       | 2050        | 2640        | 3103        | Xinjiang  | -1091       | -1850       | -4053       |
| Henan          | 918         | 111         | -716        |           |             |             |             |

China's provincial electricity supply-demand landscape during the 2023–2035 period exhibits dynamic evolutionary characteristics, marked by regional disparities and transformative trends. Nationally, while some provinces continue to face electricity deficits, others maintain supply surpluses. This differentiation reflects profound structural disparities in regional economic development stages, resource endowment conditions, and energy infrastructure levels.

Specifically, the distribution of electricity supply and demand in 2023 already demonstrates distinct regional patterns. Economically developed eastern regions such as Beijing, Shanghai, and Jiangsu experience persistent electricity deficits due to their energy-intensive industrial structures, dense populations, and robust electricity demand, which outpaces local generation capacity. In contrast, traditional energy bases like Shanxi and Inner Mongolia leverage their resource advantages to not only meet local demand but also possess considerable surplus transmission capacity. Notably, this supply-demand structure is undergoing systemic transformation. By 2030, with ongoing energy restructuring and advancements in clean energy technologies, several provinces that previously faced deficits, such as Hebei and Anhui, are projected to gradually achieve supply-demand equilibrium or even transition to surplus status.

Nevertheless, electricity security pressures remain pronounced in the eastern coastal economic core regions. Manufacturing hubs such as Jiangsu, Zhejiang, and Guangdong will continue to face significant electricity shortages before 2035, primarily due to the inherent conflict between their economic development's rigid energy demand and local resource constraints. Particularly noteworthy is the trend of year-on-year expansion in supply-demand gaps in megacities like Beijing, Shanghai, and Guangdong. Their energy transition processes must simultaneously address the pressures of phasing out traditional energy sources and the practical challenges of scaling up renewable energy.

In stark contrast to the eastern regions, the electricity surplus advantages of resource-rich central and western provinces are further consolidating. Areas such as Inner Mongolia, Shanxi, and Xinjiang, through energy structure optimization and transmission technology upgrades, have not only increased the proportion of local clean energy but also enhanced cross-regional transmission capabilities. They are evolving into critical regulatory hubs for national electricity balance. The transformation of Hebei Province is particularly exemplary. By vigorously developing renewable energy and improving energy efficiency, it has transitioned from an electricity-deficit province to a surplus one, serving as a successful model of regional energy collaborative development.

The electricity supply-demand landscape in the southwestern region presents even greater complexity and diversity. Sichuan and Yunnan maintain stable supply advantages owing to their abundant hydropower resources. Guizhou has gradually improved its supply-demand situation through energy structure optimization. Meanwhile, Chongqing and Tibet face varying degrees of supply pressure due to economic development needs and resource constraints.

## **5. Optimization model design of inter-provincial power dispatch**

### **5.1. Improved Algorithm for Artificial Fish Swarming**

The Improved Artificial Fish Swarm Algorithm has unique characteristics and advantages. It simulates the heuristic search ability of biological behavior, and by simulating the foraging, flocking and following behaviors of fish, it can effectively avoid falling into the local optimal solution, and at the same time has a It can effectively avoid falling into local optimal solutions, and at the same time has strong global search capability. The intelligence and flexibility of this algorithm enable it to adapt to complex power allocation optimization problems, especially in large-scale power networks, and quickly find the optimal paths that satisfy the conditions, which further improves the efficiency and accuracy of path planning.

In addition, this paper introduces an adaptive horizon mechanism and a solution initialization method based on greedy strategy, and also designs diversified local search strategies and population restart mechanisms, and these improvements significantly improve the convergence speed and the quality of the algorithm, making it more suitable for solving the complex practical problem of cross-province power distribution path optimization<sup>[36-9]</sup>.

## 5.2 Problem description and assumptions

The problem can be described as: there are  $A$  power supply provinces in the national market, which can be used for outward transmission of electricity, and the amount of electricity that can be used for outward transmission  $A$  is the difference between power generation and power consumption. In addition, there are  $A$  power shortage provinces, which need external power input to meet their own power needs, and the lack of electricity  $A$  is the difference between power consumption and power generation. The geographical location of each province is known. Reasonable planning of inter-provincial power transmission path, with the shortest path to meet the power demand of the provinces.

The power inter-provincial transportation problem is simplified, and the following assumptions are made for the model:

- (1) The inter-provincial power transmission mode is to choose UHV transmission, and the transportation capacity is not limited.
- (2) The electricity-deficient provinces must carry out electricity transactions, and the receiving provinces transmit electricity only once to meet their own electricity demand.
- (3) The amount of electricity that can be used for outward transmission and the amount of electricity that is missing are stable for a certain period of time.
- (4) The geographical location of each province is known, and the data is publicly available using the Gaode map, and only consider the straight line distance, without considering the height difference.
- (5) The power transmission distance in the province is neglected.
- (6) The amount of electricity that can be used for outward transmission is greater than the demand for electricity in the weak provinces.

## 5.3. Model construction

The parameters in the model are defined as follows :

$P = \{1, 2, \dots, p\}$  represents the collection of power supply provinces ;  $R = \{1, 2, \dots, r\}$  represents the collection of provinces that need electricity ;  $T = \{1, 2, \dots, t\}$  represents the collection of inter-provincial power transmission operations ;  $N = P + R$  represents the set of provinces discussed in this paper ; , represents provinces and ;  $d_{ij}$  represents the distance between and ;  $D_i$  represents the electricity demand of electricity demand province ;  $X_{kij}$  represents 0 – 1 variable, indicating whether the starting point and end point are , in the process of inter-provincial power transmission ; represents the power transmission distance.

The model is as follows.

$$\begin{aligned} \min Z &= \sum_k^r \sum_i^N \sum_j^N X_{kij} \times (d_{ij} \times D_i) \\ s. t. &\sum_i^P \sum_j^R X_{kij} = 1, k \in T \\ &\sum_i^N \sum_k^T X_{kij} = 1, j \in R \\ &\sum_i^P \sum_k^P X_{kij} = 0, k \in T \\ &X_{kij} \in \{0, 1\} \quad i, j \in N \quad k \in T \end{aligned}$$

6.1

The objective function ( 1 ) represents the minimum cost of transmission network construction ; constraint condition ( 2 ) indicates that the starting point of power transmission is one of the power supply provinces ; constraint condition ( 3 ) indicates that the province that needs electricity only accepts one power supply operation ; constraint condition ( 4 ) indicates that there is no power transmission between power supply provinces ; constraint condition ( 5 ) represents the 0 – 1 decision variable constraint. The power transmission operation occurs from to is 1, otherwise it is 0.

## 5.4. Analysis of the results

### 5.4.1. Comparative analysis of power allocation optimization paths in 2023 and 2030

In this paper, the algorithm is written in Python to simulate the predicted results for 2030, and the optimization results are shown in Table 5 and Fig. 6.

Table 5  
Optimization path of inter-provincial power allocation in 2030

| origin         | end point | Power transmission<br>( billions of kilowatt hours ) | Conveying distance ( KM ) |
|----------------|-----------|------------------------------------------------------|---------------------------|
| Inner Mongolia | Beijing   | 1221.86                                              | 403.58                    |
|                | Tianjin   | 235.74                                               | 512                       |
|                | Henan     | 110.44                                               | 695.49                    |
|                | Liaoning  | 730.19                                               | 981.55                    |
|                | Shandong  | 2639.74                                              | 661.43                    |
| Xinjiang       | Hubei     | 841.3                                                | 2764.62                   |
| Gansu          | Hubei     | 30.4                                                 | 1150.09                   |
|                | Hunan     | 854.61                                               | 1221.98                   |
|                | Qinghai   | 132.04                                               | 261.54                    |
| Shaanxi        | Hunan     | 326.08                                               | 776.02                    |
|                | Jiangsu   | 666.69                                               | 947.5                     |
| Sichuan        | Guangdong | 820.74                                               | 1219.08                   |
|                | Chongqing | 477.23                                               | 2302.66                   |
| Guangxi        | Guangdong | 87.48                                                | 502.07                    |
| Shanxi         | Jiangsu   | 1306.02                                              | 860.87                    |
|                | Zhejiang  | 1992.7                                               | 1096.08                   |
| Anhui          | Zhejiang  | 602.36                                               | 337.46                    |
|                | Shanghai  | 523.39                                               | 416.1                     |
| Yunnan         | Guangdong | 1090.24                                              | 1068.13                   |

According to simulation data for power transmission in 2030, China's inter-provincial power allocation exhibits a distinct "resource-oriented" transmission pattern. Nine resource-rich provinces, including Inner Mongolia, Xinjiang, and Gansu, serve as the primary power suppliers, delivering electricity to 13 receiving regions that encompass key urban clusters such as the Beijing-Tianjin-Hebei area and the Yangtze River Delta, while most other provinces maintain self-sufficient power supply. This resource allocation model reflects the spatial distribution characteristics of China's energy endowments and load centers, as well as the fundamental role of the UHV grid in facilitating cross-regional power dispatch.

Notably, despite the significant progress in UHV network construction, certain regions continue to face structural challenges. As a traditional industrial base, Liaoning Province's persistent power shortage is closely linked to its rapidly growing industrial electricity demand, highlighting the insufficient coordination between regional grid planning and industrial transformation. More critically, the cross-grid transmission bottleneck

between Guangdong and Sichuan serves as a typical case between the Southern Grid and State Grid systems. The current absence of direct UHV interconnections between the two provinces not only restricts the optimized cross-regional allocation of Sichuan's abundant hydropower resources but also underscores the institutional barriers posed by fragmented grid management systems to the formation of a unified national electricity market.

These phenomena collectively point to a deeper issue: the current allocation of power resources remains constrained by both administrative divisions and grid management systems. While UHV projects have achieved technical interconnection across regions, operational mechanisms have yet to fully overcome these institutional barriers. Particularly in the context of renewable energy integration, this fragmentation may lead to the simultaneous occurrence of renewable energy curtailment in resource-rich western regions and electricity shortages in load-intensive eastern areas, resulting in a dual waste of social resources.

### **5.4.2. Comparative analysis of power allocation optimization paths in 2023 and 2035**

Simulations were performed for the 2035 projections and the optimization results are shown in Table 6 and Fig. 7.

Table 6  
Optimization path of inter-provincial power allocation in 2035

| origin         | end point | Power transmission<br>( billions of kilowatt hours ) | Conveying distance ( KM ) |
|----------------|-----------|------------------------------------------------------|---------------------------|
| Inner Mongolia | Beijing   | 1527.26                                              | 403.58                    |
|                | Tianjin   | 190.92                                               | 512                       |
|                | Shandong  | 2923.46                                              | 661.43                    |
| Gansu          | Chongqing | 186.92                                               | 769.27                    |
|                | Qinghai   | 66.1                                                 | 261.54                    |
|                | Hunan     | 127.73                                               | 953.69                    |
|                | Hubei     | 473.74                                               | 1150.09                   |
| Guangxi        | Guangdong | 421.24                                               | 502.07                    |
| Jilin          | Liaoning  | 288.44                                               | 279.08                    |
| Guizhou        | Hunan     | 208.54                                               | 644.74                    |
| Jiangxi        | Hubei     | 143.96                                               | 258.32                    |
| Fujian         | Zhejiang  | 395.18                                               | 468                       |
| Sichuan        | Hunan     | 786.51                                               | 890.67                    |
| Xinjiang       | Hubei     | 1148.28                                              | 2764.62                   |
| Ningxia        | Hubei     | 165.31                                               | 1147.43                   |
|                | Shanghai  | 585.35                                               | 1607.12                   |
| Shaanxi        | Zhejiang  | 709.43                                               | 1143.85                   |
| Hebei          | Zhejiang  | 519.56                                               | 1014.02                   |
| Anhui          | Jiangsu   | 589.67                                               | 155.67                    |
| Shanxi         | Shanghai  | 997.75                                               | 1100.87                   |
|                | Jiangsu   | 819.96                                               | 860.87                    |
|                | Zhejiang  | 545.02                                               | 1096.08                   |

Simulation projections for 2035 indicate that, with the exception of Liaoning Province, the existing inter-provincial transmission network can largely meet the electricity demands of all provinces across the country. Liaoning's electricity supply gap shows a notable improvement trend, decreasing significantly from 73.019 billion kWh in 2030 to 28.844 billion kWh in 2035. This positive change is primarily attributed to the province's industrial transformation and upgrading, optimization of its energy mix, and the simultaneous expansion of renewable energy installed capacity alongside improvements in generation efficiency. Notably, its external power sources are set to undergo a significant shift from Inner Mongolia to Jilin. This adjustment is

driven not only by Jilin's relatively abundant power supply but also by the lower transmission costs between the two provinces, better complementarity in energy structures, and the synergistic advantages of grid interconnection. Progress in Jilin's new energy and grid infrastructure development further lays a solid foundation for providing stable and efficient power support to Liaoning in the future. This optimization of power flow directions holds positive implications for enhancing regional energy security and promoting efficient allocation of power resources.

In terms of transmission network optimization, the newly added Shaanxi–Zhejiang UHV direct current corridor (based on the Baihetan–Zhejiang project) will significantly enhance the transmission capacity between the resource-rich western regions and the load centers in the east. This pathway not only directly facilitates power transmission from Shaanxi to Zhejiang but also improves the flexibility and reliability of the regional grid. Simultaneously, it provides a new regulatory channel for power exports from provinces such as Hunan and Jiangxi, enhancing the overall synergistic efficiency of the Central China and East China power grids.

Guangdong Province's electricity supply and demand situation presents more complex dynamic characteristics. Its power supply gap follows a curve of initially rising and then declining during the projection period, reflecting the catch-up process between its own power supply capacity development and its substantial economic demand. Although by 2035, with the large-scale development of local clean energy sources such as offshore wind power, self-sufficiency capacity is expected to significantly improve, the inherent intermittency and instability of renewable energy determine that the province will continue to rely on inter-provincial power trading in the long term to ensure the stability and reliability of system operations.

However, the key bottlenecks currently constraining the optimal allocation of national power resources and the development of a unified market lie in the fragmentation and coordination challenges of the grid management systems. Taking the Southern Grid, to which Guangdong belongs, and the State Grid as examples, the two differ in terms of management systems, operational models, and technical standards. Such institutional barriers make it difficult for power resources to flow freely and be efficiently allocated on a national scale, particularly limiting the transmission of new energy from resource-rich northwestern regions to high-demand economic areas in the south.

## **6. Welfare evaluation of the optimal path of power allocation**

The preceding section assumes that the national unified electricity market has been fully established as the institutional context for the power supply–demand matching mechanism, with market clearing already achieved. The model outputs include clearing results, encompassing both the generation mix and inter-provincial trading volumes. Owing to the high degree of integration characteristic of the unified national electricity market, price signals converge in real time, resulting in significantly narrowed nodal price differentials across provinces. Consequently, different market participants face approximate marginal electricity prices within the same time period, thereby providing a uniform price benchmark for welfare evaluation. On this basis, this section constructs a three-dimensional quantitative analytical framework covering efficiency, equity, and environmental sustainability, aiming to systematically measure the impact of the power supply–demand matching mechanism on social welfare.

Given that, by 2035, the power supply–demand matching mechanism—across its spatio-temporal scales, policy parameters, and structural pathways—has comprehensively encompassed the evolutionary trajectory of the 2030 scenario, the welfare evaluation outcomes exhibit a high degree of convergence with those of 2030, with no statistically significant differences observed along the efficiency, equity, or environmental dimensions. Therefore, Part VI adopts 2035 as the representative period and conducts a systematic welfare effect assessment and discussion through a comparative analysis with the power supply–demand matching mechanism in 2023.

## 6.1 model framework

### 6.1.1 efficiency

This study adopts total social surplus as the core metric for welfare evaluation, for three primary reasons. First, total social surplus encompasses the sum of producer surplus and consumer surplus, thereby capturing the aggregate welfare improvements arising from market expansion, price reductions, and optimized resource allocation, while avoiding the underestimation of overall reform benefits that may result from fragmented indicator selection. Second, this metric can be decomposed across provincial, industrial, and agent-specific dimensions, providing a transparent illustration of the redistributive pathways of welfare among regions and interest groups, and thus offering a quantitative basis for assessing whether the unified national electricity market achieves both efficiency and equity objectives. Third, the increment in total social surplus primarily stems from the equalization of marginal costs across a broader geographical scope—namely, the minimization of inter-provincial transmission losses and reserve costs—which precisely aligns with the core objective of the power supply–demand matching mechanism articulated in the preceding chapter.

Under the assumption that consumer demand is fixed, the change in provincial consumer surplus resulting from the power supply–demand matching approach in 2035 is equivalent to the change in electricity consumption expenditure,

$$\Delta CS_i = -\Delta CE_i = -(CE_i^2 - CE_i^1) = -D_i \times (P_i^2 - P_i^1)$$

6.1

Let  $CE_i$  denote the electricity consumption expenditure of province,  $D_i$  represent the actual electricity demand of province (which is composed of provincial electricity generation and net electricity imports), and  $P_i$  denote the equilibrium electricity price in province. At this equilibrium, the price is entirely determined by the marginal cost of the marginal unit—specifically, when electricity is procured from multiple provinces, the equilibrium price corresponds to the highest marginal cost among those provinces.

Producer surplus is defined as the change in profits of the provincial power-generating firms, i.e., total revenue ( $TR$ ) minus total production cost ( $TC$ ). In turn, total revenue ( $TR$ ) is expressed as the sum of domestic sales revenue from intra-provincial electricity transactions ( $OM$ ) and revenue from inter-provincial electricity trade ( $IM$ ),

$$\begin{aligned} \Delta PS_i &= (TR_i^2 - TC_i^2) - (TR_i^1 - TC_i^1) \\ &= (OM_i^2 + IM_i^2 - TC_i^2) - (OM_i^1 + IM_i^1 - TC_i^1) \end{aligned}$$

6.2

The calculation methods for the variables in the above expressions are as follows,

$$OM_i = (Q_i - EI_{i,j}) \times P_i$$

6.3

$$IM_i = EI_{i,j} \times P_j$$

6.4

$$TC_i = Q_i \times MC_i$$

6.5

The total surplus is obtained by summing the producer surplus and the consumer surplus.

On this basis, to more precisely measure the marginal benefits of improvements in resource allocation and to assess the dynamic efficiency of the market integration process, this paper further computes the marginal welfare change rate. This indicator quantifies the welfare variation induced by an additional unit of inter-provincial electricity trade, thereby revealing the intensity of efficiency gains arising from the optimization of the electricity supply–demand matching mechanism.

The marginal rate of change in consumer surplus is defined as the ratio of the change in consumer surplus to the change in intra-provincial electricity consumption, and is expressed as follows:

$$\Delta CS_i = \frac{\Delta CS_i}{\Delta D_i}$$

6.6

The marginal rate of change in producer surplus is defined as the ratio of the change in producer surplus to the change in the total electricity generation of the given province, and is expressed as follows:

## 6.1.2 fairness

The unified national electricity market, through its uniform marginal electricity pricing mechanism, dismantles the price barriers that previously existed across provincial markets and enables the optimal allocation of generation resources over a broader geographical scope. This gives rise to structural adjustments in both producer surplus and consumer surplus, while simultaneously inducing inter-regional welfare transfers, which constitute the core content of the equity impact assessment. The equity-dimension analysis not only focuses on the aggregate changes in welfare redistribution, but also places greater emphasis on its structural and distributional characteristics. Specifically, by decomposing the changes in provincial consumer surplus and producer surplus, it becomes possible to identify which regions emerge as net beneficiaries and which may become net losers under the unified market, thereby providing a basis for evaluating the impact of the power supply–demand matching mechanism on inter-regional equity.

## 6.1.3 environment

The traditional approach to supply–demand matching, which relies solely on electricity quantity balance, accounts only for the geographical transfer of physical capacity shortfalls, while failing to consider the differences in carbon emissions arising from variations in generation mix, transmission pathways, and regulation modes. In the absence of quantitative comparisons along the environmental dimension, inter-provincial electricity transmission may devolve into a disguised transfer of high-carbon substitution for low-carbon alternatives—for instance, when receiving provinces over-rely on the marginal output of high-coal-consumption units in sending provinces in order to reduce their own local coal usage, potentially leading to an increase rather than a decrease in national aggregate carbon emissions. It is therefore imperative to quantify the carbon emission responsibilities associated with different matching approaches, so as to ensure that inter-provincial power matching achieves not only physical balance but also synergistic emission reductions at the national level in environmental terms, thereby providing directly applicable environmental boundaries and policy thresholds for the revision of laws and regulations governing the unified national electricity market.

Given that hydropower, wind power, and solar photovoltaic power generate approximately zero carbon emissions during their operational phase over the full life cycle, the environmental dimension focuses exclusively on the direct greenhouse gas effects induced by thermal power generation. Accordingly, carbon emissions are employed as the metric for assessing environmental impacts,

$$car_i = Q_{i,1} \times \delta \times \sigma$$

6.7

Among them,  $\delta$  represents the coal consumption of power supply, and  $\sigma$  represents the standard coal carbon emission coefficient.

## 6.2 Multidimensional impact assessment of optimal path

### 6.2.1 efficiency evaluation

The marginal welfare effect brought by the establishment of a unified national electricity market has brought more obvious and more complex regional differences. On the whole, the marginal welfare of consumers shows the characteristics of extremely high benefit in a few provinces, slightly damaged or less benefit in most provinces, while the marginal welfare of producers shows the structural imbalance of extremely high benefit in a few provinces and huge loss in hydropower provinces.

Table 7  
The change of marginal efficiency brought by the optimal path

| Province       | Marginal Change Rate of Consumer Surplus (%) | Marginal Change Rate of Producer Surplus (%) | Province  | Marginal Change Rate of Consumer Surplus (%) | Marginal Change Rate of Producer Surplus (%) |
|----------------|----------------------------------------------|----------------------------------------------|-----------|----------------------------------------------|----------------------------------------------|
| Beijing        | 53.02                                        | -18.33                                       | Henan     | 0.09                                         | -0.02                                        |
| Tianjin        | -11.80                                       | 10.92                                        | Hubei     | 6.72                                         | -61.83                                       |
| Hebei          | -4.67                                        | 9.40                                         | Hunan     | 2.56                                         | -1.76                                        |
| Shanxi         | -0.14                                        | -0.17                                        | Guangdong | -12.03                                       | 6.01                                         |
| Inner Mongolia | -0.66                                        | 6.84                                         | Guangxi   | 30.88                                        | -5.15                                        |
| Liaoning       | 5.01                                         | 3.21                                         | Chongqing | 9.55                                         | -3.79                                        |
| Jilin          | 1.04                                         | -0.11                                        | Sichuan   | 192.62                                       | -115.72                                      |
| Heilongjiang   | 4.27                                         | -0.88                                        | Guizhou   | 2.73                                         | 0.31                                         |
| Shanghai       | -12.86                                       | 49.60                                        | Yunnan    | 216.78                                       | -303.09                                      |
| Jiangsu        | -3.10                                        | 6.22                                         | Shaanxi   | -1.67                                        | 1.35                                         |
| Zhejiang       | -4.62                                        | 4.02                                         | Gansu     | 57.44                                        | -9.13                                        |
| Anhui          | 0.59                                         | -0.46                                        | Qinghai   | -27.32                                       | 133.26                                       |
| Fujian         | 0.84                                         | -0.31                                        | Ningxia   | 3.67                                         | -4.74                                        |
| Jiangxi        | -1.94                                        | 2.10                                         | Xinjiang  | -1.40                                        | 20.16                                        |
| Shandong       | 19.00                                        | -9.51                                        |           |                                              |                                              |

From the consumer perspective, electricity users in Yunnan, Sichuan, and Beijing exhibit the most significant welfare gains. Yunnan and Sichuan, endowed with ultra-low marginal cost hydropower resources, achieve full within-province absorption, which substantially reduces local electricity costs and generates considerable consumer welfare increments. Beijing, as a major load center, also realizes a marked increase in consumer surplus through inter-provincial imports of low-cost electricity. In contrast, the marginal consumer surplus change rates in Shanghai, Tianjin, Guangdong, Zhejiang, and Jiangsu are negative, indicating that consumers in these regions face rising marginal electricity costs.

From the producer perspective, the marginal producer surplus change rates in Qinghai, Shanghai, Xinjiang, Inner Mongolia, and Jiangsu are positive, suggesting that power generation enterprises in these regions have achieved notable marginal revenue growth within the market. Among these, Qinghai benefits from the high marginal value derived from inter-provincial exports of its low-cost hydropower and wind-solar resources; Shanghai likely relies on efficient thermal power units to capture high electricity prices during periods of supply scarcity; and Inner Mongolia and Xinjiang, as northern energy bases, obtain considerable marginal returns through inter-provincial transactions involving low-cost wind, solar, and coal-fired power resources. However, the marginal producer surplus change rates in Yunnan, Sichuan, Hubei, and other provinces are predominantly

negative. In Yunnan and Sichuan, which are major hydropower-producing provinces, consumers reap substantial marginal welfare gains while the generation side bears severe marginal revenue losses, indicating that market integration transfers a significant portion of resource rents from producers to consumers.

In terms of inter-provincial welfare distribution equity, consumers in Yunnan, Sichuan, Beijing, and Gansu obtain high marginal welfare gains, whereas power generators in Qinghai, Shanghai, Xinjiang, and Inner Mongolia benefit considerably from market expansion. At the same time, however, producers in Yunnan, Sichuan, and Hubei, along with consumers in Qinghai, Shanghai, Tianjin, and Guangdong, constitute distinctly disadvantaged groups. This bidirectional divergence suggests that the current matching mechanism, while pursuing overall efficiency improvements, fails to effectively balance marginal welfare distribution among all parties. In particular, producers in major hydropower provinces bear sustained marginal losses, while consumers in certain load centers also face upward cost pressures.

The marginal analysis demonstrates that market integration simultaneously generates aggregate efficiency gains and induces substantial marginal welfare redistribution effects. A matching mechanism driven solely by economic cost minimization may impose disproportionate marginal losses on certain provinces or stakeholders, thereby posing threats to the long-term sustainability and social equity of the market. Consequently, future policy design should not focus exclusively on aggregate welfare, but should place greater emphasis on the fairness and inclusiveness of marginal distribution.

## **6.2.2 fair evaluation**

By 2035, through the implementation of more optimized inter-provincial power supply–demand matching, the resource allocation improvements brought about by the construction of the unified national electricity market have become markedly evident. National total social surplus increases by RMB 50.43 billion, indicating that the power supply–demand matching mechanism facilitates the optimal allocation of electricity resources across a broader geographical scope, thereby enhancing overall economic efficiency.

In terms of surplus changes, consumer surplus increases by RMB 94.29 billion, while producer surplus decreases by RMB 43.86 billion. This pattern—where consumers as a whole gain while producers as a whole lose—is consistent with theoretical expectations: intensified competition on the generation side drives down on-grid electricity prices, and the resulting cost reductions are primarily passed on to electricity users.

From an equity perspective, the welfare changes in 2035 reveal that efficiency gains are accompanied by significant inter-provincial welfare redistribution. This indicates that the process is not a Pareto improvement, but rather a substantial reorganization of interest patterns, which poses a serious challenge to market equity.

Table 8  
Welfare changes brought by the optimal path

| Province       | Consumer Surplus | Producer Surplus | Total Social Surplus | Province  | Consumer Surplus | Producer Surplus | Total Social Surplus |
|----------------|------------------|------------------|----------------------|-----------|------------------|------------------|----------------------|
| Beijing        | 41.54            | -2.92            | 38.62                | Henan     | 0.23             | -0.09            | 0.14                 |
| Tianjin        | -6.29            | 6.39             | 0.10                 | Hubei     | 15.94            | -8.36            | 7.58                 |
| Hebei          | -12.78           | 49.99            | 37.21                | Hunan     | 3.99             | -1.78            | 2.21                 |
| Shanxi         | -0.23            | -1.21            | -1.44                | Guangdong | -79.07           | 47.70            | -31.36               |
| Inner Mongolia | -2.47            | 82.17            | 79.70                | Guangxi   | 59.11            | -16.13           | 42.98                |
| Liaoning       | 6.85             | 4.95             | 11.80                | Chongqing | 11.61            | -5.41            | 6.20                 |
| Jilin          | 0.49             | -0.19            | 0.31                 | Sichuan   | 430.61           | -242.63          | 187.98               |
| Heilongjiang   | 2.58             | -1.09            | 1.50                 | Guizhou   | 3.60             | 0.36             | 3.96                 |
| Shanghai       | -11.41           | 9.82             | -1.59                | Yunnan    | 406.03           | -512.79          | -106.77              |
| Jiangsu        | -13.37           | 28.84            | 15.47                | Shaanxi   | -3.81            | 5.29             | 1.47                 |
| Zhejiang       | -22.02           | 17.84            | -4.18                | Gansu     | 49.47            | -23.09           | 26.37                |
| Anhui          | 1.75             | -2.14            | -0.39                | Qinghai   | -13.54           | 76.44            | 62.90                |
| Fujian         | 2.08             | -0.92            | 1.16                 | Ningxia   | 2.86             | -13.68           | -10.82               |
| Jiangxi        | -3.49            | 5.46             | 1.97                 | Xinjiang  | -2.23            | 91.94            | 89.71                |
| Shandong       | 74.17            | -32.83           | 41.33                |           |                  |                  |                      |

First, welfare changes exhibit strong dependence on resource endowments and market positions, resulting in considerable disparities in gains and losses across provinces. In provinces rich in hydropower resources, such as Sichuan and Yunnan, intra-provincial welfare distribution displays a pattern of consumer gains and producer losses, yet the net total social surplus trajectories are diametrically opposed. In Sichuan, consumer welfare gains are sufficient to offset producer losses, yielding a substantial increase in provincial net welfare. In contrast, Yunnan experiences a sharp decline in producer surplus that cannot be compensated by consumer welfare gains, leading to a severe net welfare loss. This divergence may stem from differences in inter-provincial power export contract structures, local absorption capacities, and contributions to and cost allocation of system balancing. It indicates that even among major power-exporting provinces under the West-to-East power transmission framework, subtle variations in initial conditions and market design can yield markedly divergent equity outcomes under market mechanisms.

Second, the equity positions of traditional energy bases and emerging load centers have reversed, reflecting a regional mismatch in transition costs. The northwestern energy bases, represented by Xinjiang, Inner Mongolia, and Qinghai, achieve substantial increases in producer surplus through low-cost wind, solar, and coal-fired resources, emerging as primary beneficiaries of the market and demonstrating market recognition of the value of resource exports. However, the eastern coastal economic provinces, which serve as major power-receiving

regions and bear primary responsibility for system balancing—including Guangdong, Zhejiang, Shanghai, and Jiangsu—experience declining or only modestly increasing total social surplus.

Third, the pricing mechanism embedded in market design profoundly influences equity distribution outcomes. In the 2035 simulation scenario, the substantial welfare changes observed in certain provinces—such as the severe producer losses in Yunnan and the enormous consumer gains in Sichuan—suggest that these provinces may have adopted relatively aggressive market clearing mechanisms that amplify the redistributive effects of price signals on resource rents. The introduction or adjustment of price ceilings and floors could effectively moderate such extreme transfers, protecting specific provinces or stakeholders from excessive shocks, and thereby achieving a better balance between efficiency and equity, as well as between incentives and stability. Furthermore, the significant consumer surplus increases in receiving provinces such as Shandong and Beijing, alongside the substantial producer gains in Hebei—which serves as a critical transmission corridor and potentially a regulatory hub—demonstrate the win-win potential of optimized allocation across specific regions. However, such beneficial outcomes have not been universally extended to all receiving provinces.

## 6.2.3 green assessment

First, while optimizing resource allocation, changes in the power supply–demand matching mechanism may induce spatial transfer and concentration of carbon emission responsibilities, thereby exacerbating regional environmental inequity. Simulation results indicate that major energy-exporting provinces—such as Xinjiang, Inner Mongolia, and Hebei—experience substantial increases in producer surplus, yet simultaneously face significant rises in carbon emissions, as they assume more critical roles in meeting broader regional electricity demand. This implies that these regions bear heavier environmental costs alongside economic gains, creating a predicament in which economic benefits and environmental burdens escalate in tandem. For ecologically fragile areas such as Xinjiang and Inner Mongolia in particular, additional emission pressures may exceed local environmental carrying capacity. Meanwhile, load-center provinces and municipalities—including Shanghai, Jiangsu, Zhejiang, and Guangdong—exhibit limited or even negative total social surplus growth. In the absence of adequate economic compensation, these regions may reduce imports of clean electricity and increase local thermal power output, potentially leading to rising rather than declining carbon emissions. This reveals a critical contradiction: when the market mechanism pursues nationwide cost minimization in electricity supply without internalizing carbon costs, environmental objectives may be sacrificed in favor of economic efficiency.

Second, major clean-energy provinces, while providing positive environmental externalities, face a misalignment between economic welfare and environmental benefits, which undermines the incentive for green power supply. Sichuan, as a major hydropower province, achieves substantial gains in consumer welfare and overall provincial welfare, primarily due to the full within-province absorption of low-cost hydropower that displaces high-cost, high-emission thermal generation. However, from a national perspective, a reduction in Sichuan's hydropower exports implies a corresponding decrease in its contribution to carbon emission reductions in eastern provinces. This indicates that, in the absence of a robust mechanism for valorizing green attributes, the positive environmental externalities of clean energy cannot be fully translated into economic incentives, resulting in insufficient impetus for inter-provincial optimal allocation. Green resources tend to be utilized locally, which is detrimental to the achievement of nationwide emission reduction targets.

Table 9  
The carbon emission change rate of power generation in each province

| Province          | 2023<br>Carbon<br>Emissions | 2035<br>Carbon<br>Emissions | Change<br>Rate | Province  | 2023<br>Carbon<br>Emissions | 2035<br>Carbon<br>Emissions | Change<br>Rate |
|-------------------|-----------------------------|-----------------------------|----------------|-----------|-----------------------------|-----------------------------|----------------|
| Beijing           | 8,556.78                    | 6,912.53                    | -23.79%        | Henan     | 49,612.74                   | 71,161.78                   | 30.28%         |
| Tianjin           | 14,973.11                   | 18,291.96                   | 18.14%         | Hubei     | 30,069.09                   | 23,621.77                   | -27.29%        |
| Hebei             | 52,812.34                   | 84,956.82                   | 37.84%         | Hunan     | 19,303.89                   | 22,895.13                   | 15.69%         |
| Shanxi            | 71,905.78                   | 120,538.59                  | 40.35%         | Guangdong | 92,725.40                   | 117,153.20                  | 20.85%         |
| Inner<br>Mongolia | 116,663.19                  | 149,759.61                  | 22.10%         | Guangxi   | 22,933.92                   | 30,508.37                   | 24.83%         |
| Liaoning          | 26,640.50                   | 28,087.92                   | 5.15%          | Chongqing | 15,718.44                   | 18,678.85                   | 15.85%         |
| Jilin             | 13,822.85                   | 21,052.02                   | 34.34%         | Sichuan   | 13,725.30                   | 8,942.07                    | -53.49%        |
| Heilongjiang      | 17,524.08                   | 23,088.40                   | 24.10%         | Guizhou   | 27,107.31                   | 25,740.90                   | -5.31%         |
| Shanghai          | 18,077.59                   | 15,138.83                   | -19.41%        | Yunnan    | 7,564.04                    | 4,199.98                    | -80.10%        |
| Jiangsu           | 94,151.99                   | 120,908.80                  | 22.13%         | Shaanxi   | 48,878.66                   | 86,353.80                   | 43.40%         |
| Zhejiang          | 60,250.59                   | 92,306.93                   | 34.73%         | Gansu     | 20,178.29                   | 30,919.23                   | 34.74%         |
| Anhui             | 58,051.76                   | 79,574.41                   | 27.05%         | Qinghai   | 2,471.90                    | 2,172.30                    | -13.79%        |
| Fujian            | 30,995.95                   | 36,265.87                   | 14.53%         | Ningxia   | 34,090.35                   | 59,700.86                   | 42.90%         |
| Jiangxi           | 25,412.68                   | 40,861.28                   | 37.81%         | Xinjiang  | 74,061.65                   | 71,074.96                   | -4.20%         |
| Shandong          | 95,849.30                   | 91,380.47                   | -4.89%         |           |                             |                             |                |

Furthermore, the lack of policy coordination on environmental issues may distort market outcomes and amplify the negative linkages between welfare and environmental impacts. On the one hand, major hydropower-producing provinces such as Yunnan experience severe losses in producer surplus, which substantially undermines their capacity to obtain reasonable returns from supplying clean electricity and may, in the long run, diminish their incentives for hydropower maintenance and new energy investment. On the other hand, although provinces and municipalities such as Shandong and Beijing achieve improvements in consumer welfare and reductions in carbon emissions, such reductions are realized, to a certain extent, through the transfer of emission pressures to sending provinces such as Shanxi and Inner Mongolia, rather than through an optimal reduction in national aggregate emissions.

## 7. The conclusion and revelation

### 7.1 Conclusions

This paper constructs an "analysis–forecasting–matching–evaluation" framework to systematically assess the impacts of power supply–demand matching mechanisms under different temporal scenarios within the unified

national electricity market. The main conclusions are as follows:

First, the national power supply–demand landscape is undergoing a profound structural transformation, characterized by intensifying geographical decoupling between supply and demand and accelerating role differentiation among provinces. On the demand side, growth momentum exhibits regional divergence: eastern coastal provinces stabilize, while central and western provinces emerge as new growth drivers. On the supply side, northern energy bases (Inner Mongolia, Shanxi, Xinjiang) will achieve surpluses reaching hundreds of billions of kWh by 2035, reinforcing their core export status; southwestern hydropower provinces (Yunnan, Sichuan) steadily increase supply capacity. In contrast, major load centers (Beijing, Shanghai, Jiangsu, Zhejiang, Guangdong) face persistent and widening deficits with rising external dependence. This evolution creates extreme inter-provincial imbalances, with surpluses and deficits coexisting at unprecedented scales. The role transition of provinces such as Hebei and Hubei from receiving to sending ends further complicates the national power flow pattern. Future planning must adapt to these large-scale, long-distance, and dynamic resource allocation demands.

Second, national power balance will rely heavily on a UHV inter-provincial transmission system, forming a stable "north-to-south and west-to-east" backbone pattern. Northern energy bases will serve as primary sources to fill deficits in eastern and central load provinces, underscoring the critical importance of UHV infrastructure. Transmission pathways are dynamically optimized—Liaoning's supply source shifts from Inner Mongolia to Jilin, while Hubei emerges as a multi-directional power hub. Two major obstacles constrain optimal allocation: institutional barriers between China Southern Power Grid and State Grid (exemplified by Guangdong's inability to absorb northern surplus power), and weak physical interconnections. Both institutional and physical impediments must be addressed to establish a unified national grid.

Third, the 2035 matching pathway significantly improves economic efficiency but poses equity and environmental challenges. Total social surplus increases by RMB 91.541 billion, with consumer surplus rising by RMB 145.973 billion and producer surplus declining by RMB 54.432 billion. Inter-provincial redistribution shows marked disparities: Sichuan, Xinjiang, and Inner Mongolia gain substantially, while Guangdong, Zhejiang, Shanghai, and Jiangsu experience losses. Price policy tools are critical for stabilizing expectations and preventing extreme outcomes. Environmentally, the pathway induces spatial carbon transfer—exporting provinces bear heavy emission pressures, while some eastern provinces increase local emissions due to reduced clean imports. Sichuan's environmental contribution declines without adequate market incentives. Without coordination with carbon markets, economic dispatch alone may offset provincial mitigation efforts and exacerbate regional environmental inequity. Moreover, rising external dependence in load centers and expanding outputs from energy bases demand unprecedented transmission capacity and institutional frameworks for equitable cost and risk allocation.

Several limitations of this study should be acknowledged. First, the inter-provincial transmission model simplifies the physical power network by assuming unconstrained UHV transmission capacity and using straight-line geographical distances, without explicitly incorporating actual line capacities, transmission losses, or intra-provincial network constraints. Second, the forecasting framework is based primarily on historical provincial data and scenario-based assumptions, and therefore cannot fully capture unexpected technological, policy, or market changes. Third, the welfare analysis focuses on the major economic and environmental effects of inter-provincial power matching, while some factors, such as grid-security constraints, short-term

market fluctuations, and heterogeneous behavioral responses of market participants, are not explicitly modeled. Future research could incorporate detailed grid topology, stochastic scenarios, and more comprehensive market mechanisms to improve the practical applicability of the framework.

## 7.2 Policy Recommendations

First Strengthen transmission infrastructure and local renewable development in Liaoning and Guangdong. Liaoning should accelerate UHV lines to Jilin, develop wind/solar with storage integration, and diversify supply through regional cooperation. Guangdong should improve offshore wind-grid integration and reduce transmission dependence, while enhancing coordination between China Southern Power Grid and State Grid to break regional barriers. Both coastal provinces should advance wind power with smart grid and flexible DC technologies to improve renewable integration and self-sufficiency.

Second Remove institutional barriers between China Southern Power Grid and State Grid. Establish unified market rules and technical standards, strengthen inter-grid coordination through joint dispatch, accelerate UHV backbone lines connecting both grids, and deepen electricity system reform with market competition mechanisms to promote a unified national market.

Third Establish a risk mitigation system to prevent generation centralization from creating security vulnerabilities. As low-cost resources concentrate in exporting regions, receiving provinces face heightened external supply ratios and cascade risks. Strengthen medium- and long-term contract enforcement with credit-linked eligibility and default replacement mechanisms. Develop capacity and ancillary service markets to enable receiving provinces to retain local reserves. Accelerate UHV ring networks, flexible DC, and storage deployment to enhance redundancy and fault recovery. Use spot prices to guide normal operations, with government-backed dispatch under emergencies and compensation mechanisms to ensure backstop entities receive reasonable returns, thereby safeguarding grid stability amid rising external dependence.

## Declarations

## Author Contribution

L.Q. and D.Y drafted the manuscript and revised it critically for important intellectual content; L.W. and X.C. performed the computational analyses and made substantive revisions; all authors reviewed and approved the final version of the manuscript.

## Data Availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

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## Figures

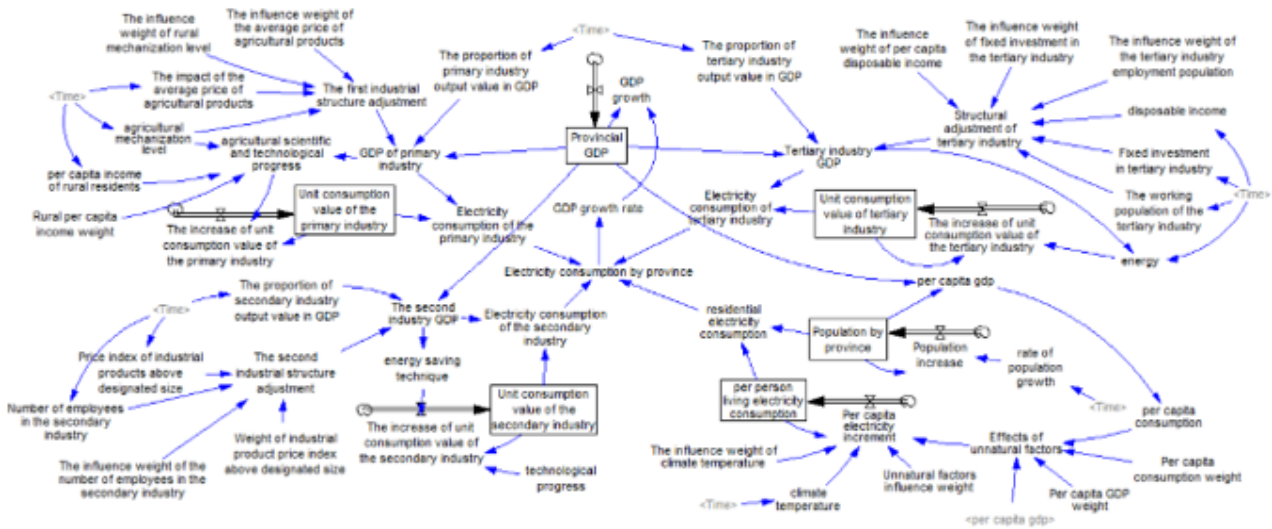


Figure 1

Prediction model of power demand system

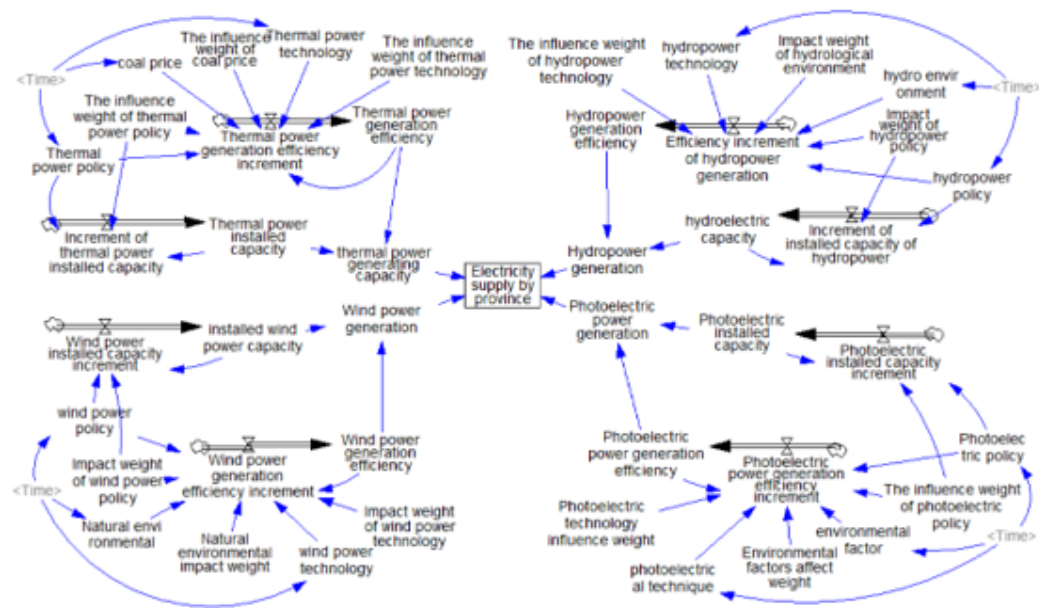


Figure 2

Prediction model of power supply system

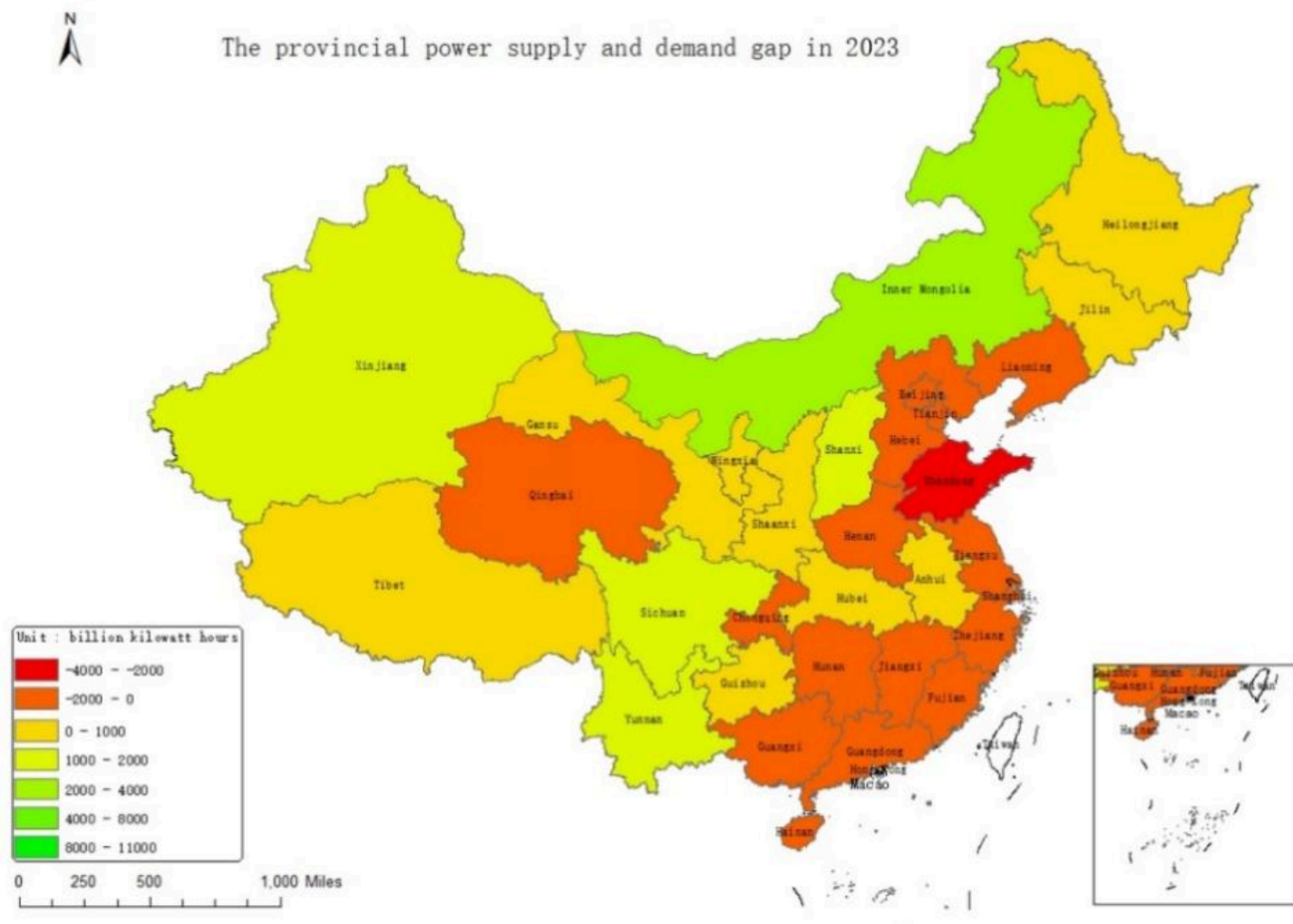


**Figure 3**

Power supply and demand gap in each province



**Figure 4**

Provincial power supply and demand gap in 2030

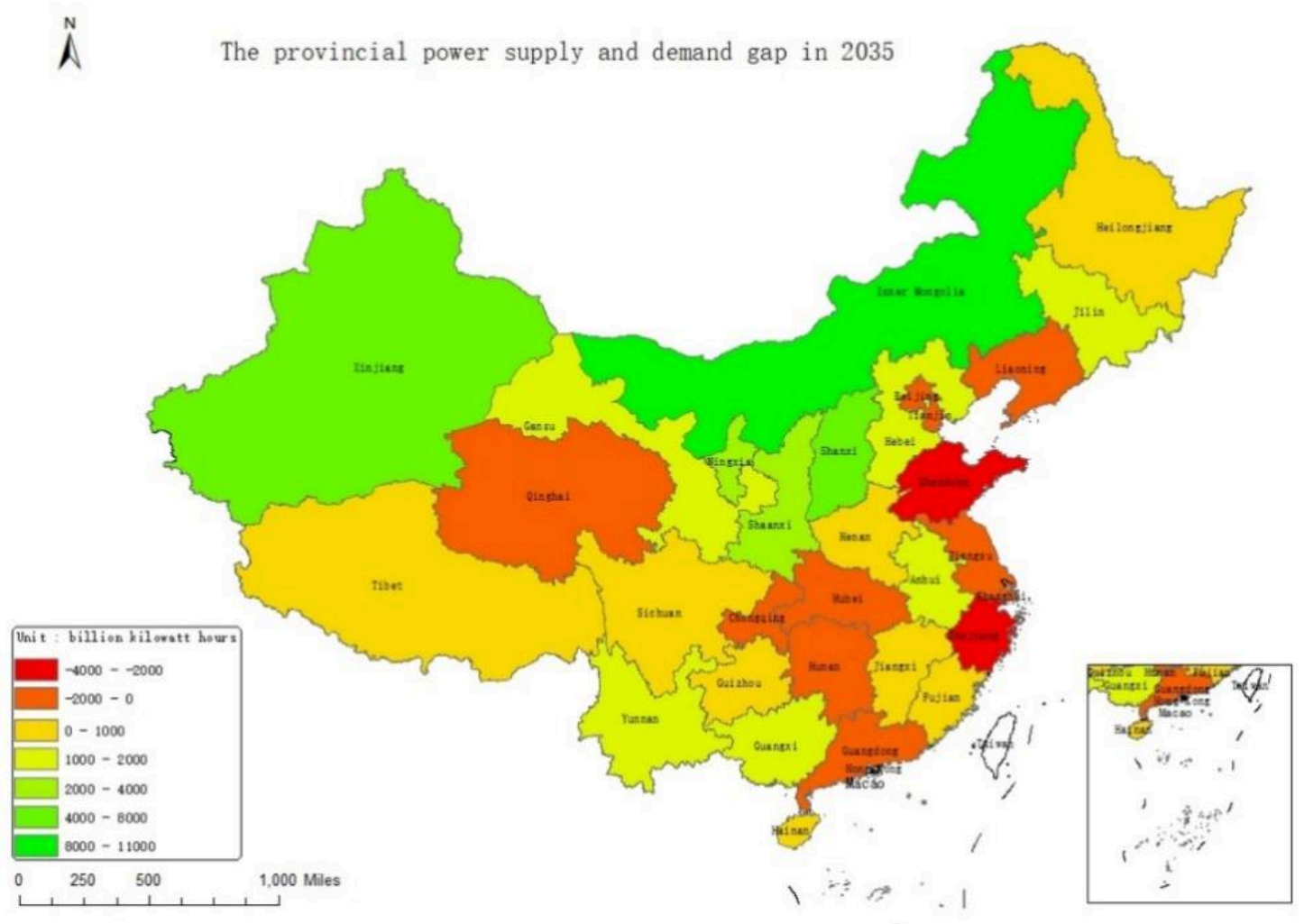


**Figure 5**

Provincial power supply and demand gap in 2035

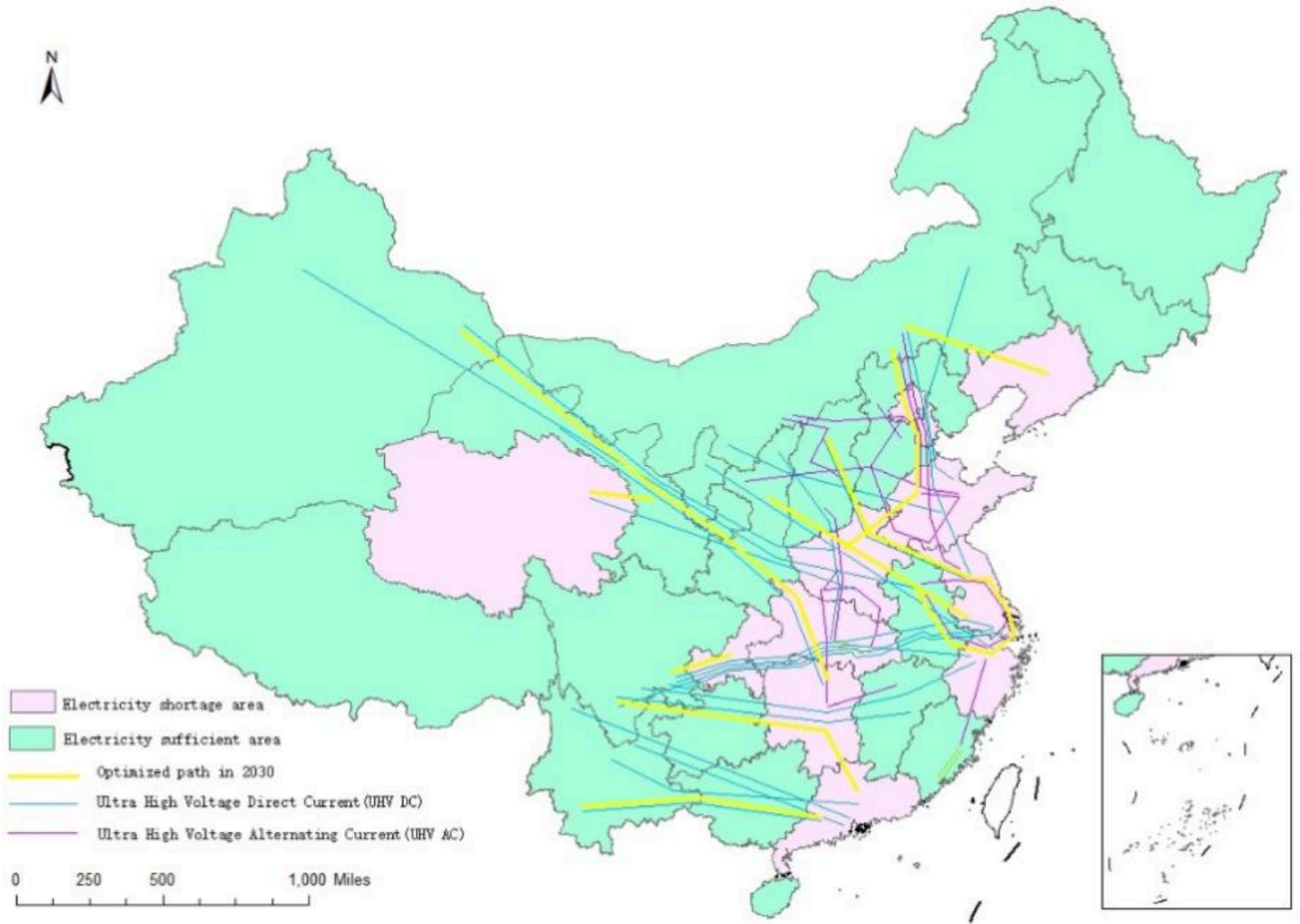


**Figure 6**

Comparison of inter-provincial power allocation paths in 2023 and 2030



**Figure 7**

Comparison of inter-provincial power allocation paths in 2023 and 2035

## Supplementary Files

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