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Layout optimization of China's power transmission lines for renewable power integration considering flexible resources and grid stability

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A B S T R A C T

To eliminate power transmission bottleneck and improve cross-regional consumption of renewable power in China, a multi-objective optimization model for transmission line layout is established by considering grid stability and the flexible resource. The optimal line route, technology selection among eleven types of direct current (DC) and alternating current (AC) transmission technologies, transmission capacity, and completion time of inter-regional transmission lines among the six major regions are determined. The results show that power transmission capacity of Northwest-to-East and North-to-Central will increase by 265% and 160%, respectively, in 2039, compared with that in 2018. DC of 800 kV (10 GW) will become the main transmission technology from 2033. The peak period of the line-construction completion will be 2036–2039. The central and eastern regions have registered the fastest growth in the proportion of wind and solar power-installed capacity in China. The proportion of wind and solar power-installed capacity in these areas in 2039 will be 4–6 times that in 2018. Increasing energy storage and improving demand-side response can increase the on-grid renewable power by 1.7% and 2.6%, respectively; however, it will lead to a reduction of 2–6 and 7–9 newly-built lines, respectively.

1. Introduction

The electrification of energy end-use consumption is one of the important measures to improve energy efficiency and reduce carbon emissions. However, there is inconsistency between the power generation area and the power load area. Electricity transmission is an efficient means to solve this inconsistency, particularly in China. China's energy resources and electricity load show reverse regional distribution, along with serious imbalance of energy supply and demand between the eastern and western regions [22]. However, the current cross-region transmission capacity does not meet the requirements of power consumption in the eastern regions, particularly for renewable power transmission. The wind power curtailment in northeast and northwest China and the hydropower curtailment in Southwest China have been severe in the recent years. The insufficient grid infrastructure and limited number of inter-provincial transmission lines have been the most important reasons for the curtailment [13,26]. Moreover, the development of renewable electricity and the realization of electricity decarbonization are critical for China to accomplish its ambitious "dual-carbon" goals, that is, to achieve the peak of carbon emissions by 2030 and carbon-neutrality before 2060. Therefore, improving the capacity of inter-regional power transmission is one of the important measures to strengthen the penetration of renewable power and facilitate China's electricity decarbonization [6]. However, planning of the transmission lines is fundamental for improving the transmission capacity.

Particularly under the feasible, reliable, and economic operation conditions of the power system, a power transmission line planning is required to obtain the minimum cost selection of capacity, location, and timing for new transmission lines to be installed in the power systems among regions [14]. The early linear programming model for transmission expansion planning (TEP) only considered the expansion of transmission capacity, and power generation capacity was predetermined as an exogenous parameter [21,45]. Indeed, power source layout and grid layout are inseparable. Power source distribution directly affects the determination of the grid structure, while the direction and location of transmission lines in turn affect the location and capacity of power generation installations. In addition, separate transmission expansion planning can cause a mismatch between power generation and transmission capacity, thereby increasing the transmission capacity expansion costs [47]. Therefore, to obtain a safe, reliable, and economic operation of power system, many optimization models focus on integrated generation and transmission expansion planning. For example, Wang et al. [55] determined the inter-regional

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Nomenclature

Sets

K Set of regions
I Set of provinces
L Set of power transmission technology
J Set of power generation sources
S Set of renewable power generation sources
T Set of years

Indices

k Region index.$k = 1, 2, \ldots, 6$ represents North, Northeast, East, Central, South, and Northwest of China
i Province index.$i = 1, 2, \ldots, 31$ represent 31 provinces in China
l Power transmission technology index. $l = 1, 2, \cdots, 11$ represents ±500 kv (3GW), ±500 kv (3.2GW), ±660 kv (4GW), ±800 kv (5GW), ±800 kv (7.2GW), ±800 kv (8GW), ±800 kv (10GW), ±1000 kv (9GW), ±1100 kv (12GW), 500 kv (0.3GW), and 1000 kv (5GW)
j Power generation source index. $j = 1, 2, \cdots, 6$ represent thermal power, nuclear power, hydropower, wind power, solar PV power, and biomass power.
t Year index. Planning period is 2019-2039 with sub-period of three years.

Parameters

$a_{j,t}$ Levelized cost of electricity(LCOE) of power generation source j in year t(yuan/kwh)
$c_{l,t}$ Fixed cost of transmission technology l in year t (yuan)
d_l^{min} Maximum economical transmission distance of transmission technology l(km)
d_l^{max} Minimum economical transmission distance of transmission technology l(km)
$d_{k,k'}$ Distance between region k and region k'(km)
DC_t Cost of demand response in year t (yuan)
EC_t Environmental cost in year t (yuan)
$e_{l,t}$ Variable cost of transmission technology l in year t (yuan/km/kw)
ec_t Carbon price in year t (yuan/g CO_2-eq)
$ed_{k,i,t}$ Power demand of province i in region k in year t (kwh)
$q_{k,i}$ Maximum growth rate of thermal cumulative installed capacity of province i in region k (%)
ex_j Non-carbon external cost of power generation source j (yuan/kwh)
f_t Unit cost of energy storage in year t(yuan/kwh)
GC_t Total generation cost in year t(yuan)
HD Annual operation hour of demand response (h)
HT Annual operation hour of transmission line (h)
HS Annual operation hour of energy storage (h)
$h_{k,i,j}$ Annual average operation hour of power generation source j in province i in region k in year t (h)
IC_t Investment cost of transmission line construction in year t (yuan)
Lr_j Learning rate of LCOE of power generation source j (%)
Lr_l Learning rate of investment cost of transmission technology l (%)
MC_t Operation and maintenance cost of power transmission in year t (yuan)
nr Risk-free interest rate (%)
r Discount rate (%)
SC_t Energy storage cost in year t(yuan)
TR Lifetime of transmission line (year)
$U_{k,i,j,t}$ Technology developable potential of power generation source j in province i in region k in year t (kw)
v_l Rated transmission capacity of transmission technology l (kw)
$w_{k',k}$ Expectation value of power outage between region k and region k' (%)
$y_{k,i,j,t}$ Decommissioning capacity of power generation source j in province i in region k in year t (kw)
α_l Line loss rate of transmission technology l (%)
β Minimum utilization rate of transmission line (%)
θ Maximum share of power loss caused by power outages in total electricity demand (%)
η Carbon emission factor of thermal power (g CO_2-eq /kwh)
γ Free carbon emission quota of thermal power in power sector (g CO_2-eq /kwh)
λ Operation and maintenance ratio of transmission line (%)
κ Decommissioning rate of thermal power capacity (%)
τ Capacity cost of demand response (yuan/kw)
δ Electricity cost of demand response (yuan/kwh)
σ Reserve factor of peak load (%)
ϕ Loss rate of energy storage charging and discharging (%)
φ_L Minimum share of energy storage capacity in total capacity of wind and solar power (%)
φ_H Maximum share of energy storage capacity in total capacity of wind and solar power (%)
ε_L Minimum share of capacity in regional peak load (%)
ε_H Maximum share of capacity in regional peak load (%)
$\partial_{k,i,j}$ Auxiliary power ratio of power plant j in province i in region k(%)
ρ_k Share of imported power in total power demand in region k (%)
μ_t Minimum share of non-fossil energy generation in total power generation in year t(%)
$pl_{k,t}$ Peak load of region k in year t(kw)

Decision variables

$X_{k,i,j,t}$ New installed capacity of power generation source j in province i in region k in year t (kw)
$V_{k,k',l,t}$ New transmission capacity of technology l between region k and region k' in year t (kw)
$O_{k,t}$ Demand response capacity of region k in year t (kw)
$G_{k,i,t}$ Energy storage capacity of province i in region k in year t (kw)

Other variable

$M_{k,i,j,t}$ Cumulative installed capacity of power generation source j in province i in region k in year t (kw)
$PT_{k',k,l,t}$ Power transmission in transmission technology l between region k and region k' in year t (kwh)
$VT_{k',k,l,t}$ Power transmission capacity in transmission technology l between region k and region k' in year t (kw)
$Z_{i,j,k,t}$ Number of transmission lines in transmission technology l between region k and region k' in year t
$N_{k,k',l,t}$ Rated transmission capacity of transmission technology l between region k and region k' in year t (kw)

power transmission in 2030 under different emission control policy scenarios by minimizing the total cost of generation and inter-regional transmission for all the six Chinese regions across the entire planning horizon. Yi et al. [59] categorized the entire province of China into 12 highly detailed regions, considering coal transportation and pollutant control, and obtained the future optimum power generation mix, the capacity of inter-regional power transmission line, and the amount of inter-regional resource transportation. Similar studies have been conducted by Zhang et al. [67] and Wang et al. [57]. This type of optimization model requires the management of large sets of variables and parameters and constraints of diverse nature over different timescales. However, the models are usually single-objective, being the minimization of cost in the only one objective of the model. Furthermore, few studies considered the impact of renewable energy (RE) development on the layout and stability of the transmission grid. In the context of global response to climate change and reduction of carbon emissions, RE development has become an important direction for global energy development [60,62]. To improve RE power consumption, a high RE penetration should be considered to strengthen the construction of power grid and enhance the consumption capacity, rather than determining the scale of RE development based on the existing consumption ability [68]. Therefore, considering the maximization of the on-grid RE power as one of the objectives in the transmission line layout optimization is an important means to achieve clean substitution in the power sector.

To promote RE consumption, few studies have considered the RE integration in TEP and the uncertainty resulting from the integration of RE on the power generation side and at the grids. For instance, Sun et al. [49] proposed a framework for the TEP problem to generate load and wind power, while capturing inter-spatial dependencies between the loads and the output of the wind generation units in various locations. Mortaz and Valenzuela [33] solved the TEP problem through the assessment of the correlation effects among variable resources, installed capacities, and fluctuations and by modifying the harvesting locations on the network expansion plan. In the study conducted by Ramirez et al. [42], a dynamic, stochastic, adaptive, robust approach was proposed to solve long-term and short-term uncertainties caused by the renewable generation in integrated TEP and the generation expansion planning (GEP) problem. These studies have considered the uncertain output of RE on an hourly scale, and the finer time resolution mainly describes the variability in power generation; therefore, the main application scenarios are minor power systems or test systems. However, transmission line construction is generally time-consuming, particularly for inter-regional long-distance transmission lines. The uncertain output is highly detailed and cannot therefore significantly impact the optimal solution of TEP. Even if long-term uncertainty is considered, to reduce the complexity of the model and solution, the hourly output fluctuations are divided into seasons, and the representative days are chosen to reduce the solution scale [42]. It can be seen that the existing studies on the uncertainty of RE in TEP still focus on the output fluctuation on the power generation side, neglecting the impact of uncertain RE output on power transmission process, particularly during the assessment of the impact of time-varying changes on transmission grid in the medium and long-term planning.

Energy storage and demand response, as flexibility resources, can provide flexibility in demand and supply at different physical and temporal scales [44]. Energy storage refers to the entire process of converting electricity (when there is an excess of electricity) from the grid into another form and storing it in an energy storage equipment, and subsequently, converting it back into electricity to meet the load demand when the power supply is insufficient [25]. Demand response refers to changes in the normal consumption patterns owing to the consumers responding to changes in electricity price or financial incentives, thereby causing a reduction or shift in the power load over a certain period [12]. Both energy storage and demand response can make RE technologies dispatchable and can manage peak demand to mitigate the impact of RE integration on the power grid [44]. Several studies have demonstrated the positive role of energy storage and demand response in dealing with the uncertainty of RE output [40,16]. For example, Zhang et al. [65] incorporated demand response as load side resources into the proposed model. The model application in China's power sector indicates that the areas with a rich variable RE should pay more attention to the allocation of flexible dispatch resources. Liu et al. [25] developed a 31-node hourly-resolved techno-economic optimization model, demonstrating the necessity of energy storage in reducing system costs and balancing load demand. Li et al. [22] proposed a long-term multi-regional power system planning model to optimize generation capacity, power grids, and storage facilities in Southwest China. These studies consider the role of energy storage or demand response in balancing load fluctuations in long-term power system planning, from a macro perspective. However, the previous studies did not explore how energy storage and demand response can be integrated simultaneously to ensure a stable supply of electricity. In practice, there are interactions between the two flexibility options. For example, energy storage can contribute to demand response by increasing the amount of discharge to achieve load shedding during the response period. From the perspective of optimization results, these studies either determine the direction and amount of power transmission between regions [25] or expand capacity on the existing transmission channels [65], without considering the addition or deletion of inter-regional transmission channels. However, they have not been able to obtain the optimal layout of inter-regional transmission lines. Particularly, in the study conducted by Li et al. [22], it is presupposed that inter-regional power transmission only occurs between adjacent regions that further restricts the construction of long-distance power transmission lines and is clearly irrelevant. In particular, the inverse distribution and long distances between enriched areas of renewable resources, such as, wind power and solar photovoltaic (PV) power, and areas of high-power load in China, make it difficult to achieve a reasonable power transmission pattern when the power transmission is restricted between the adjacent regions.

In addition, the stability of power transmission, that is, the safety of transmission line operation is another important factor that affects transmission line layout planning. The core of power security is grid security, and an unreliable grid system may cause large-scale power outages and high economic and social costs [30]. Therefore, Das et al. [9] considered N-1 network security constraints and proposed an efficient four-stage solution methodology for multi-year dynamic alternating current TEP. Dini et al. [10] presented a security-constrained generation and transmission expansion planning for the 6-bus and 118-bus IEEE networks. These studies are based on the N-1 principle to measure the security of the power grid, that is, after any independent component (generator, transmission line, transformer, etc.) of the N components of the power system fails and is removed, it will not cause power failure owing to overload trip of the other lines; this also tests the model validity in the limited node system. However, in large-area power grids, the intensity and frequency of natural disasters and the extreme weather vary across different geographical positions, terrain features, and climate conditions, causing a difference in the amount of loss due to power failure in the process of power transmission. This potential safety hazard is an important reason that restricts the construction of inter-regional transmission lines. Existing studies either pay only slight attention to this safety factor or optimize the safety of small power systems from a micro perspective. Therefore, the safety considerations for the medium and long-term TEP in national-level power grids need to be studied further.

In addition, the existing TEP studies optimize the optimal transmission capacity between regions; however, such studies cannot provide the composition of different technology types and voltage levels in this total amount. Different power transmission technologies differ significantly in the transmission capacity and cost. It requires more detailed planning. Direct current transmission technology has a large transmission capacity and can be asynchronously connected to the grid. The cost of line construction is low; however, the construction cost of its converter station is high, and no other connection point can be set on the entire line [1]. On the contrary, although the construction cost of alternating current transmission technology lines is higher, the grid can be formed according to the actual needs of electricity by adding a connection point on the entire line arbitrarily, making the access, transmission, and consumption of electricity more flexible [48]. Different voltage levels have significant differences in economics. With the expansion of grid area, the transmission capacity and transmission distance of electric energy continue to increase, necessitating a higher grid voltage level. The unit cost of transmission capacity decreases with an increase in voltage grade. Therefore, it is important to consider the economic advantages and disadvantages of different transmission technology types and voltage levels when optimizing the transmission line layout. Few studies optimize transmission grid considering different voltage levels [59] and the guiding significance is enhanced. However, these studies only roughly divide the voltage levels into ultra-high voltage (UHV) and extra-high voltage (EHV). It is also impossible to obtain the construction number and capacity of lines with specific voltage levels under ultra-high voltage and extra-high voltage levels, providing limited decision-making information.

Therefore, addressing the shortcomings of the existing studies, a multi-objective optimization model is proposed in this study from the perspective of the macro national level to solve the problem of medium- and long-term power transmission line planning in China. Against the background of the existing studies, the main contributions of the present study are as follows:

a) The influence of multiple combinations of energy storage and demand response on the layout of transmission lines is considered. This study explores the impacts of multiple combinations on the grid during the large-scale integration of renewable power. Results of the present study can provide a more practical avenue for the scientific construction of transmission lines in the context of high renewable power.
b) The safety of transmission line is measured from a macro perspective. Based on the relationship between power outages and accident frequencies in accordance with the self-organized criticality theory, the present study describes the loss of power transmission caused by component failures, extreme weather, and natural disasters. This study overcomes the difficulty in modeling the safety factors of transmission network from the macro level and provides a more stable and safe construction scheme for the transmission line layout.
c) The differences in capital costs and economical transmission distance of 11 transmission technologies in power transmission lines are considered. The existing nine direct current and two alternating current transmission technologies with the voltage of ± 500 kV and above, are selected as alternatives. The time sequence, spatial layout, installed capacity, and technology selection of lines construction are optimized based on multiple objectives. This study compensates for the inadequacy of only focusing on the transmission capacity allocation without classification of transmission technologies in the existing literature, to provide a more detailed and accurate decision-making guidance for the development of transmission line construction scheme.

2. Methodology

2.1. Assumptions

The proposed inter-regional power transmission line layout optimization model is based on the following three assumptions:

a) The entire power grid is divided into six regions based on the areas covered by six power grid companies in China. Specific provinces are listed in Table A1 and the distance of between regions is shown in Table A2.
b) The average construction period of the cross-regional power transmission lines is set to three years, based on the lines that have been completed and put into operation in China.
c) The proposed model focuses on the construction of cross-regional power transmission lines; therefore, power transmission within the region is not considered.

2.2. Objectives

2.2.1. Maximization of on-grid renewable power

Renewable resource endowments and load centers exhibit a significant reverse distribution in China. As the only feasible carrier of large-scale renewable energy between regions, the UHV transmission grid is a fundamental solution to the unbalanced distribution of energy resources and power load [27]. Therefore, the construction of inter-regional power transmission lines aims to maximize the on-grid power of renewable energy, promote the consumption of renewable energy in resource-rich areas and achieve a clean energy consumption structure in the load areas. Maximizing on-grid renewable power by considering auxiliary power is set as the first objective function in the proposed model.

$$maxf_1 = \sum_{t\in T}\sum_{k\in K}\sum_{i\in k}\sum_{j\in S}(1-\partial_{k,i,j})M_{k,i,j,t}h_{k,i,j} \tag{1}$$

where $(1-\partial_{k,i,j})$ and $M_{k,i,j,t}h_{k,i,j}$ denote the proportion of electricity transmitted to the grid of the total power generation and total power generation of power source *j* in region *k* in province *i* in year *t*, respectively.

$M_{k,i,j,t}$ is the cumulative installed capacity, considering decommission generator units. Thermal power is retired at a fixed annual decommissioning rate (κ), and the other power sources determine the annual decommissioning amount based on its life cycle that is calculated as follows:

$$M_{k,i,j,t} = \begin{cases} M_{k,i,j,t-1}(1-\kappa)+X_{k,i,j,t}, j=1 \\ M_{k,i,j,t-1}+X_{k,i,j,t}-y_{k,i,j,t}, j=2,3,4,5,6 \end{cases}, \tag{2}$$

where $X_{k,i,j,t}$ is the decision variable in this article, representing the new built capacity of power source *j* in region *k* in province *i* in year *t*.

2.2.2. Minimization of total cost

Minimization of cost is the primary objective considered during investment activities. The proposed model determines the optimal power generation mix, transmission line layout, demand response capacity, and energy storage capacity. The total cost is composed of the power generation cost, investment cost and operation and maintenance (O&M) cost of transmission lines, demand response cost, energy storage cost, and environmental cost. The cost minimization is given by:

$$minf_2 = \sum_{t\in T}\left(GC_t+IC_t+MC_t+DC_t+SC_t + EC_t\right)/(1+nr)^{3t} \tag{3}$$

i) Power generation cost: The levelized cost of electricity (LCOE) of each power source is used to characterize all the costs per unit of electricity during its life cycle [41]. Combined with the amount of power generation, the total power generation cost is obtained considering the time value of capital cost and the depreciation of fixed assets, as follows.

$$GC_t = \sum_{k\in K}\sum_{i\in k}\sum_{j\in J}M_{k,i,j,t}h_{k,i,j,t}a_{j,t} \tag{4}$$

where $a_{j,t}$ denotes the LCOE of power source j in year t. Existing research shows that the development process of power generation technology conforms to the law of the learning curve, that is, as the technology matures, the related costs gradually decrease [18]. Therefore, the generation cost of each power generation technology is assumed to follow the learning curve shown in Eq. (5) to reflect the learning effect of technology development [59].

$$a_{j,t} = a_{j,t_0}\left(\sum_{k\in K}\sum_{i\in k}M_{k,i,j,t}/\sum_{k\in K}\sum_{i\in k}M_{k,i,j,t_0}\right)^{-b_j} \quad (5)$$

$$Lr_j = 1 - 2^{-b_j} \quad (6)$$

where Lr_j denotes the learning rate of LCOE of the power generation source j, and b_j denotes the progress rate.

ii) Investment cost and O&M cost of power transmission lines: The investment cost is divided into two parts: fixed investment cost caused by the construction of the converter station and variable investment cost related to the transmission distance and transmission capacity. The O&M cost includes the costs of line loss and labor charges during operation that is calculated according to the proportion λ of the total investment cost.

$$IC_t = \sum_{t'=t+1-T^{tr}}^{t}\sum_{k\in K}\sum_{k'\in K}\sum_{l\in L}\left[\left(c_{l,t} + e_{l,t}d_{k,k'}v_l\right)Z_{k,k',l,t}\right]\left[r(1+r)^{TR}/\left((1+r)^{TR} - 1\right)\right] \quad (7)$$

$$MC_t = \lambda\cdot IC_t \quad (8)$$

where $Z_{k,k',l,t}$ denotes the number of newly built lines between region k and k' with technology l in year t and is obtained by dividing the actual transmission capacity by the rated capacity, $Z_{k,k',l,t} = \lceil V_{k,k',l,t}/v_l\rceil$. $V_{k,k',l,t}$ denotes the actual transmission capacity between region k and k' with technology l in year t and is the decision variable.

The unit fixed investment cost and unit distance investment cost of the transmission line follow the law of learning curve that is similar to the investment cost of the power generation source [59].

$$c_{l,t} = c_{l,t_0}\left(\sum_{k\in K}\sum_{k'\in K}N_{k,k',l,t}/\sum_{k\in K}\sum_{k'\in K}N_{k,k',l,t_0}\right)^{-b_l} \quad (9)$$

$$e_{l,t} = e_{l,t_0}\left(\sum_{k\in K}\sum_{k'\in K}N_{k,k',l,t}/\sum_{k\in K}\sum_{k'\in K}N_{k,k',l,t_0}\right)^{-b_l} \quad (10)$$

$$N_{k,k',l,t} = N_{k,k',l,t-1} + v_l\cdot Z_{k,k',l,t} \quad (11)$$

$$Lr_l = 1 - 2^{-b_l} \quad (12)$$

where $N_{k,k',l,t}$ denotes the cumulative capacity of transmission technology l, and N_{k,k',l,t_0} denotes the cumulative capacity in the base year.

iii) Demand response cost: Demand response (DR) refers to achieving a balance between supply and demand by reducing or delaying the power load on the demand side. With the development of smart grid, DR is becoming an effective energy solution that can not only reduce the peak load of the power system, but also improve the regulation ability of the system and promote the integration of renewable energy [64]. Therefore, the model considers the implementation of DR, and the corresponding costs are as follows.

$$DC_t = \sum_{k\in K}O_{k,t}\tau + \sum_{k\in K}\delta\cdot O_{k,t}HD \quad (13)$$

where $O_{k,t}$ denotes the decision variable, demand response capacity in region k in year t. $O_{k,t}\tau$ denotes the capacity cost in region k in year t, and $\delta\cdot O_{k,t}HD$ is the electricity cost in region k in year t.

iv) Energy storage cost

The energy storage equipment can store energy when the grid load is low or output energy when the grid load is high; therefore, it can be used for peak shaving and valley filling to reduce grid fluctuations. It can effectively balance the volatility of renewable power to ensure power supply reliability and power system flexibility [22]. Therefore, the combination of energy storage technology and renewable energy power generation facilitates the realization of the large-scale application of renewable energy in the future. The corresponding costs are as follows.

$$SC_t = \sum_{k\in K}\sum_{i\in k}f_t\cdot G_{k,i,t}HS \quad (14)$$

where $\sum_{k\in K}\sum_{i\in k}f_t\cdot G_{k,i,t}HS$ denotes the total energy storage cost in year t.

v) Environmental cost

To comprehensively reflect the environmental cost of the power sector, both the carbon trade cost and the non-carbon external cost of each power source are considered.

$$EC_t = \sum_{k\in K}\sum_{i\in k}M_{k,i,j,t}h_{k,i,j,t}ex_j + \sum_{k\in K}\sum_{i\in k}\sum_{j=1}\left(M_{k,i,j,t}h_{k,i,j,t}\eta - M_{k,i,j,t-1}h_{k,i,j,t-1}\gamma\right)\cdot ec_t \quad (15)$$

where $\sum_{k\in K}\sum_{i\in k}M_{k,i,j,t}h_{k,i,j,t}ex_j$ denotes the non-carbon external cost in year t. It is an inherent attribute of power generation source [61]. This cost represents all kinds of losses to the environment caused by each power generation source except for carbon emissions, including the amount of pollution, health effects, or other factors that are created by all forms of power systems. $\sum_{k\in K}\sum_{i\in k}\sum_{j=1}\left(M_{k,i,j,t}h_{k,i,j,t}\eta - M_{k,i,j,t-1}h_{k,i,j,t-1}\gamma\right)\cdot ec_t$ denotes the carbon trade cost that the power sector has to pay for exceeding the free carbon allowance in year t.The quota factor is the product of the power generation ratio, power supply reference value, and unit cooling mode correction coefficient [34].

2.3. Constraints

2.3.1. Power supply and demand constraints

Providing a safe and stable power supply and effectively guaranteeing power demand is an important goal of the construction of power transmission lines [10]. In the power transmission lines layout optimization, the available electricity for consumption in each region cannot be less than the required electricity. The actual required electricity is the power demand, $\sum_{i\in k}ed_{k,i,t}$, together with the energy storage loss, $\sum_{i\in k}G_{k,i,t}HS\cdot(1-\phi)$, from which the reduced electricity caused by the demand response, $O_{k,t}HD$, is subtracted. The available electricity for consumption is obtained by summing the power generated, $\sum_{i\in k}\sum_{j\in J}M_{k,i,j,t}h_{k,i,j,t}$, and the electricity transmitted-in $\sum_{k'\in K}\sum_{l\in L}PT_{k',k,l,t}(1-w_{k',k})(1-\alpha_l d_{k,k'})$, where the loss of power outage accident and transmission line loss are taken into account, and finally, the electricity transmitted-out,$\sum_{k'\in K}\sum_{l\in L}PT_{k,k',l,t}$, is subtracted.

$$\sum_{i\in k}\sum_{j\in J}M_{k,i,j,t}h_{k,i,j,t}+\sum_{k'\in K}^{k'\neq k}\sum_{l\in L}(PT_{k',k,l,t}(1-w_{k',k})(1-\alpha_l d_{k,k'}) - PT_{k,k',l,t})\geqslant\sum_{i\in k}(ed_{k,i,t}+G_{k,i,t}HS\cdot(1-\phi) - O_{k,t}HD) \quad (16)$$

Here, $PT_{k,k',l,t}=\sum_{t=1}^{t}(V_{k,k',l,t})\cdot HT+PT_{k,k',l,t_0}$ represents the electricity transmitted between region k and region k'.

2.3.2. Peak-load constraints

Peak-load reflects the power output required by the power system at the maximum load. The reserve capacity is used to balance the power production and power load to provide a reliable power supply [17]. Therefore, the sum of the regional total available installed capacity $\sum_{i\in k}M_{k,i,j,t}$ and transmitted in-capacity $\sum_{k'\in K}^{k'\neq k}\sum_{l\in L}VT_{k',k,l,t}(1-w_{k',k})(1-\alpha_l d_{k,k'})$, minus the transmitted out-capacity $\sum_{k'\in K}^{k'\neq k}\sum_{l\in L}VT_{k,k',l,t}$, plus the energy storage capacity $\sum_{i\in k}G_{k,i,t}$, should not be less than the sum of the load after the demand response reduction and the necessary reserve capacity $(1+\sigma)(pl_{k,t}-O_{k,t})$.

$$\sum_{i\in k}M_{k,i,j,t}+\sum_{k'\in K}^{k'\neq k}\sum_{l\in L}(VT_{k',k,l,t}(1-w_{k',k})(1-\alpha_l d_{k,k'})-VT_{k,k',l,t})+\sum_{i\in k}G_{k,i,t}\geqslant(1+\sigma)(pl_{k,t}-O_{k,t}) \quad (17)$$

where, $VT=\sum_{t=1}^{t}(V_{k,k',l,t})+VT_{k,k',l,t_0}$ represents the transmission capacity between region k and region k'.

2.3.3. Grid stability constraint

Power transmission cannot occur if the power transmission systems break down. Therefore, the loss of power transmission reflects the reliability of the transmission grid and transmission technology. Based on the theory of self-organized criticality [11], the power loss caused by the power outage to the power system, as a reliability indicator, is taken into account in the model. To ensure the grid stability, the proportion of power loss caused by the future national power outages is assumed to be lower than a certain value. This value is the ratio of the power transmission loss caused by the power outage in the base period to the national power demand.

$$\sum_{k'\in K}^{k'\neq k}\sum_{l\in L}PT_{k',k,l,t}w_{k',k}/\sum_{k\in K}\sum_{i\in k}ed_{k,i,t}\leqslant\theta \quad (18)$$

2.3.4. Capacity utilization constraint

Owing to the exorbitant load forecasts, large changes in the market supply and demand, and the lack of coordination between power engineering and power supply development, the maximum transmission power of transmission lines in operation usually does not reach the rated capacity [38]. Therefore, the utilization rate of transmission capacity in the actual application will be less than 100%. To promote the utilization of transmission lines and facilitate the development of renewable power sources, the utilization rate of transmission capacity needs to be greater than the lower limit β.

$$\beta\leqslant V_{k',k,l,t}/Z_{k,k',l,t}v_l\leqslant 1 \quad (19)$$

where, $V_{k',k,l,t}/Z_{k,k',l,t}v_l$ is the utilization rate of the rated transmission capacity, that is, the ratio of the total annual transmission capacity to the rated transmission capacity of the transmission line.

2.3.5. Selection of transmission technology constraints

Each voltage level of DC transmission technology has an applicable range of transmission distance [48]. When the transmission distance is within the economic range, the line loss rate is at a reasonable level. For example, if a ±500-KV transmission line is built between regions 2500 km apart (that is, from northwest to east, in China), the line loss rate will be more than twice that of the 800-KV UHV DC technology, and the cost-effectiveness will be significantly affected due to the considerable high power loss. Therefore, the transmission distance of each transmission technology is limited within a certain range, according to the completed line engineering and related information.

$$V_{k',k,l,t}d_l^{min}\leqslant V_{k',k,l,t}d_{k,k'}\leqslant V_{k',k,l,t}d_l^{max} \quad (20)$$

where d_l^{min} and d_l^{max} are the lower and upper limits of economic distance for transmission technology l, respectively.

2.3.6. Power transmission direction constraints

Considering differences in the distribution of energy resources and the level of economic development among regions in China, this study suggests that there should not be any power backflow when the direction of power transmission is determined. For example, when a transmission line from the northwest to the east is completed in China, the reverse transmission from the east of China to the northwest is unrealistic and should not occur. Therefore, this study sets the power transmission direction constraints.

$$V_{k',k,l,t}V_{k,k',l,t}=0 \quad (21)$$

2.3.7. Proportion of input power constraints

The construction of power transmission lines will promote power transmission among regions; this particularly benefits the regions with a high power demand by allowing the use of more power from resource-rich regions. Therefore, it is assumed that the ratio of power transmitted from other regions to the total power demand is not lower than that in the base year, reflecting the increasingly abundant power exchanges between regions.

$$\sum_{k\in K}\sum_{k'\in K}\sum_{l\in L}PT_{k',k,l,t}(1-w_{k',k})(1-\alpha_l d_{k,k'})/\sum_{i\in k}ed_{k,i,t}\geqslant\rho_k \quad (22)$$

2.3.8. Regional power generation potential constraints

The fuel for coal-fired and gas-fired power plants is easy to store and transport; therefore, the location of these two plants is not limited by resources. However, renewable energy cannot be stored and transported in its original state and must be converted into electricity before storage and transmission. Although renewable energy is sustainable, its potential is still limited owing to the constraints of climate, geography, and technology [61]. Therefore, the cumulative installed capacity of renewable energy in service should be less than the upper limit of its exploitable resource potential.

$$M_{k,i,j,t}\leqslant U_{k,i,j,t} \quad j = 2,3,4,5,6 \quad (23)$$

where $U_{k,i,j,t}$ is the maximum developable installed capacity of power generation source j in province i in region k in year t (MW), obtained by the technology diffusion model of renewable energy based on logistic regression.

In addition, the location of nuclear power plants is restricted by the geographic location, population density, and water resources. The existing nuclear power plants in China are located in eight provinces: Liaoning, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan. According to the *Research on China's Nuclear Power Development Planning*, few inland provinces have clear nuclear power development plans, that is, the potential of nuclear power development. However, during the 14th Five-Year Plan period, coastal areas will continue to be priority areas for nuclear power; the average construction period of nuclear power plants is 6.88 years [58]. The nuclear power plants in Jilin, Anhui, Jiangxi, Henan, Hunan, Hubei, Chongqing, Sichuan, Qinghai, and other places are assumed to be established and operative after 2030.

Table 1
Parameters for power transmission technologies.

No.	Voltage (kV)	Capacity (GW)	Fixed cost (billion yuan)[a,b]	Variable cost (million yuan/ km*GW)[a,b]	Line loss rate(%/thousand km)[c]	Economic distance (km)	Learning rate[d]
l_1	±500	3	4.1	4.9	7.9	500–1200	0.01
l_2	±500	3.2	4.1	4.9	7.5	800–1200	0.01
l_3	±660	4	6.4	6.2	4.5	1000–1500	0
l_4	±800	5	8.4	3.8	4.1	1200–2000	0.05
l_5	±800	7.2	8.34	3.8	3.9	1200–2500	0.05
l_6	±800	8	8.4	3.8	3.9	1200–2500	0.05
l_7	±800	10	8.4	3.8	4.3	1200–2700	0.05
l_8	±1000	9	14.0	5.1	2.5	1500–4000	0.1
l_9	±1100	12	20.4	5.7	2.5	2000–4000	0.1
l_{10}	500	0.3	6.3	4.1	5	500–1000	0.01
l_{11}	1000	5	13.2	5.8	3	1500–4000	0.1

[a] Mao [29], [b] Zhang [66], [c] Chen et al. [7], and [d] Yi et al. [59].

2.3.9. Growth rate of thermal power installed capacity constraints

To realize the low-carbon transformation of the power sector, the growth rate of the cumulative installed capacity of thermal power has gradually slowed down. Under the influence of policies, such as, the stringent control of the coal power development scale, the cumulative installed capacity growth rate of thermal power has been set to be less than the upper limit $q_{k,i}$.

$$M_{k,i,1,t} \leqslant q_{k,i} M_{k,i,1,t-1} \tag{24}$$

2.3.10. Proportion of non-fossil energy power generation constraints

Shifting from fossil energy power generation to clean renewable power generation is the direction for future power generation structure optimization. In the future, the power transmission lines will transmit a higher amount of non-fossil power, and the layout optimization also needs to consider changes in the power generation structure. Therefore, the lower limit of the proportion of non-fossil energy power generation in the total power generation is set according to NDRC [35].

$$\left(\sum_{j=2}^{6} M_{k,i,j,t} h_{k,i,j}\right) \Big/ \left(\sum_{j \in J} M_{k,i,j,t} h_{k,i,j}\right) \geqslant \mu_t \tag{25}$$

2.3.11. Energy storage constraints

Owing to the volatility of renewable energy, the power systems need to be equipped with energy storage to ensure reliability and flexibility of power supply [22]; the energy storage system configuration ratio has been proposed in the wind-solar-storage, combined with the power station planning lower limit [32]. Therefore, this study sets the lower limit of the energy storage capacity ratio. At the same time, when an extremely high energy storage capacity is installed, the marginal benefit diminishes; therefore, the upper limit of the energy storage ratio is set.

$$G_{k,i,t} \geqslant \varphi_L \left(M_{k,i,4,t} + M_{k,i,5,t}\right) \tag{26}$$

$$G_{k,i,t} \leqslant \varphi_H \left(M_{k,i,4,t} + M_{k,i,5,t}\right) \tag{27}$$

2.3.12. Demand response capacity constraints

Affected by smart grid, policy planning, market environment, and the other factors, the capacity of demand response should not be greater than a certain upper limit; otherwise, it will not only be inconsistent with the actual development speed, but also cause reliability risk to the power grid. Therefore, the upper limit and lower limit constraints are set based on the demand response capacity.

$$\sum_{k \in K} O_{k,t} \geqslant \varepsilon_L PL_{k,t} \tag{28}$$

$$\sum_{k \in K} O_{k,t} \leqslant \varepsilon_H PL_{k,t} \tag{29}$$

where $\varepsilon_L, \varepsilon_H$ represent the lower limit and upper limit of peak load adjustment ratio of demand response, respectively.

2.3.13. Power transmission constraints

Electricity transmitted from one region to another comes from the power generated in that region or received from other regions; therefore, the transmitted electricity from each region should not be greater than the local electricity generation plus the electricity transmitted in.

$$\sum_{k' \in K} PT_{k,k',l,t} \leqslant \sum_{i \in k} \sum_{j \in J} M_{k,i,j,t} h_{k,i,j,t} + \sum_{k' \in K} PT_{k',k,l,t} \tag{30}$$

2.3.14. Nature of the decision variables

$$M_{k,i,j,t}, V_{k',k,l,t}, N_{k,k',l,t}, Z_{k,k',l,t}, G_{k,i,t}, O_{k,i,t}, VT_{k',k,l,t}, PT_{k',k,l,t} \geqslant 0 \qquad k \in K, i \in I, j \in J, t \in T \tag{31}$$

3. Data sources, parameters, and scenario settings

3.1. Data sources and parameter settings

3.1.1. Capacity mix of existing technologies

The installed capacity of six power sources in 31 provinces during the base period is obtained from the *China Electric Power Yearbook, 2019*, as shown in Table A3. The rated capacity, construction time, and voltage level of the inter-regional lines built in history are collected from Wang et al. [56], Chen et al. [7] and Guo et al. [15]. The specific lines are shown in Table A4.

3.1.2. Power demand and peak load

The GDP growth rate in the future is set according to the historical power demand of each province in 2001–2017, the "*14th Five-year Plan*", and the "*outline of long-term goals for 2035*". Combined with the power consumption per unit GDP that obtained by the fitting function based on the historical data of *China Statistical Yearbook* 2010–2018, the power demand of each province is obtained. The regional power demand is obtained by summing up the power demand of each province, as shown in Table A5. The maximum power load of the region in the future is predicted by the fitting function based on the historical data of *China Electric Power Yearbook 2014–2018* [4], as shown in Table A6. The maximum load reserve factor is obtained from Zhang et al. [65].

3.1.3. Power transmission technologies

The specific parameters of transmission technology, including transmission investment cost, line loss rate, and transmission capacity, and learning rate, are shown in Table 1. The learning rate of different transmission technologies is assumed to remain unchanged during the

Table 2
Parameters for power generation technologies.

Power generation source	LCOE (Yuan/Mwh)[a,b]	Lifetime (Year)[c,d]	learning rate[c]	Non-carbon external costs (Yuan/Mwh)[e]
Thermal	290	30	0.08	29.6
Nuclear	310	60	0.1	1.4
Hydro	250	70	0	14.1
Wind	380	20	0.13	0.9
PV	650	20	0.18	5.5
Biomass	390	40	0.15	57.7

[a]Child et al. [8], [b]IRENA [20], [c]Yi et al. [59] [d]Tang et al. [50], and [e]NEEDS [39]

Table 3
Share of non-fossil energy generation, carbon price and energy storage cost.

	2021	2024	2027	2030	2033	2036	2039
Proportion of non-fossil energy (%)	0.35	0.4	0.45	0.5	0.53	0.56	0.59
Carbon price (yuan/t)	58	79	100	121	142	163	184
Unit cost of energy storage (yuan /kwh)	0.62	0.55	0.48	0.42	0.37	0.33	0.32

Table 4
Value and source of model parameters.

Parameter	Value	Source
nr	2%	Yi et al. [59]
r	5%	Yu et al. [61]
λ	3%	Yi et al. [59]
σ	20%	Zhang et al. [65]
θ	6.3%	Base year value
β	70%	Yi et al. [59]
φ_L	10%	MoHURD [32]
φ_H	20%	MoHURD [32]
ε_L	3%	NDRC [35]
ε_H	9%	NDRC [35]
ϕ	15%	Li et al. [22]
TR	40 year	SGCC [46]
τ	100 yuan/kw	Zhang et al. [64]
δ	2 yuan/kwh	Zhang et al. [64]
HD	200 h	Zhang et al. [64]
HS	600 h	Zakeri et al. [63]
HT	5000 h	Guo et al. [15]
η	821 gCO_2-eq/kwh	Wang et al.[54]
γ	0.7	MEE [34]

Table 5
Scenario settings.

Scenario	GDP growth rate	Minimum ratio of demand response capacity to peak load	Minimum ratio of energy storage capacity to WD&SOLAR PV capacity
BAU	Medium	3%	10%
H-TB	High	5%	15%
H-TS	High	5%	5%
H-LB	High	1%	15%
L-LS	Low	1%	5%
L-TS	Low	5%	5%
L-LB	Low	1%	15%

whole planning period, and the unit investment cost of a specific transmission technology in a certain year is obtained based on its learning curve function, combining the learning rate and the cumulative capacity of that year.

3.1.4. Power generation technologies

The specific parameters of power generation source, such as the levelized cost of energy (LCOE), lifetime, and learning rate, are shown in Table 2. The annual utilization hours and auxiliary power consumption rate of the power generation technologies in each province are considered as the average hours from 2014 to 2018, shown in Table A7 and Table A8. Owing to the short lifetime of wind and PV power generation, it is necessary to consider units decommissioning in the planning period. The decommissioning capacity and time are shown in Table A9 and Table A10. The specific data of the maximum exploitable potential of different power generation technologies in 2039 is shown in Table A11.

3.1.5. Other parameters

The base year of the proposed model is 2018, and the planning period is 2018–2039 with a sub-period of 3 years. In the *Strategy of energy production and consumption revolution (2016–2030)*, the target share of non-fossil energy power generation in 2030 is set to 50%, and the proportion of non-fossil energy generation between 2018 and 2039 can be estimated by the interpolation method. The carbon price in the future is obtained by the interpolation and fitting method according to CCF [3]. The unit cost of energy storage during the planning period is calculated by the base period value from He et al. [19] and future reduction rate from Li et al. [22]. The specific data are shown in Table 3. The expectation values of power outage between regions are calculated by multiplying the scale of power outage accidents by the frequency of power outage accidents in the corresponding area (in Table A2). Other specific parameter value settings and basis or source of the proposed model are listed in Table 4.

3.2. Scenario settings

Power demand directly affects power generation and power transmission in each region. The primary goal of the transmission line layout optimization is to meet the regional power demand. Energy storage and demand response ensure the balance of power supply and demand by adjusting the power load, which is an important means to provide a stable power supply in the future. To further explore the influence of power demand, energy storage, and demand response on the optimal transmission line layout, this study sets up several scenarios based on these three factors. The regional GDP growth rate is an important factor affecting its power demand [53]. Based on the provincial GDP growth rate settings, three high, medium, and low power demand scenarios are formed. The specific settings are shown in Table A5. It is mentioned in the *Power Demand Side Management Measures* that each region should gradually form a demand response capacity that accounts for approximately 3% of the annual maximum power load. Based on this, the different demand response capacity scenarios accounting for 1% and 5% are also set up. The *Specifications for Design of Wind and Solar Energy Storage Combined Power Stations* proposes that the rated power of the energy storage system configuration not be less than 10% of the total installed power of wind power and photovoltaic power generation. Based on this, different energy storage capacity scenarios, with the ratios of 5% and 15% are further set. Therefore, a total of 27 scenarios are obtained based on permutation and combination. This study selects seven representative scenarios for analysis. The specific settings are shown in Table 5.

4. Results and discussion

4.1. Model solutions

Different methods (such as branch and bound, extended cutting plane, and extended supporting hyperplane) or programs (DICOPT and BARON) can be used to solve MINLP. Among them, program DICOPT is

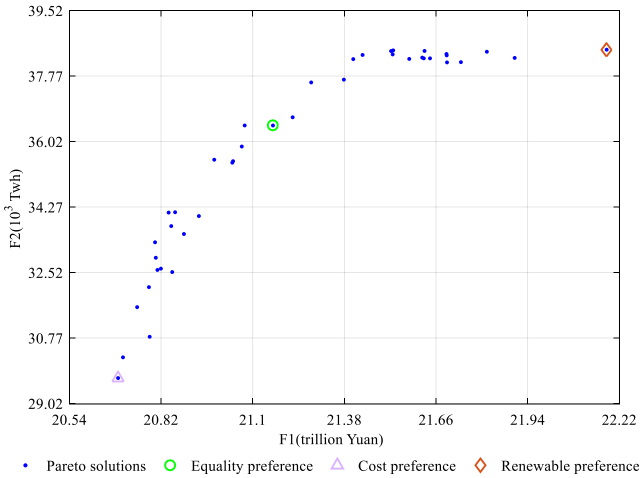

Fig. 1. Solutions obtained under different weight combinations.

very popular in solving the MINLP model of power system planning [51]. DICOPT is a program for solving mixed-integer nonlinear programming (MINLP) problems [52].The program bases on the extensions of the outer-approximation algorithm for the equality relaxation strategy. The MINLP algorithm inside DICOPT transforms the original problem into a series of nonlinear programming (NLP) and mixed-integer programming (MIP) sub-problems and then these sub-problems can be solved using any NLP or MIP solver such as CONOPT and CPLEX [2].

In the present study, all calculations in this study were implemented on the GAMS 25.1 platform, with the CPU of Intel(R) Core i5-10210U@1.6 GHz. The proposed model was transformed to a mixed integer nonlinear single target model through the weighted sum method. In addition, a normalization process was used to eliminate the dimensional influence of the two objectives. DICOPT was selected to solve the MINLP problem. After specifying the solution type, CONOPT and CPLEX were selected as local solvers to solve the MILP and NLP sub-problems, respectively.

Assigning weights ω_1 and ω_2 to the two objectives, and considering the values between 0 and 1 with a step of 0.025, 41 sets of weight combinations and the corresponding 41 sets of solutions, were obtained. The objective values are shown in Fig. 1. The Pareto frontier curve shows that there is a significant contradiction between the two objectives because each solution obtained is the optimal value under the weight combination.

4.2. *Optimal layout of transmission lines*

The optimization results of the transmission line layout in China under the BAU scenario are considered as an example to conduct further analysis. Following optimization, a total of 27 new transmission lines will be constructed in China in 2018–2039, as shown in Fig. 2. Line

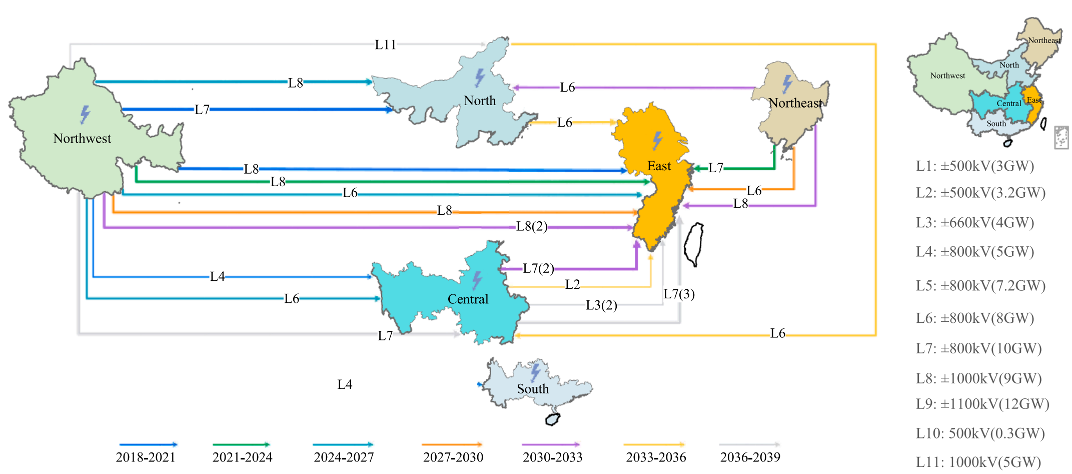

Fig. 2. Newly built transmission lines (2018–2039, BAU).

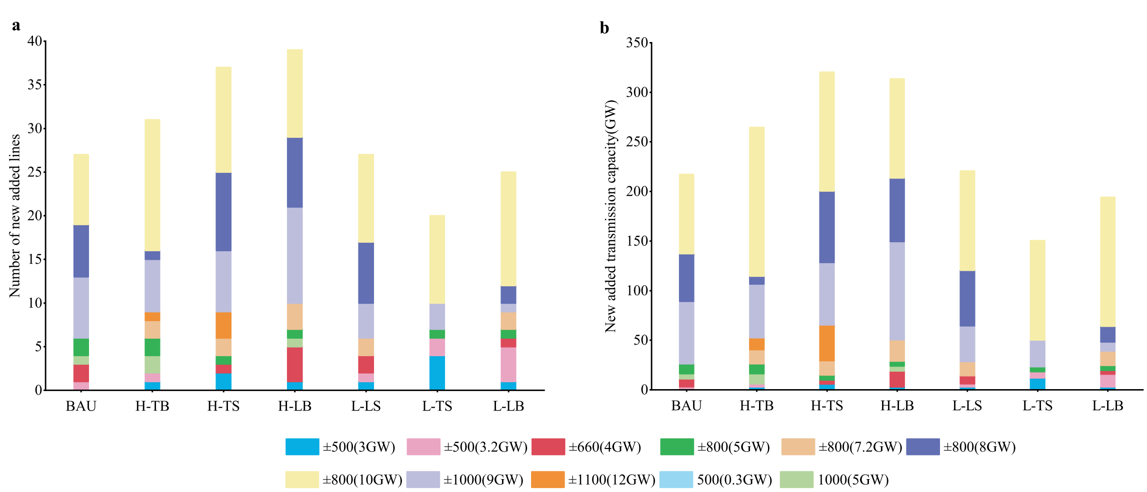

Fig. 3. Total number and capacity of new lines in different transmission technologies (2018–2039).

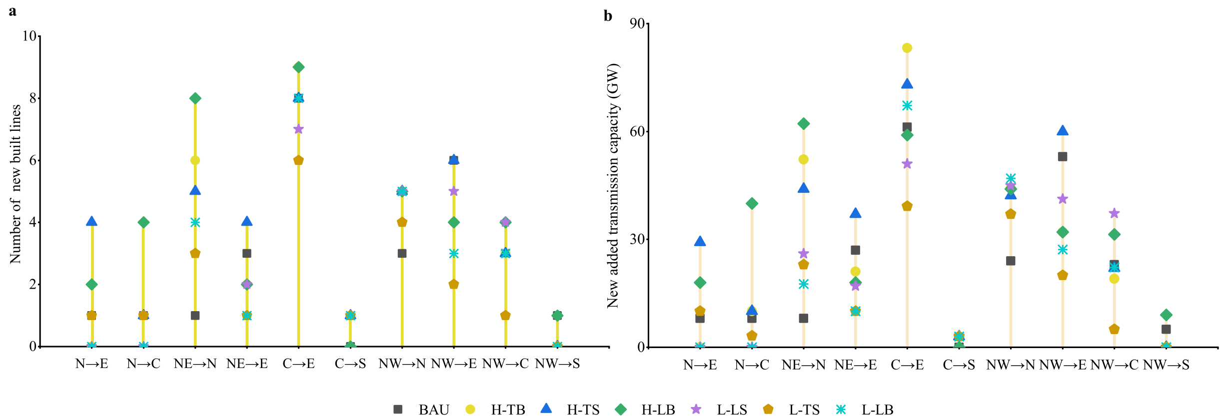

Fig. 4. Total number and capacity of newly built transmission lines (2018–2039).

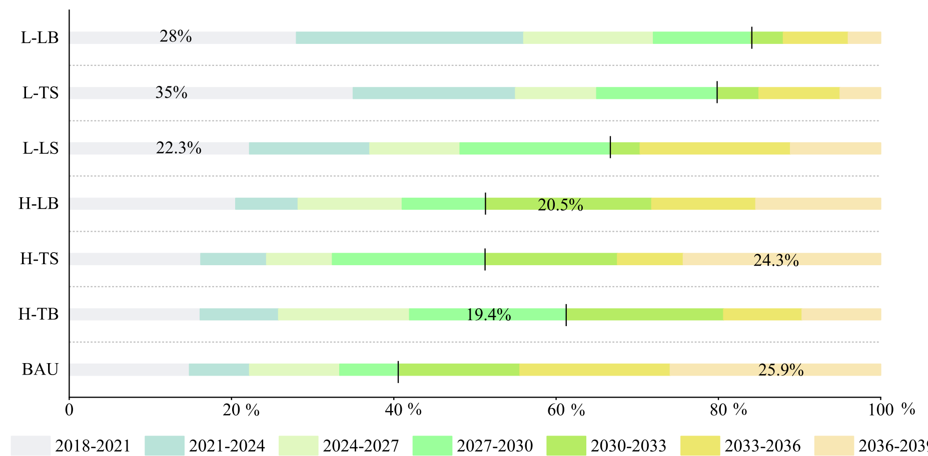

Fig. 5. Share of newly added line number in each sub-period in the entire planning period.

construction will be concentrated in the period 2036–2039, and the number of newly built lines will be at most 6, accounting for 22% of the total number of lines newly built during the planning period. Among them, as an important power hub, Central China not only receives power from the northwest, but also transmits power to the neighboring East China, which has the highest power demand. Therefore, during the entire planning period, most of the newly built lines, that is approximately eight, will lie between Central China and East China. Northwest China transmits a large amount of power to East China by virtue of the abundant power generation resources; six new power lines are built from northwest to East China, relying on its own excellent hydropower resources. South China only needs to import electricity from the northwest to meet its own needs, and it only requires a new ± 800-KV line in 2021. These results are very similar with the Li et al.'s [23] study although the regional division is different.

4.3. Transmission technology selection

±800 KV (10 GW) is the underlying transmission technology for the largest number of newly built lines and enables the largest capacity under seven scenarios, as shown in Fig. 3. A total of 8 (BAU)–15 (H-TB) lines were newly built during 2018–2039, and the newly added transmission capacity reached 80 (BAU)–150 (H-TB) GW. With its cost advantage, ±800 KV (10 GW) will become the most important power transmission technology in the future, accounting for 31.9% (H-LB)–66.9% (L-LB) of the total newly-built transmission capacity. The newly built number and capacity of ± 1000 KV (9 GW) are only less than ± 800 KV (10 GW). A total of 1 (L-LB)–11 (H-LB) lines will be newly built during the planning period, and the newly added transmission capacity will reach 9 (L-LB)–99 (H-LB) GW. On the contrary, the AC transmission technology is not sufficiently economical; therefore, it is seldom used in transmission lines. In reality, transmission projects of ± 800 kV and ± 1000 kV accounted for 55.6% and 20% of the total construction transmission capacity respectively in 2019, much higher than the 24.4% proportion of all EHV construction projects [5]. This is because UHV AC generally requires three transmission lines, while UHV DC only requires two transmission lines [24] that further increases the construction cost. In addition, the power loss of UHV AC in the long-distance power transmission is significant [31], and the capacity of AC energy transmission under the same level of voltage is less than DC [43]; therefore, there are fewer new AC lines. Only 1 (BAU)–2 (H-TB) lines are newly built for 1000 KV (5 GW), and no new lines are built under the H-TS and low GDP growth scenarios. These results are consistent with Lugovoy et al.'s [28] conclusion that ultra-high voltage direct current (UHVDC) is the most efficient long-distance transmission technology.

4.4. Number and capacity of newly built lines

Among the 10 route groups of inter-regional transmission line, 4 groups (C → E, NE → N, N → C, and NW → S) have the maximum number of transmission lines in the H-LB scenario, as shown in Fig. 4a. In the H-LB scenario, the high power demand with a high energy storage capacity and low demand response makes it necessary to strengthen the construction of transmission lines and improve the transmission capacity in areas that generate or transfer electricity. For example, power export from Northeast China under the H-LB scenario is 53.3% higher than that

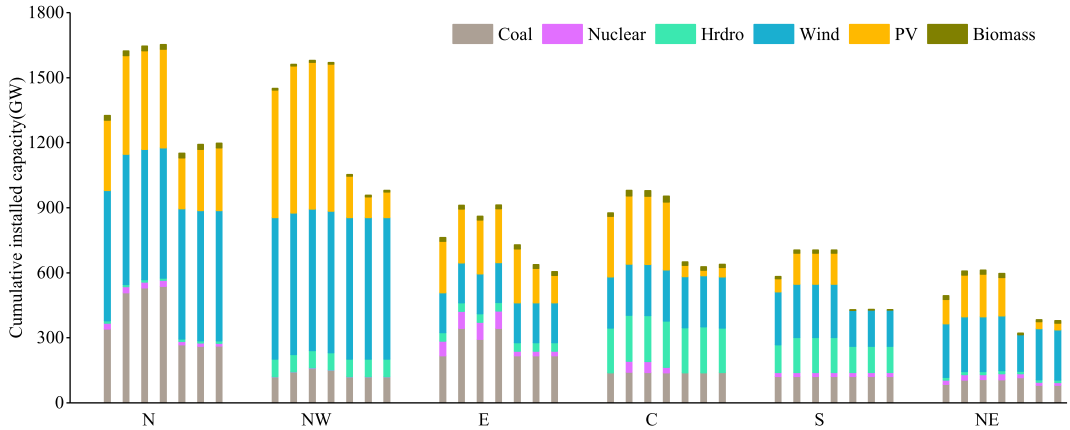

Fig. 6. Cumulative installed capacity of six regions in 2039. Note:From left to right, the BAU, H-TB, H-TS, H-LB, L-LS, L-TS, and L-LB scenarios are represented.

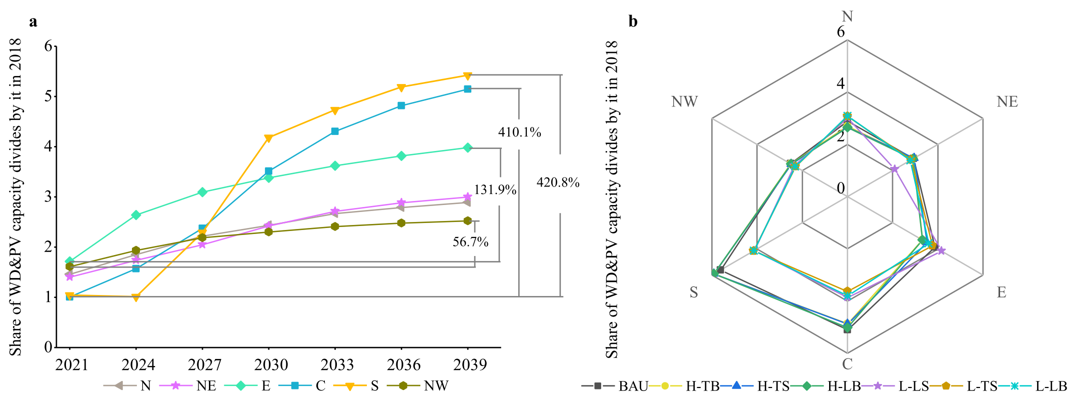

Fig. 7. Growth in share of wind and solar photovoltaic capacity, compared with that in 2018 (BAU).

in the BAU scenario; at the same time, the inter-regional power exchange is more abundant, and the total newly built transmission capacity of all the regions is 44.4% higher than that in case of BAU. Among them, the number of new transmission lines between Central China and East China is at most 9 (H-TB), and the corresponding transmission capacity is increased by 83.2 GW. This is mainly because East China has the highest power demand, and its own power generation capacity is limited. As an important power hub, the power transmission between Central China and East China has the advantage of distance. On the contrary, the minimum number of new lines in Central China-South is only 0 (H-LB)–1 (H-TS), and the newly added transmission capacity is only 3 GW. The low power demand lowers the power gap, and the energy storage loss under the low energy storage capacity is small; accordingly, the self-generated electricity and the existing transmission lines can meet the power transmission requirements. Therefore, in the L-TS and L-LS scenarios, new lines in N → E, N → C, and NW → S are not required. From the perspective of newly added transmission capacity, in addition to C → E, the other routes to East China, such as N → E, NE → E, and NW → E, have a significantly higher transmission capacity in the H-TS scenario than in the other six scenarios, as shown in Fig. 3b. This is because the power demand in this scenario is high and the power gap in East China is as large as 920 TWH (16.5% higher than that in case of BAU). At the same time, in this scenario, the power reduction (power reduction caused by demand response minus the power loss caused by energy storage) in the Northwest is higher (60.8% higher than that in case of BAU); therefore, the new transmission capacity is the largest.

4.5. Completion time of newly built transmission lines

In the three scenarios of low GDP growth (L-LB, L-TS, and L-LS), the peak period of line construction completion is 2018–2021, as shown in Fig. 5. Under the condition of low GDP growth, the growth of power demand is also low, resulting in a smaller power deficit. Therefore, after the early rapid construction of lines, a smaller number of new lines can meet the power demand after 2030. The peak period of new line construction under a high GDP growth is 2027–2030 (H-LB) and 2030–2033 (H-TS and H-TB). This is because the construction of new lines will be accelerated as the inland nuclear power plant can be built and operative by 2030. When the demand response is higher (H-TS), the new lines construction will lag further because the regional self-regulation capacity can be better utilized to meet the demand. Under the BAU scenario, the peak period of construction is 2036–2039. It can be seen that the policies emphasizing a high demand response and energy storage are positive towards the construction of transmission lines in China. Particularly, under the L-LB scenario, the proportion of newly built lines will exceed 80% before 2030; this is because the power reduction (power reduction caused by demand response minus power loss caused by energy storage) in the region is low. For example, the net reduction of

Table 6
Objective function values, newly built lines under different scenarios.

Scenarios	Total cost (trillion yuan)	On-grid RE power (10^3 TWh)	Total transmission capacity (GW)
BAU	21.54	37.20	217.2
H-TB	23.83	39.42	264.6
H-TS	23.46	39.54	320.4
H-LB	23.78	39.36	313.6
L-LS	19.33	31.07	220.6
L-TS	19.23	31.60	150.4
L-LB	19.35	31.89	194.2

power in East China in 2030 is 25 times less than that in BAU, resulting in a large power gap. Therefore, a large amount of power needs to be imported in the early stage. Under the constraint of the proportion of non-fossil energy, renewable energy based on wind and PV power grows rapidly after 2030, resulting in a reduction in the amount of transmitted-in power.

4.6. Power generation capacity

The cumulative installed capacity in North China and Northwest China will exceed 1300 GW by 2039, as shown in Fig. 6. The proportion of non-fossil installed capacity in the total generation capacity in China will reach 81.3% (BAU), of which the proportion of wind power and solar photovoltaic power will exceed 68.6% (BAU), and the proportion of wind power and photovoltaic power in the three northern areas will exceed 67%. Under the constraint of the planning policy of China, striving to achieve 50% of the non-fossil energy generation by 2030 [35], the thermal power capacity is rapidly reducing. To meet the growing power demand, the renewable energy capacity based on the wind power and photovoltaic power shows a high proportion in all regions under the seven scenarios, particularly in the three northern regions.

In central China and southern China, nuclear power as well as high-quality hydropower-based renewable energy are developing steadily. Particularly in Central China, under the high GDP growth scenarios (H-TB, H-TS), nuclear power has achieved a rapid growth from 0 to 50.3 GW. In East China, on the basis of a large amount of import electricity, non-fossil energy is still developed in this region, and the proportion of non-fossil installed capacity will increase from 29% in 2018 to 62.3% (H-TB)–71.5% (BAU) by 2039. From the perspective of installed capacity structure under a high GDP and low GDP growth, it can be found that the wind power capacity occupies a dominant position in all the

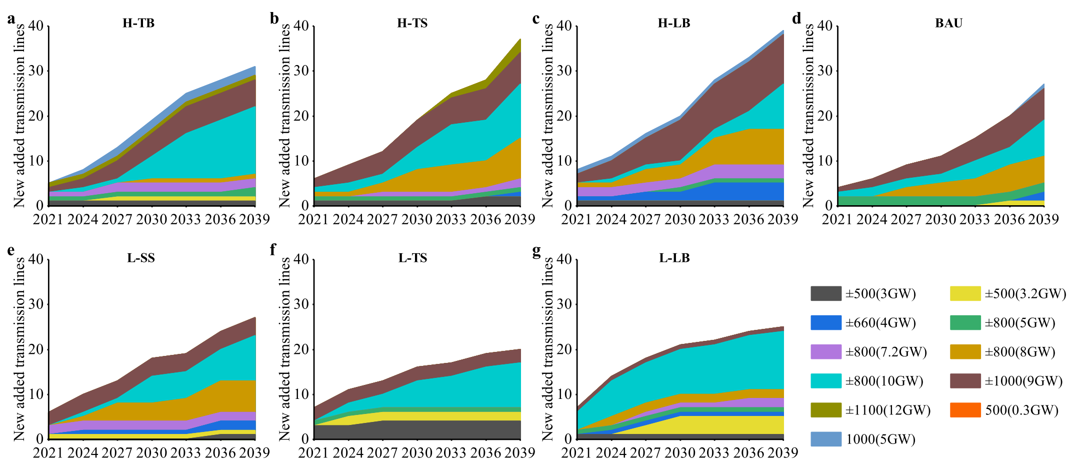

Fig. 8. Number of new transmission lines under different scenarios.

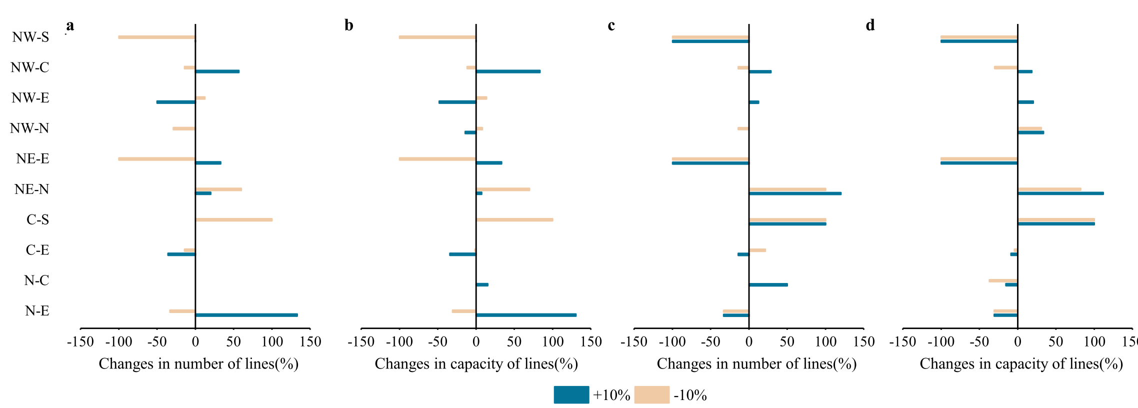

Fig. 9. (a) and (b) Sensitivity analysis of utilization rate of transmission lines; (c) and (d) Sensitivity analysis of the proportion of non-fossil energy power generation.

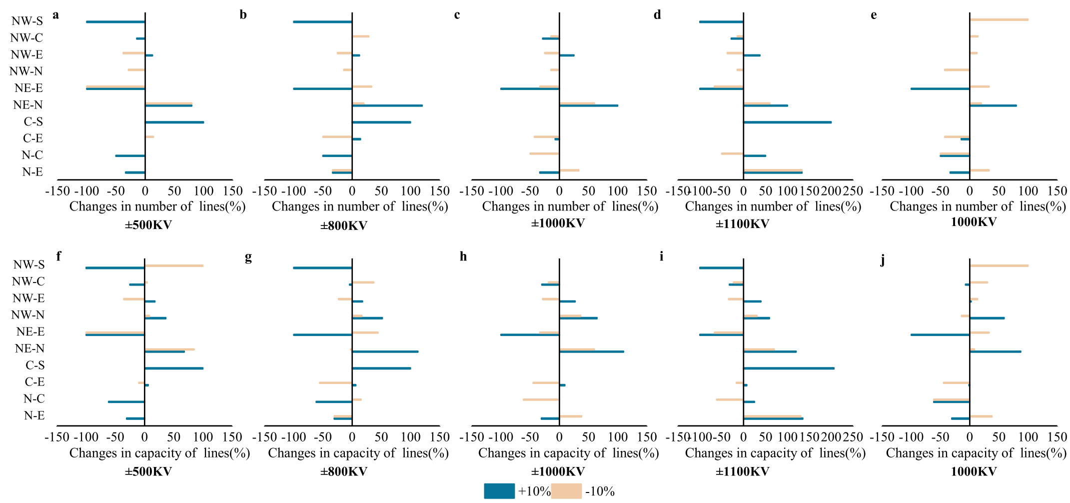

Fig. 10. Sensitivity analysis of learning rate of transmission technology investment cost.

scenarios, particularly under low GDP-growth scenarios; owing to the smaller power deficit and the cost advantage of wind power resources, there is a high wind power capacity, resulting in a sharp decrease in the solar photovoltaic power capacity by more than 60%, compared with the BAU scenario.

With the steady development of centralized wind and solar photovoltaic power installations in the three northern regions, the distributed wind and solar photovoltaic installations in the central and southeast regions have also developed rapidly. The accumulative installed capacity of wind power and solar photovoltaic generation has the largest growth rate in central China and southern China in 2019, with the growth rate of 37.4% [37] and 35.3% [36], respectively. Wind power and solar photovoltaic power also are the power generation with the fastest growth rate in East China in 2019, with the growth rate of 18.5% and 13.9%, respectively. As shown by Fig. 7a, the proportion of wind and solar photovoltaic power capacity in South and Central China will have increased rapidly since 2024. The proportion of wind and solar photovoltaic power capacity in the South and Central China is only about 10% in 2018, and this proportion will increase by 5–6 times by 2039. It can be seen that the proportion of wind and photovoltaic power installed capacity in the central and southeast regions will increase under seven scenarios, compared with that in 2018. Among them, the proportion of wind and solar photovoltaic installed capacity in the southern region has increased significantly. Except for the low GDP growth scenario (L- LS, L-TS, L-LB), the proportion of wind and solar photovoltaic installed capacity in the other scenarios reached nearly 6 times the proportion of the base period; this also enables the southern region to meet its own power requirement by the increased local generation. Similarly, the wind and solar photovoltaic capacity in central China and east China also develops rapidly, and the growth rate of the installed capacity is higher than that in the three northern areas. The evolution pathway of four types of renewable energy from 2015 to 2030 is similar with Li et al.'s [23] findings in BAU scenario. Furthermore, the increase in solar PV is mainly observed in the Shanxi, West Inner Mongolia and East regions, i.e. northern and eastern regions in our region devision.

4.7. Impacts of different combinations of energy storage and demand response

Under the seven scenarios considered, the total cost and on-grid RE power reaches 19.23 (L-TS)–23.83 (H-TB) trillion yuan and 31,070 (L-LS)–39540 (H-TS) TWh, respectively, as summarized in Table 6. In the low power demand level, energy storage and demand response can effectively promote on-grid RE power. Compared with the L-LS scenario, the increasing demand response and energy storage capacity increases the on-gird RE power by 531.36 TWh (L-TS) and 822 TWh (L-LB), respectively. However, the increase in storage capacity in the H-TS scenario with a high power demand leads to a decrease in 123.02 TWh on-grid RE power, compared with that in the H-TB scenario. Although the increasing power demand can be met by RE to promote RE consumption, the high capital cost caused by the strict requirement of energy storage configuration makes it more preferable to exchange a part of the on-grid RE power for the economic cost savings. As can be seen, with the gradual expansion of wind and solar photovoltaic power installed capacity, the role of energy storage in promoting the grid-connected RE power will gradually diminish.

The total transmission capacity will reach 150.4 (L-TS)–320.4 (H-TS) GW in the seven scenarios, as briefed in Table 6. Energy storage, demand response, and transmission lines work together as flexibility parameters to achieve a stable power supply. High energy storage and high demand response capacity can reduce the demand for inter-regional transmission line construction. For example, compared with the H-TS and H-LB scenarios, the total capacity of the newly constructed transmission lines in the H-TB scenario is reduced by 55.8 GW and 49 GW, respectively. Similarly, the capacity of the newly constructed transmission lines in the L-LS scenario, with low energy storage and low demand response capacity is 70.2 GW and 26.4 GW higher than that of the L-TS scenario with a high demand response and L-LB scenario with a high energy storage, respectively. Without energy storage and demand response, more transmission lines will need to be built to meet the inter-regional power supply and demand.

Increasing the ratio of energy storage and demand response reduces the total number of lines from 35 (H-TS) and 38(H-LB) to 29 (H-TB), as shown in Fig. 8 a–c. Increasing the energy storage and demand response capacity will promote the local grid-connected power consumption and reduce the need for inter-regional transmission line construction. Among them, the decrease is the most significant in the case of ± 800 KV (8 GW), from 9 (H-TS) and 8 (H-LB) to 1 (H-TT). The most significant increase in the number of lines is observed for 800 kV (10 GW) that increased from 12 (H-TS) and 10 (H-LB) to 15 (H-TT), becoming the technology with the largest number of newly constructed transmission lines.

Similarly, the reduction of energy storage and demand response ratios under a low power demand increases the total number of constructed lines from 25 (L-LB) and 20 (L-TS) to 27 (L-LS), as shown in Fig. 8 e–g. UHV lines will become the preferred technology for new lines owing to their cost advantages, and the number of new lines will increase by 25% (L-LB) and 78.6% (L-TS), compared with that in the L-SS scenario. Among them, ±800 KV (8 GW) will increase the most, from 2 (L-LB) and 0 (L-TS) to 7 (L-SS). 800 KV (10 GW) will decrease the most, from 13 (L-LB) to 10 (L-SS); however, it is still the technology with the largest increase; ±500 (3 GW) will decrease from 4 (L-TS) to 1 (L-SS), and ± 500 (3.2 GW) will decrease from 4 (L-LB) and 2 (L-TS) to 1 (L-SS).

4.8. Sensitivity analysis

Sensitivity analysis is conducted to explore the influence of parameters on the optimal solution, considering the parameter settings in the BAU scenario as a reference. The low utilization rate of transmission lines will lead to a large number of additional lines to meet the transmission requirements and directly affect the total capacity of transmission lines. Transmission capacity planning forecasts the inter-regional power trading. Factors such as transmission capacity at the sending end and power consumption level at the receiving end should be considered in this planning. Therefore, transmission capacity planning is easily affected by demand and price estimation. The proportion of non-fossil energy generation affects regional power generation structure that in turn affects the construction layout of inter-regional transmission lines. In the future, the development level of non-fossil energy will be affected by policies and markets and is uncertain as well. The investment cost level of transmission technology directly affects the choice of transmission technology, while the learning rate reflects the change in investment cost of transmission technology with the accumulation of experience. However, the level of technology development cannot be accurately predicted. Therefore, this study selects the three aforementioned parameters that have a significant impact on the transmission line layout and have uncertain future values for sensitivity analysis. Subsequently, the influence of 10% increase or decrease in the parameters on the capacity and number of inter-regional transmission lines, is assessed.

The number and capacity of transmission lines are sensitive to the change in the utilization rate of transmission lines and the proportion of non-fossil energy power generation. In the total 10 route groups, 5 groups (N → E, C → E, NE → E, NW → E, NW → C) change more than 30% in both capacity and number of lines when the utilization rate of lines increases by 10%. Among them, the number and capacity of transmission lines in N → E are the most sensitive to the changes in utilization rate of the transmission lines. When the utilization rate of lines increases by 10%, the maximum transmission capacity and the number of lines increase by 130.8% and 133.3%, respectively, as shown in Fig. 9a and Fig. 9b. When the proportion of the non-fossil energy power generation increases by 10%, there are 6 groups (N → E, C → S, NE → N, NE → E, NW → N, NW → S) of transmission line capacity and 6 groups (N → E, N → C, C → S, NE → N, NE → E, NW → S) of the number of transmission lines with a change rate of more than 30%. The number and capacity of transmission lines in NE → N are most sensitive to the change of non-fossil energy generation share. When the proportion of non-fossil energy power generation increases by 10%, the maximum transmission capacity and the number of lines increase by 112% and 120% respectively, as shown in Fig. 9c and Fig. 9d.

The number and capacity of transmission lines are sensitive to the learning rate of the transmission technology investment cost. When the learning rate increases or decreases by 10%, the change rate of both the total construction lines and the maximum transmission capacity in more than half of the inter-regional route groups exceed 30%, as shown in Fig. 10. Among them, the number and capacity of transmission lines are the most sensitive to the learning rate of UHV ± 1100-kV transmission technology. When the learning rate increases by 10%, the number and capacity of transmission lines in the five groups (N → E, C → S, NE → N, NE → E, NW → S) change more than 100%. Particularly, when the learning rate of UHV ± 1100-kV cost increases by 10%, the total number of transmission lines and the maximum transmission capacity increase by 200% and 206%, respectively. Relatively speaking, the number and capacity of transmission lines are not sensitive to the change of the learning rate of ± 800-kV and 1000-kV transmission technology.

5. Conclusions and policy recommendations

5.1. Conclusions

The present study proposes an integrated multi-objective optimization model for determining the optimal layout of transmission lines by considering flexible resources and grid stability. Eleven types of direct current and alternating current transmission technologies, including UHV and EHV, were considered. The stability of power grid in the medium- and long-term planning was described from a macro perspective, based on the relative power loss caused by large power outages. The optimal layout of transmission lines, the optimal installed capacity, and energy storage capacity in each province were ascertained based on the proposed model. Following are the conclusions of this study:

a) The power transmission pattern of West-to-East and North-to-South is further expanded in China. Compared with that in 2018, the transmission capacity of Northwest-to-East, Northwest-to-North, Central-to-East, and North-to-Central in China might increase by 265%, 209%, 200%, and 160%, respectively, by 2039. In particular, 800 kV (10 GW) will become the main transmission technology from 2033. The peak period of the line construction completion is 2036–2039.
b) The average annual growth rate of the share of wind and solar photovoltaic power installed capacity in the total generation capacity in Central, East, and South China will reach 6.7–8.6%, becoming the fastest growing regions in China, higher than 4.5% in Northwest China. The distributed photovoltaic and distributed wind power can become the main force of renewable power growth in the future, owing to the flexibility and small occupied area.
c) Between 2018 and 2039, the on-grid renewable power in the high energy storage (L-LB) and high demand response (L-TS) will be 822 TWh and 531.36 TWh higher than that in the low energy storage and demand response scenario (L-LS), respectively, and the latest transmission capacity will reduce by 26.4 GW and 70.2 GW, respectively.
d) The optimal number and capacity of power transmission lines are sensitive to changes in the utilization rate of the rated transmission

capacity, ratio of non-fossil energy generation, and learning rate of transmission technology investment cost. Improving the utilization rate of transmission lines, increasing the regional proportion of non-fossil energy generation, and reducing the investment cost of transmission technology will facilitate an optimal transmission line layout.

5.2. Policy recommendations

To achieve the optimal layout of power transmission lines in China, the following policy recommendations are suggested based on the optimization results.

a) The construction of power transmission lines from the three northern regions to east and central China should be strengthened, particularly, the ± 800 kV power transmission lines. With the rapid development of renewable power in the three northern regions and the rapid economic growth in East and South China, the transmission of power from the west to east and from the north to south will be further expanded in the future. In particular, it is necessary to strengthen the construction of power transmission lines in the Northwest-to-East, Central-to-East, and Northeast-to-North in China. Among them, ±800 kV transmission technology should be widely used, making it the core technology of trans-regional large-scale transmission, owing to its large transmission capacity, long transmission distance, and advanced technical level.
b) Considerable attention should be paid to wind power and solar photovoltaic power generation in central China and the provinces along the southeast China, particularly for distributed power generation. The wind and solar photovoltaic installed capacity in central, eastern and southern China will significantly increase from 2024 onwards. Although the share of wind and solar photovoltaic installed capacity in the total generation capacity was only approximately 10% in 2018, it will go up to 5–6 times of that by 2039. Therefore, it is necessary to effectively utilize the advantages of distributed solar photovoltaic power generation and distributed wind power generation, such as, low construction cost and nearby utilization, to promote the rapid development of wind and solar photovoltaic power generation in central and southeastern China and to improve energy utilization rate through the implementation of terminal integrated energy supply system and micro-grid demonstration projects.
c) The synchronous construction of energy storage and demand response should be promoted, and energy storage in the early stage of wind and solar photovoltaic power development should be particularly focused on. Energy storage and demand response, as important flexible parameters, can effectively promote the nearby consumption of power generation, and reduce the construction demand of inter-regional transmission lines. Particularly in the early stage of wind and solar photovoltaic power development, using energy storage equipment based on the installed capacity of wind and solar photovoltaic power, could effectively improve the on-gird renewable power. However, as the capacity of renewable energy expands, the continued requirement of energy storage equipment based on a fixed ratio will lead to a large amount of capital costs and will not play a role in promoting the consumption of renewable power.

CRediT authorship contribution statement

Shiwei Yu: Conceptualization, Project administration, Writing–original draft, Writing – review & editing. **Shuangshuang Zhou:** Programming, Writing – review & editing. **Junpeng Qin:** Writing–original draft.

Declaration of Competing Interest

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

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Appendixes

See Tables A1–A11.

Table A1
Regional division.

Regional power grid	Provinces, municipalities and autonomous regions
Northeast(NE)	Liaoning, Jilin, Heilongjiang, East Inner Mongoria
North(N)	Beijing, Tianjin, Hebei, Shanxi, Shandong, West Inner Mongoria
East(E)	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian
Central(C)	Henan, Hubei, Hunan, Jiangxi, Chongqing, Sichuan
South(S)	Yunnan, Guizhou, Guangxi, Guangdong, Hainan
Northwest(NW)	Shaanxi, Gansu, Qinhai, Ningxia, Tibet, Xinjiang

Table A2
Distance (km) and expectation value of power outage (%) between regions.

		North	Northeast	East	Central	South	Northwest
North	Distance[a]	0	1200	1400	1200	1650	1600
	Expectation	0.1	0.2	0.1	0.8	0.2	0.4
Northeast	Distance	1200	0	2000	2300	2800	2700
	Expectation	0.2	0.3	0.2	0.9	0.3	0.4
East	Distance	1400	2000	0	1030	1400	2500
	Expectation	0.1	0.2	0.0	0.8	0.2	0.3
Central	Distance	1200	2300	1030	0	800	1600
	Expectation	0.8	0.9	0.8	1.5	0.9	1.0
South	Distance	1650	2800	1400	800	0	1630
	Expectation	0.2	0.3	0.2	0.9	0.3	0.4
Northwest	Distance	1600	2700	2500	1600	1630	0
	Expectation	0.4	0.4	0.3	1.0	0.4	0.6

[a] Data is calculated as the straight-line distance between the geographic center of regions.

Table A3
Power generation capacity in China in 2018 (GW).

Province	Thermal	Nuclear	Hydro	Wind	Solar PV	Biomass
Beijing	11.19	0	0.98	0.19	0.4	0.28
Tianjin	15.29	0	0.01	0.52	1.28	0.14
Hebei	46.17	0	1.82	13.91	12.34	0.73
Shanxi	66.28	0	2.23	10.43	8.64	0.39
Inner Mongolia	82.27	0	2.42	28.69	9.45	0.21
Liaoning	33.83	4.48	2.99	7.61	3.02	0.16
Jilin	18.92	0	3.85	5.14	2.65	0.65
Heilongjiang	22.12	0	1.04	5.98	2.15	0.98
Shanghai	23.65	0	0	0.71	0.89	0.27
Jiangsu	97.49	4.37	2.65	8.65	13.32	1.63
Zhejiang	62.09	9.07	11.61	1.48	11.38	1.8
Anhui	54.13	0	3.12	2.46	11.18	1.67
Fujian	31.28	8.71	13.22	3	1.48	0.52
Jiangxi	21.65	0	6.27	2.25	5.36	0.32
Shandong	103.67	1.25	1.08	11.46	13.61	2.58
Henan	68.21	0	4.01	4.68	9.91	0.62
Hubei	28.84	0	36.75	3.31	5.1	0.75
Hunan	22.84	0	15.98	3.48	2.92	0.8
Guangdong	80.69	13.3	15.3	3.57	5.27	1.43
Guangxi	22.91	2.17	16.75	2.08	1.24	0.36
Hainan	4.65	1.3	1.54	0.34	1.36	0.08
Chongqing	15.57	0	7.53	0.5	0.43	0.32
Sichuan	15.75	0	78.24	2.53	1.81	0.53
Guizhou	32.63	0	22.12	3.86	1.78	0.16
Yunnan	15.14	0	66.66	8.57	3.43	0.13
Tibet	0.42	0	1.6	0.01	0.97	0.03
Shaanxi	39.37	0	3.86	4.05	7.16	0.07
Gansu	20.64	0	9.27	12.82	8.28	0.1
Qinghai	3.79	0	11.92	2.67	9.56	0
Ningxia	28.45	0	0.43	10.11	8.16	0.11
Xinjiang	53.77	0	7.02	19.21	9.92	0.04

Table A4
Existing inter-regional transmission lines by 2018.

No	Pathway	Voltage (kV)	Capacity (MW)	Linked regions	Operation year	Length (km)	Construction period (year)[a]
1	Three Gorges-Changzhou	±500	3000	Central-East	2003	860	3
2	Three Gorges-Guangdong	±500	3000	Central -South	2004	946	2
3	Three Gorges-Shanghai	±500	3000	Central-East	2006	1043	3
4	Liaoning-Hebei	±500	3000	Northeast-North	2008	1000	3
5	Baoji-Deyang	±500	3000	Northwest-Central	2010	574	3
6	Tuanlin-Fengjing	±500	3000	Central-East	2011	976	3
7	Ningxia-Shandong	±660	4000	Northwest-North	2011	1335	2
8	Xiangjia Dam-Shanghai	±800	6400	Central-East	2010	1907	3
9	Jinping -Suzhou south	±800	7200	Central-East	2012	2100	4
10	Hami South-Zhengzhou	±800	8000	Northwest-Central	2014	2210	2
11	Xiluodu Dam- Zhejiang west	±800	8000	Central-East	2014	1670	2
12	Longxi-Jiangxi	±800	7500	North-Central	2015	1600	3
13	Ningxia-Zhejiang	±800	8000	Northwest-East	2016	1711	3
14	Jiuquan-Hunan	±800	8000	Northwest-Central	2017	2383	3
15	Shanxi north-Jiangsu	±800	8000	Northwest-East	2017	1119	3
16	Tongliao-Weifang	±800	10,000	Northeast-North	2018	1234	3
17	Zhundong- Wannan	±1100	12,000	Northwest-East	2018	3304	3
18	Ximeng-Taizhou	±800	8000	North-East	2018	1619	3
19	Jin Southeast-Jingmen	1000	5000	North-Central	2011	654	3
20	Yuheng-Weifang	1000	5000	Northwest-North	2017	1048.5	3
21	Ximeng-Jinan	1000	5000	Northeast-North	2017	730	3

[a] Data on the construction period of some DC transmission projects is missing. Considering factors such as trial operation and delayed commissioning, this article replaces the average construction period data with DC transmission projects.

Table A5
Electricity demand for six regions under different GDP growth rates (TWh).

Region	Growth rate	2021	2024	2027	2030	2033	2036	2039
North	Low	1718	1889	2054	2222	2357	2486	2588
	Medium	1784	2019	2258	2515	2745	2981	3195
	High	1836	2138	2460	2819	3166	3538	3903
Northeast	Low	516	560	601	642	672	700	720
	Medium	536	598	661	727	784	841	890
	High	552	634	720	815	905	999	1088
East	Low	1798	1956	2097	2234	2327	2408	2455
	Medium	1867	2089	2306	2527	2710	2886	3029
	High	1922	2212	2511	2832	3124	3424	3699
Central	Low	1280	1375	1459	1538	1588	1630	1650
	Medium	1329	1469	1603	1739	1848	1952	2034
	High	1368	1555	1745	1948	2129	2315	2482
South	Low	1141	1209	1262	1308	1326	1334	1323
	Medium	1185	1292	1387	1480	1543	1598	1631
	High	1220	1367	1511	1657	1779	1896	1991
Northwest	Low	823	944	1069	1207	1334	1467	1592
	Medium	854	1008	1174	1364	1551	1755	1961
	High	879	1067	1278	1527	1787	2080	2391

Table A6
Maximum load for six regions from 2021 to 2039 (GW).

Region	2021	2024	2027	2030	2033	2036	2039
North	263	295	327	360	392	424	456
Northeast	71	79	87	95	103	111	119
East	330	376	422	468	514	560	606
Central	230	263	296	329	362	396	429
South	191	214	238	261	285	309	332
Northwest	107	124	141	158	175	192	209

Table A7
Average power generation operation hours in each province from 2014 to 2018 (h).

Province	Thermal	Nuclear	Hydro	Wind	Solar PV	Biomass
Beijing	4147	0	940	1821	1253	5630
Tianjin	4517.8	0	0	2096	833	8800
Hebei	5039	0	837	2064	1263	5577
Shanxi	4205.4	0	1555	1935	1404	5867
Inner Mongolia	4876.2	0	1746	2003	1566	4500
Liaoning	4308.2	6278	1519	1970	1240	6000
Jilin	3457.6	7376.4	1855	1609	1286	5248
Heilongjiang	3980.2	0	2208	1798	1449	5623
Shanghai	3676.2	0	0	2214	896	5147
Jiangsu	4988.6	8145	1222	2000	1066	6780
Zhejiang	4151.6	7781	1973	2086	1030	6216
Anhui	4721.8	7376.4	1633	1935	988	6100
Fujian	4048.8	7307	3424	2597	859	5525
Jiangxi	4922.8	7376.4	2803	1991	911	5277
Shandong	4998.6	7376.4	724	1841	1132	5492
Henan	4027	7376.4	2653	1844	907	4243
Hubei	4131.4	7376.4	3912	2056	1006	5238
Hunan	3647	7376.4	3240	2022	703	5124
Guangdong	4131.8	7708	2893	1888	819	7689
Guangxi	3292.6	6512	3929	2179	962	4611
Hainan	4852.6	6532	2388	1747	1034	8007
Chongqing	3856.8	7376.4	3606	2110	576	5700
Sichuan	2638.2	7376.4	4301	2328	1512	6979
Guizhou	4121.2	0	3429	1644	911	4788
Yunnan	1920.6	0	4027	2482	1305	5143
Tibet	255	0	3138	1674	1215	5731
Shaanxi	4725.6	0	2830	1956	1284	3668
Gansu	3861.4	7376.4	4148	1422	1120	5731
Qinghai	4362.2	0	3312	1718	1456	5731
Ningxia	5262.4	0	3932	1736	1390	4265
Xinjiang	4822.4	0	3534	1729	1213	2845

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Table A8
Average auxiliary power ratio of power plant from 2014 to 2018 (%).

Province	Thermal	Nuclear	Hydro	Wind	Solar PV	Biomass
Beijing	8.4	0	1.1	2.3	1.7	11.4
Tianjin	6.3	0	1.1	2.8	1.7	11.4
Hebei	5.7	0	1.1	2.8	1.6	11.4
Shanxi	6.9	0	1.2	2.6	1.5	11.4
Inner Mongolia Mongolia Mongolia	8.4	0	2.3	2.3	2	3.1
Liaoning	6.3	7.7	2.9	2.7	2.1	13.4
Jilin	7.1	6.2	1.2	3	3.3	7.7
Heilongjiang	6.5	0	3	3	1.9	11.2
Shanghai	3.9	0	1.1	3.3	0.8	17.5
Jiangsu	3.9	6.7	0.8	2.7	1.6	11.4
Zhejiang	4.9	6.2	1.2	1.1	0.7	11.4
Anhui	4	6.2	1.9	2.4	0.9	11.4
Fujian	4.6	7.5	0.9	2.2	1.3	11.4
Jiangxi	4.1	6.2	1.7	2.3	1.2	11.4
Shandong	5.3	10.6	1.9	2.6	3	11.6
Henan	5.4	6.2	2.7	2.9	1	10.6
Hubei	4.6	6.2	0.7	4.3	1.5	11.5
Hunan	5.3	6.2	1.7	3.1	0.5	10.2
Guangdong	5	5.4	1.1	3.1	1.7	5.8
Guangxi	6.3	7	0.9	3.5	1.7	11.4
Hainan	5.5	8.6	1.3	3.7	1.8	11.4
Chongqing	5.7	6.2	0.9	3.4	1.7	14.3
Sichuan	5.9	6.2	1.1	2.8	1.8	14.8
Guizhou	6.7	0	0.8	2.5	1.3	8.1
Yunnan	6.8	0	0.7	2.5	2.3	24.9
Tibet	6.9	0	1.1	2.8	1.7	11.4
Shaanxi	7.2	0	1.7	1.7	1.3	11.4
Gansu	6.2	0	1.6	3	1.4	9.8
Qinghai	6.3	6.2	1	2.5	1.4	11.4
Ningxia	5.8	0	2.2	3.9	1.4	11.4
Xinjiang	6.9	0	1.3	2.6	2.2	11.4

Table A9
Wind power decommissioned installed capacity from 2021 to 2039 (MW).

Province	2021	2024	2027	2030	2033	2036	2039
Beijing	0	0	0	110	150	190	190
Tianjin	0	0	0	30	230	290	520
Hebei	0	4	410	3720	8250	11,380	13,910
Shanxi	0	0	0	370	3160	7710	10,430
Inner Mongolia	0	8.8	1080	9730	18,540	25,570	28,690
Liaoning	0	21.5	350	3080	5630	6950	7610
Jilin	0	7.1	470	2210	3770	5050	5140
Heilongjiang	0	3.6	230	1910	3920	5610	5980
Shanghai	0	0	20	140	320	710	710
Jiangsu	0	0	250	1370	2560	5610	8650
Zhejiang	0	5	40	250	450	1190	1480
Anhui	0	0	0	0	490	1770	2460
Fujian	0	1.9	230	550	1460	2140	3000
Jiangxi	0	0	0	80	300	1080	2250
Shandong	0	1.6	210	1380	5000	8390	11,460
Henan	0	0	0	50	270	1040	4680
Hubei	0	0	10	60	350	2010	3310
Hunan	0	0	0	40	337	2167	3480
Guangdong	0	83.4	250	620	1740	2680	3570
Guangxi	0	0	0	0	120	700	2080
Hainan	0	8.7	10	210	300	310	340
Chongqing	0	0	0	50	100	280	500
Sichuan	0	0	0	0	110	1250	2530
Guizhou	0	0	0	0	1350	3620	3860
Yunnan	0	0	0	340	1650	7370	8570
Tibet	0	0	0	0	0	10	10
Shaanxi	0	0	260	0	590	1790	4050
Gansu	0	5.7	0	1390	7030	12,770	12,820
Qinghai	0	0	0	0	100	690	2670
Ningxia	0	4.6	50	510	3020	9420	10,110
Xinjiang	0	24.3	330	1360	5210	17,760	19,210

Table A10
Solar photovoltaic power decommissioned installed capacity from 2021 to 2039 (MW).

Province	2021	2024	2027	2030	2033	2036	2039
Beijing	0	0	0	0	0	150	400
Tianjin	0	0	0	0	16	600	1280
Hebei	0	0	0	0	251	4430	12,340
Shanxi	0	0	0	0	35	2970	8640
Inner Mongolia	0	0	0	0	1368	6380	9450
Liaoning	0	0	0	0	23	520	3020
Jilin	0	0	0	0	10	560	2650
Heilongjiang	0	0	0	0	11	170	2150
Shanghai	0	0	0	0	7	350	890
Jiangsu	0	0	0	0	1046	5460	13,320
Zhejiang	0	0	0	0	180	3380	11,380
Anhui	0	0	0	0	50	3450	11,180
Fujian	0	0	0	0	26	270	1480
Jiangxi	0	0	0	0	85	2280	5360
Shandong	0	0	0	0	118	4550	13,610
Henan	0	0	0	0	20	2840	9910
Hubei	0	0	0	0	48	1870	5100
Hunan	0	0	0	0	1	300	2920
Guangdong	0	0	0	0	44	1170	5270
Guangxi	0	0	0	0	42	160	1240
Hainan	0	0	0	0	89	290	1360
Chongqing	0	0	0	0	0	0	430
Sichuan	0	0	0	0	33	960	1810
Guizhou	0	0	0	0	0	460	1780
Yunnan	0	0	0	0	110	2080	3430
Tibet	0	0	0	0	110	330	970
Shaanxi	0	0	0	0	63	2460	7160
Gansu	0	0	0	0	4298	6860	8280
Qinghai	0	0	0	0	3481	6820	9560
Ningxia	0	0	0	0	1551	5260	8160
Xinjiang	0	0	0	0	2771	8930	9920

Table A11
Technology developable potential and growth rate of thermal capacity.

Province	$q_{k,i}$	Technology developable potential in 2039 (GW)					
		Thermal	Nuclear	Hydro	Wind	Solar PV	Biomass
Beijing	1.02	40.1	0	1.5	0.4	5.5	0.4
Tianjin	1.06	54.8	0	0.0	2.2	6.4	0.5
Hebei	1.12	90.0	7.5	2.6	149.8	89.4	5.4
Shanxi	1.21	237.5	0	2.7	110.1	70.3	3.0
Inner Mongolia	1.24	516.2	0	3.1	278.7	185.5	1.4
Liaoning	1.19	121.2	20	3.4	53.8	51.6	1.1
Jilin	1.13	36.9	10	5.6	62.3	46.9	6.6
Heilongjiang	1.15	79.3	0	3.3	52.9	43.0	10.3
Shanghai	1.01	46.1	0	0.0	6.4	5.1	0.4
Jiangsu	1.27	611.7	20	2.8	73.0	88.4	5.9
Zhejiang	1.04	121.0	24	18.0	24.7	59.9	2.1
Anhui	1.23	339.7	10	4.2	38.8	73.2	7.2
Fujian	1.07	112.1	25	14.1	41.1	21.8	1.6
Jiangxi	1.41	135.9	10	6.3	36.6	59.5	3.3
Shandong	1.3	650.5	20	1.3	143.4	153.2	11.0
Henan	1.14	244.4	10	4.7	63.9	83.0	1.7
Hubei	1.15	103.3	15	36.8	36.6	86.3	3.1
Hunan	1.2	81.8	15	18.2	34.2	45.8	7.0
Guangdong	1.02	289.1	45	21.8	49.0	60.0	4.1
Guangxi	1.11	391.4	20	17.6	30.4	18.5	5.8
Hainan	1	29.2	10	1.6	3.6	21.6	0.7
Chongqing	1.18	164.1	4	13.8	9.1	4.7	2.4
Sichuan	1.04	30.7	8	132.4	55.5	34.8	8.6
Guizhou	1.42	204.7	3	23.4	45.5	29.4	2.7
Yunnan	1.53	54.2	0	100.0	124.0	57.0	1.8
Tibet	1.16	0.8	0	21.0	0.5	16.5	0.9
Shaanxi	1.97	415.0	0	11.4	103.0	94.3	0.9
Gansu	1.12	74.0	0	12.9	162.0	146.6	2.4
Qinghai	1.34	13.6	2	14.9	62.4	180.3	0.4
Ningxia	1.7	486.1	0	0.7	37.7	42.9	1.3
Xinjiang	1.48	566.8	0	19.7	287.4	196.6	1.6

Note: $q_{k,i}$ is the maximum growth rate of thermal cumulative installed capacity.

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