Optimal Generation Expansion Planning Model of a Combined Thermal-wind-PV Power System Considering Multiple Boundary Conditions: A Case Study in Xinjiang, China

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Optimal Generation Expansion Planning Model of a Combined Thermal-wind-PV Power System Considering Multiple Boundary Conditions: A Case Study in Xinjiang, China

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Abstract

Background: The scarcity of fossil fuels and their high emissions impact on the environment have forced the rapid development of renewable energy. Wind and photovoltaic power play a more and more important role in today's power system because of their clean and renewable characteristics. However, with the large-scale grid connection of wind and photovoltaic power, the contradiction between renewable energy and thermal power is becoming more and more serious. The unreasonable planning of power generation resources has also caused a lot of waste of electric power.

Methods: To solve this problem, this paper comprehensively considers the construction and operation costs of power plants, and constructs an optimal generation expansion planning model of a combined thermal-wind-PV power system with the objective of minimizing total cost. The planning is calculated under the boundary conditions of ensuring the safe operation of the power grid and taking into account the share requirement, utilization requirements and construction requirements for renewable energy. The model is applied to the self-use and external power plants in Xinjiang.

Results: The results show that this generation expansion plan can reduce the total cost of the power plants while ensuring the load demand. The renewable energy has also received more consumption share and its abandonment rate has dropped significantly. Numerical examples show that the optimization model has good applicability.

Conclusion: The proposed optimization model can realize the coordinated development of three types of power sources under multiple boundary conditions, which can not only guarantee the economy of power construction, but also take into account the optimization of environmental benefits. Reasonable generation expansion planning can improve energy efficiency, achieve clean and low carbon in the process of power generation, and promote the sustainable development of society.

Keywords: Optimization Model; Generation Expansion Planning（GEP）; Multiple Boundary Conditions; Renewable Energy

1. Background

The energy and power industry is an important support for the rapid development of the national economy [1]. With the rapid consumption of fossil fuels in the past, it has not only caused the global energy crisis, but also aggravated the environmental problems [2]. Therefore, clean and renewable energy, represented by wind and PV power, has gradually gained attention [3]. Many countries have taken positive measures to increase the installed capacity of renewable energy [4-6]. China has also promulgated a number of policies to promote the development of renewable energy [7-9]. As of 2018, China's renewable energy installed capacity reached 728GW, accounting for about 32% of the world. The installed capacity of hydropower, wind and PV power reached 352, 185 and 175GW respectively, ranking first in the world [10]. However, the excess installed capacity has brought about a serious situation of renewable energy abandonment. According to the National Energy Administration, the national abandoned amount of hydropower, wind and PV power reached 69, 28 and 5TWh respectively in 2018 [11]. In provinces with more renewable energy installed capacity, such as Xinjiang and Gansu, the abandonment rate even exceeds 20% [12]. Therefore, how to properly plan the development of renewable energy has become the main problem at present.

China's electricity demand and supply are inversely distributed. The load centers are mainly concentrated in the central and eastern regions, while the power supply centers are mainly concentrated in the northwest [13]. To solve this problem, China has implemented the West-East Power Transmission Strategy and built several UHV transmission channels [14]. As a major energy province in China, Xinjiang undertakes an important responsibility and its power supply and power grid are in a critical period of large-scale construction and leaping development. With its own resource advantages and policy support, Xinjiang's power industry has made considerable progress. By the end of 2018, the total installed capacity of power supplies in Xinjiang was 86GW, including wind power of 19GW and PV power of 10GW [15]. However, the large installed capacity of renewable energy has also brought a lot of problems to the Xinjiang power grid. On the one hand, due to the self-use demand has not been deeply excavated and the external transmission space has not been effectively developed, there is a serious phenomenon of renewable energy abandonment in Xinjiang. The high spillage rate has caused Xinjiang to be included in the red warning zone of developing renewable energy for three consecutive years, suspending the construction of wind and

PV power [16,17]. On the other hand, in order to solve environmental problems and promote clean energy development, China has issued a series of policies to promote priority dispatch of renewable energy [18]. These one-size-fits-all policies has made even if there is a waste of renewable energy in Xinjiang, its thermal power has not received a corresponding share of power generation, which makes it more difficult to distribute load demand that is already insufficient. The economic interest conflict between thermal power and renewable energy is becoming increasingly serious. In addition, the randomness and volatility of wind and PV power pose great challenges to the security and stability of Xinjian's power grid. How to satisfy the interests of thermal, wind and PV power plants under the premise of ensuring the safe operation of the power grid is of great significance to the coordinated development of various types of power sources in Xinjiang.

Optimizing the structure of the power system involves a lot of funds and resources. The GEP model is a good way to solve this kind of problem, which can choose the best energy distribution at an acceptable economic cost [19-21]. The GEP model can be divided into three categories: optimization models, general/partial equilibrium models and alternative models, but the optimization model is the most widely used [22]. S.Y. Chen et al. proposed a multi-regional power GEP model considering air pollutants emission constraints [23]. He applied the model to China and found that replacing large coal-fired power plants with renewable power sources can well reduce pollutant emissions. Chen et al. analyzed the impact of the non-carbon external cost of different power generating technologies on China's power planning [24]. M.D. Rodgers et al. introduced the damage caused by the power industry to human health into the GEP and constructed the optimization model with the objective of minimizing social costs [25]. I. Khan. analyzed the feasibility and sustainability of the GEP from the social, environmental and economic aspects and he pointed out that the design of energy policies must strike a balance between all three aspects [26]. With the massive integration of renewable energy resources, the formulation of GEP has become more and more complicated [27-29]. J. English et al. applied short-term constraints to the long-term GEP model to deal with the increasing demand for power system flexibility caused by the large-scale penetrations of renewable energy [30]. Based on an analysis of the current situation of Spain's power system, R. Gómez-Calvet et al. used the Linear Programming Optimization Technique (LPOT) to optimized the mix of renewable energy to reduce the need of reserve capacity and surplus power [31]. B. Canizes et al.

constructed a two-stage GEP model considering the effects of seasonal and daily periods impact on renewable energy and the optimization scheme achieves the lowest cost and line loss at the same time [32]. D. Quiroga et al. set up five scenarios that represent different trends and energy policies over the next decade, and on this basis studied the impact of pollutant emission policies GEP. The results shown that the availability of renewable energy may improve the effectiveness of emission policies [33]. S. Pineda et al. proposed a GEP model that included both electricity and certificate markets to analyze the impact of quotas and penalty costs on the capacity expansion of renewable energy generation, and found that the introduction of the markets reduced its installed capacity [34].

Although the above papers have studied GEP models from multiple aspects, they mostly focus on the dispatching side or the user side. These papers set the main optimization goal to minimize the cost of power construction or minimize environmental pollution, while ignoring the economics of the power plants. Of course, the method they proposed cannot be applied well to Xinjiang's complex power background. Therefore, based on the current power operation status in Xinjiang, this paper constructed an optimal GEP model of a combined thermal-wind-PV power system considering multiple boundary conditions from the power supply side. First of all, this paper analyzed the income and expenditure of the thermal, wind and PV power plants in Xinjiang, and calculated their break-even hours. Then, according to the various national policies for the development of renewable energy resources, three boundary conditions were set up: share requirements, utilization requirements and construction requirements. Finally, under these conditions, the optimal GEP of thermal, wind and PV power plants in Xinjiang in from 2020 to 2030 was designed based on the self-use and external load demand, which could provide reasonable suggestions for the coordinated development of various power resources in Xinjiang during the “14th Five-Year Plan” and the “15th Five-Year Plan”.

The rest of the paper is organized as follows. Section 2 states the presuppositions for developing the GEP model, and details its objective function and constraints, as well as the three boundary conditions. Section 3 introduces the operating status of Xinjiang power supply and the related data in the model. The optimal GEP is analyzed and discussed in Section 4, and Section 5 provides a summary and concluding remarks.

2. Model and Methods

2.1 Presupposition

The construction of the planning model needs to consider a variety of influencing factors. In order to improve the applicability of the model, this paper proposes the following assumptions combined with the energy development status of Xinjiang.

(1) The fuel of thermal power only consider coal and the unit does not carry out major technical upgrading during the planning period, so the coal consumption coefficient will not drop significantly;

(2) The cost of the thermal power unit includes fuel cost and operation cost excluding coal transportation costs, and the remaining renewable power units only include operation cost;

(3) The break-even utilization hours will be affected by the income and expenditure costs for the individual power generation units. Therefore, this paper selects the average break-even utilization hours of each types of power sources in Xinjiang for calculation;

(4) Because the self-use and external power supply cannot be used interchangeably, it needs to be separately constrained;

(5) The construction of UHV transmission channels needs to be considered from multiple aspects. In the case that there is no new UHV line put into operation in the future, the capacity of the supporting power supply will not be increased during the planning period.

Based on the above assumption, the generation planning model is constructed with the minimum total investment and operating cost as the optimization goal.

2.2 Generation expansion planning model

2.2.1 Objective function

In the power planning, the main consideration is the investment cost of the new power plants, as well as the operation cost of the generators. Therefore, the optimization goal is to minimize the total cost.

$$MinZ = C + C^{*} \quad (1)$$

$$\begin{aligned} C &= \sum_{t=1}^{T}\sum_{i=1}^{N}\Delta Q_{i,t}P_{i,t} + \sum_{t=1}^{T}\sum_{i=1}^{N}H_{i,t}Q_{i,t}\delta_{i,t} \\ C^{*} &= \sum_{t=1}^{T}\sum_{i=1}^{N}\Delta Q_{i,t}^{*}P_{i,t}^{*} + \sum_{t=1}^{T}\sum_{i=1}^{N}H_{i,t}^{*}Q_{i,t}^{*}\delta_{i,t}^{*} \end{aligned} \quad (2)$$

2.2.2 Constraints

(1) Power balance constraint

The power consumption and generation in the power system must be balanced in real time [35].

$$
\begin{gathered}
(1-\lambda)\sum_{i=1}^{N} H_{i,t} Q_{i,t}\left(1-\theta_{loss}\right)=G_t \\
\lambda\sum_{i=1}^{N} H_{i,t}^{*} Q_{i,t}^{*}\left(1-\theta_{loss}^{*}\right)=G_t^{*}
\end{gathered}
\tag{3}
$$

(2) Reserve capacity constraint

In order to achieve stable operation of the power system, it is necessary to select a power supply unit with adjustment capability for peak shaving to cope with random changes in load. In this paper, thermal power is selected as the peaking unit, and it should be able to provide a certain reserve capacity [36].

$$
\begin{gathered}
Q_{1,t} \geq \eta A_t \\
Q_{1,t}^{*} \geq \eta^{*} A_t^{*}
\end{gathered}
\tag{4}
$$

(3) Power generation economic constraint

In order to ensure the economic benefits of power plants, the utilization hours should not be lower than the average break-even utilization hours, but not higher than the theoretical utilization hours.

$$
\begin{gathered}
S_i \leq H_{i,t} \leq H_{i,max} \\
S_i^{*} \leq H_{i,t}^{*} \leq H_{i,max}^{*}
\end{gathered}
\tag{5}
$$

(4) Renewable energy utilization constraints

According to the relevant national policy, the minimum utilization rate of renewable energy should be constraint.

$$
\begin{gathered}
\frac{H_{i,t}}{H_{i,max}} \geq \alpha_{i,t}, i=2,3 \\
\frac{H_{i,t}^{*}}{H_{i,max}^{*}} \geq \alpha_{i,t}^{*}, i=2,3
\end{gathered}
\tag{6}
$$

(5) Construction capacity constraint

Due to the overcapacity of Xinjiang's renewable energy, it is necessary to improve the utilization rate of the unit before increasing new capacity.

$$
\begin{gathered}
\Delta Q_{i,t}=\begin{cases} Q_{i,t}-Q_{i,t-1}, \dfrac{H_{i,t-1}}{H_{i,max}} \geq \beta_{i,t-1} \\ 0, \dfrac{H_{i,t-1}}{H_{i,max}} < \beta_{i,t-1} \end{cases} \\
\Delta Q_{i,t} \geq 0
\end{gathered}
\tag{7}
$$

(6) Renewable energy penetration constraint

Renewable energy power generation is greatly affected by natural resources. The characteristics of random intermittent output pose challenges to the stable operation of the power grid. Therefore, it is necessary to constrain the maximum penetration rate of wind and PV power [37].

$$
\begin{aligned}
&\vartheta G_t \le \sum_{i=2}^{N} H_{i,t} Q_{i,t}\left(1-\theta_{loss}\right) \le \gamma_t G_t \\
&\vartheta_t^* G_t^* \le \sum_{i=2}^{N} H_{i,t}^* Q_{i,t}^*\left(1-\theta_{loss}^*\right) \le \gamma_t^* G_t^*
\end{aligned}
\tag{8}
$$

2.3 Multiple boundary conditions

2.3.1 Share requirements for non-hydropower renewable energy

According to the Notice on Establishing and Improving the Safeguard Mechanism for Renewable Energy Power Consumption, renewable energy power consumption responsibility weights are set by the province's power consumption. The requirements for Xinjiang from 2018 to 2020 are 11.5%, 12% and 13%, respectively. However, since this paper only considers three types of power resources, the weights of non-hydropower renewable energy in 2020, 2025, and 2030 are set to 30%, 35%, and 40%, respectively.

2.3.2 Utilization requirements for renewable energy

According to the Clean Energy Dissipation Action Plan (2018-2020), it is necessary to optimize the power structure, reasonably control the pace of power development, and improve the utilization rate of power supply during the 13th five-year Plan period. The target for clean energy consumption in Xinjiang is that the utilization rate of PV power should reach 85% in 2018, 90% in 2019 and 2020, and wind power utilization rates should reach 75%, 80% and 85% in 2018, 2019 and 2020 respectively. With the increasingly serious problems of energy and environment, the requirements for energy efficiency will become stricter. Therefore, the utilization rate of wind and PV power is set to 95% and 90% respectively in 2025, and it will reach to 95% in 2030 in this paper.

2.3.3 Construction requirements for renewable energy

According to the Notice on Establishing Monitoring and Early Warning Mechanism to Promote Sustainable and Healthy Development of Wind Power Industry and Notice on Establishing a Market Environment Monitoring and Evaluation Mechanism to Guide the Healthy and Orderly Development of the Photovoltaic Industry, Xinjiang has been in the red warning zone for three years, and it is not allowed to increase the installed capacity of renewable energy. Since the red warning requires multiple indicators to judge, in order to simplify the calculation, this paper sets the wind and PV abandonment rates are less than 15% and 10% respectively as the red warning release standard.

3. Application

3.1 Problem statement

In recent years, due to the energy red warning, the growth rate of renewable energy installed capacity in Xinjiang has slowed down, and the proportion of renewable energy decreased slightly. Although the power supply structure is constantly being optimized, there is still some irrationality. On the one hand, renewable energy power generation has squeezed the share of thermal power, making the profitability of various power generation resources different. The contradiction of interest between renewable energy and thermal power has intensified. On the other hand, subject to load demand, the abandonment of wind and PV caused by excessive installed capacity still exists. Therefore, the current principle of power supply construction in Xinjiang is to promote coordinated and orderly development of all kinds of power sources under the condition of ensuring the safety and stability of power system. Specifically, it is necessary to avoid disorderly competition and prevent redundant construction. While optimizing the development of thermal power and improving energy efficiency, renewable energy sources represented by wind and PV power should be actively developed to reduce environmental pollution, thereby achieving efficient, clean, low-carbon power supply.

3.2 Data

3.2.1 Break-even hours

Under the current average on-grid price level, the break-even hours are calculated according to the cost and benefit data of the power plants (Table 1).

Table 1 The current break-even hours of three power recourses

Thermal power		Wind power		PV power	
Self-use	External	Self-use	External	Self-use	External

4779	2507	1755	1789	1246	1314

During the planning period, the coal price is on the rise and the on-grid price of renewable energy will fall because of the new electricity price policy, which would reduce the income of three kinds of power plants resulting an increase in their break-even hours (Table2).

Table 2 Break-even hours under multiple boundary conditions

Thermal power		Wind power		PV power	
Self-use	External	Self-use	External	Self-use	External
4779	2507	1755	1789	1246	1314

3.2.2 Self-use demand

In recent years, the self-use demand in Xinjiang has been increasing, but the growth rate has shown a downward trend. The average annual growth rate from 2015 to 2018 was 13.84% and the largest rate occurred in 2017 at 21.30%. After the rapid increase in demand, it has become relatively saturated. It is expected that the self-use demand in Xinjiang will reach 129, 190 and 270 TWh by 2020, 2025 and 2030 respectively. The five-year average growth rate is 10.36%, 8.14%, 7.28%. The growth trend of self-use demand in Xinjiang is shown in Fig.1.

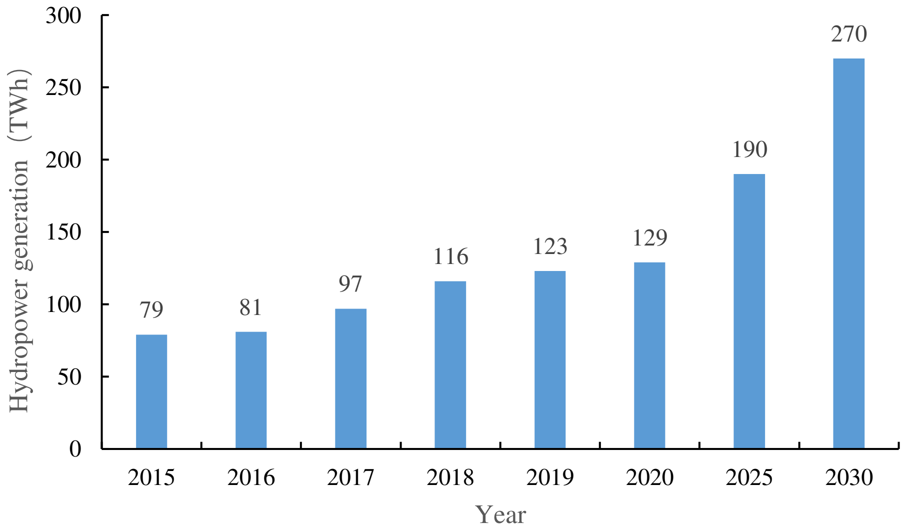

Figure 1 Self-use demand in Xinjiang during the planning period

Since this paper does not consider the hydropower generation, it must be deducted from the above self-use demand, and the rest is the total power generation of thermal, wind and PV power in Xinjiang. Affected by water flow, the change of hydropower generation is relatively stable. It is estimated that hydropower generation will increase by 4.5 TWh per year from 2020 to 2025, and continue to grow at 4 TWh per year from 2026 to 2030. The growth trend of hydropower generation is shown in Fig.2 and the total generation amount of thermal, wind and PV power during the planning period is shown in Fig.3.

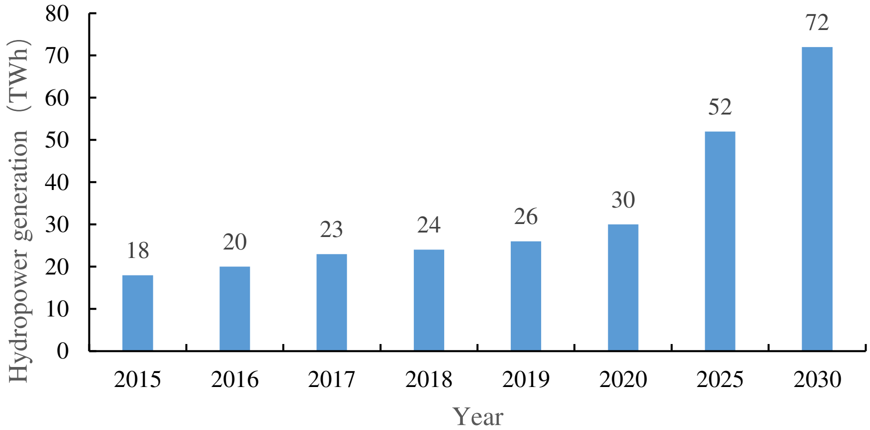

Figure 2 Hydropower generation amount during the planning period

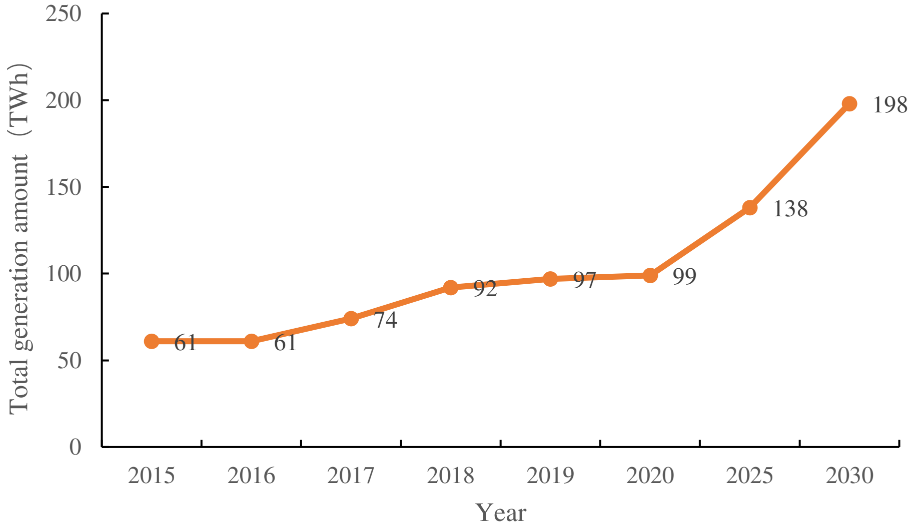

Figure 3 Total generation amount of three power resources

3.2.3 External demand

The demand for external power transmission is mainly related to the receiving end. According to the actual electricity consumption in 2015-2018, the external power demand is expected to increase by 12 TWh per year from 2020 to 2025 and continue to grow at 8 TWh per year from 2026 to 2030. The growth trend of external power demand is shown in Fig.4.

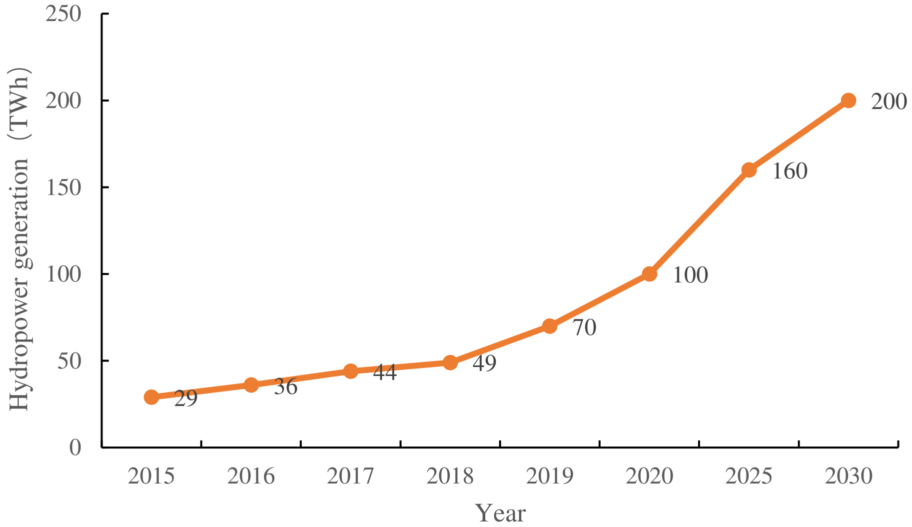

Figure 4 Total external power demand during the planning period

4. Result and discussion

4.1 Generation expansion analysis

The existing installed capacity can achieve the break-even of the three types of power supply in the case of meeting the power load and various policies in 2020. By 2025, in order to meet the increasing demand, compared with 2020, it needs to increase the thermal power of 6 GW, wind power of 9 GW, and PV power of 7.5 GW. And by 2030, with the further increase of the self-use and external load demand, it needs to increase thermal power by 3GW, wind power by 13 GW and photovoltaic by 14.5 GW, compared with 2025.

As can be seen from the Table 3, with the increase in the self-use and external demand of Xinjiang, the three types of power operation hours are higher than the break-even hours, which can obtain a certain profit. However, the utilization hours of the supporting thermal power in 2020 are low. This is because in the case of insufficient total load demand in Xinjiang, the self-use thermal power can only increase revenue by seizing the share of external thermal power in the UHV transmission channel to achieve profitability. And since the break-even utilization hours of the supporting thermal power plants are relatively low, they can still make a profit after dividing part of the grid share to the self-use thermal power plants. This phenomenon will be alleviated as the total demand increases. Although the power delivery ratio is gradually increasing, this is due to the fact that there is no increasing in the UHV supporting power plants and make more full use of the self-use power plants. Although the total investment operating cost is gradually rising due to the construction cost caused by the new installed capacity, the growth rate is slowing down, which is because the gradual saturation of the power supply and the reduction in unit cost.

Table 3 Optimal capacity results of thermal, wind and PV power in Xinjiang

		2020		2025		2030	
		Capacity (GW)	Hours	Capacity (GW)	Hours	Capacity (GW)	Hours
Thermal	Self-use	20.96	5035	26.96	5198	29.96	5500
	External	13.20	2832	13.20	4319	13.20	5225
Wind	Self-use	10.09	2201	19.09	2450	32.09	2511
	External	13.20	2177	13.20	2245	13.20	2371
PV	Self-use	7.74	1409	15.24	1507	29.24	1537
	External	3.75	1541	3.75	1602	3.75	1657
Power delivery ratio		27.14%		33.83%		36.65%	
Total cost (billion yuan)		99.54		130.41		165.77	

Under the optimized generation expansion plan, the operation hour of thermal, wind and PV power plants are high, which can realize the break-even of three kinds of power sources under the condition of coal price fluctuation. The generation planning model has good applicability.

4.2 Renewable energy efficiency analysis

As clean and low-carbon renewable energy, the utilization efficiency of wind and PV power is also a key factor in generation expansion planning. Fig. 5 shows the utilization rate of Xinjiang's renewable energy during the planning period. Influenced by policies and social responsibilities, the utilization rate of renewable energy is increasing year by year, and the development trend is unchangeable. The utilization rate of wind power has gradually increased from 85.85% to 96.42%, and that of PV power is even close to 98%. This may be caused by the following two reasons. On the other hand, the power structure in Xinjiang is also gradually optimized to clean and low carbon. As can be seen from Fig 6, the proportion of thermal power installation has remained below 50% and decreased year by year. While the renewable energy penetration rate is increasing and reached over 41.23% in 2030, which is far higher than the requirement of national policy.

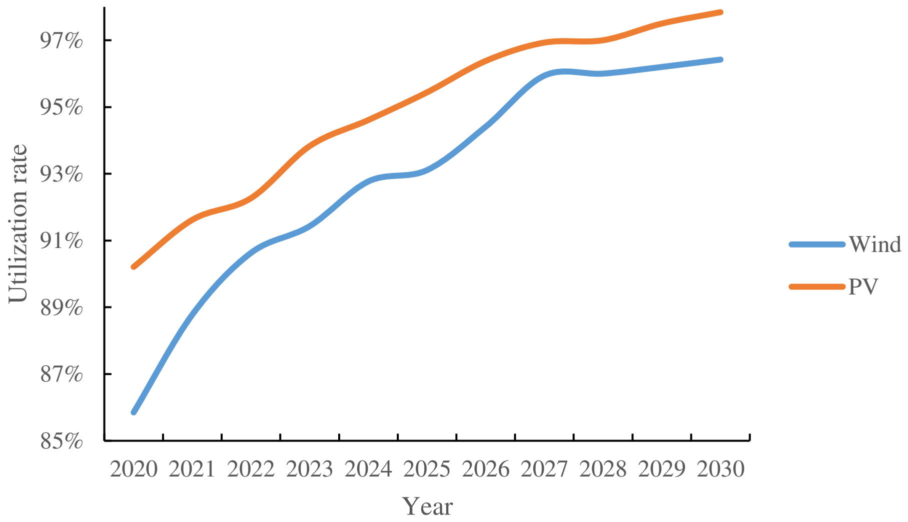

Figure 5 Utilization rate of renewable from 2020 to 2030

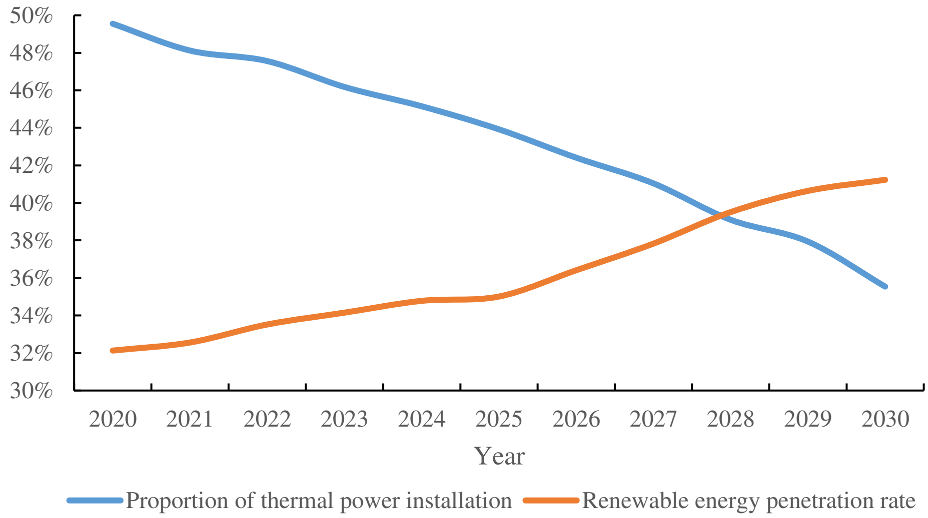

Figure 6 The power structure of Xinjiang

4.3 Sensitivity analysis

Total load demand is the decisive factor affecting the installed capacity. Therefore, based on the above plan, the influence of self-use and external demand changes on the optimization model is analyzed. The change rate is set to ±5% and the results are shown in Fig. 7. Thermal power is the most sensitive to total demand changes, followed by wind power, and PV power is the least sensitive. On the one hand, due to the limitation of renewable energy penetration, wind and PV power can't be installed in large quantities. The grid connection of renewable energy requires the power system to provide spare capacity, which will also increase the installed capacity of thermal power.

On the other hand, because of the high break-even hours of thermal power plants, it accounts for the most power generation amount in the case of the same installed growth in order to meet the economic benefits of all kinds of power resources.

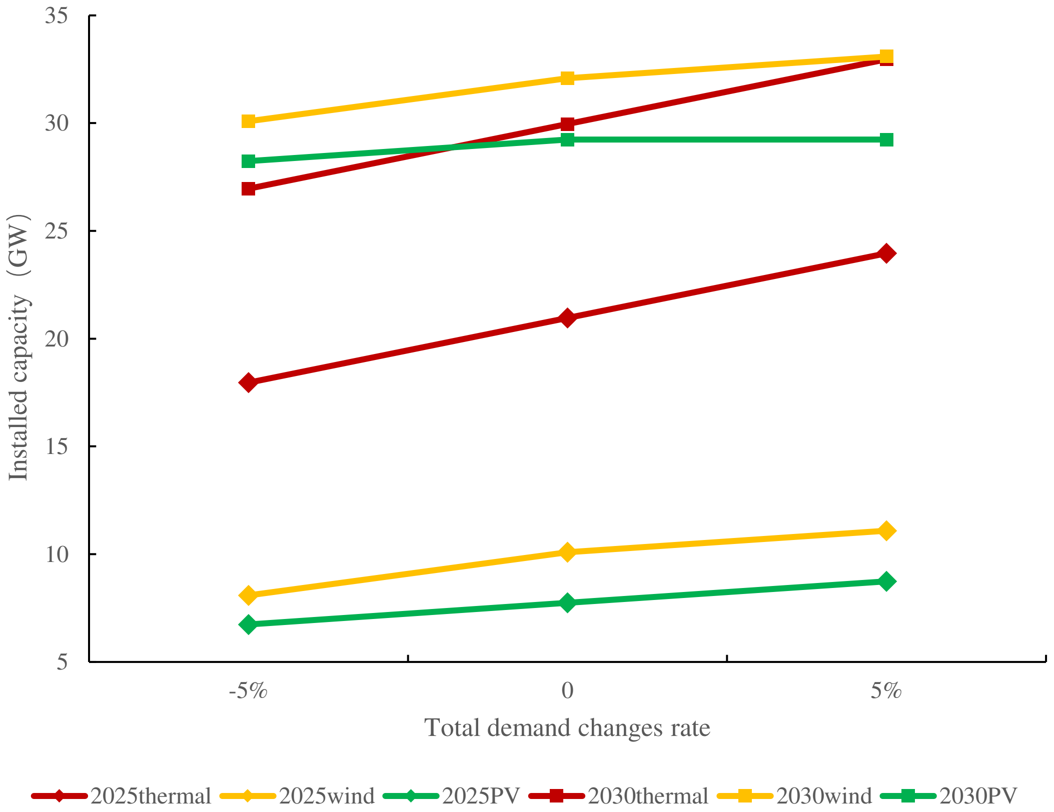

Figure 7 Sensitivity analysis result of optimization model (excluded the external power plants)

5. Conclusion

In order to realize the coordinated development of power supply, this paper studies the optimal configuration of Xinjiang's thermal, wind and PV power capacity from 2020 to 2030 based on the operating status of power plants. Firstly, the self-use and external demand in Xinjiang and hydropower generation amount are estimated, thus obtaining the development space of thermal, wind and PV power supply. Then, the break-even utilization hours are calculated according to the power plants' cost and income data obtained from field research. Finally, with the objective of minimizing the total investment and operating cost, the optimal generation planning model of thermal, wind and PV power plant is constructed and solved under multiple boundary conditions. The results show that there is a certain redundancy in the existing installed capacity in Xinjiang, which can achieve the break-even of the three types of power supply in the case of meeting the power load and various policies in 2020. Affected by national policies and the economic advantages of renewable energy, the generation expansion rate of wind and PV power is higher than that of thermal power. The profitability of the UHV supporting power supply is higher than that of the self-use power plants. Therefore, the proper development of the UHV transmission channels will help improve the economics of power generation. The generation planning model proposed in this paper can help to realize the optimal allocation of thermal, wind and PV power in Xinjiang. The proposed plan can improve the penetration rate and utilization rate of renewable energy and meet the economic demands of the three types of power sources in the context of the gradually stringent national environmental protection policy.

Abbreviations

GEP: Generation Expansion Planning; PV: Photovoltaic

Nomenclature

Subscripts and decision variables	
t	Time period, t=2020-2030
i	Type of power-generation facilities, i=1-3;coal-fired power, wind power, and photovoltaic power
C/C^*	Total investment and operating cost of self-use/external power unit
$H_{i,t}/H_{i,t}^*$	Generating equipment availability hours of self-use/external power unit i in period t
$Q_{i,t}/Q_{i,t}^*$	Installed capacity of self-use/external power unit i in period t
$\Delta Q_{i,t}/\Delta Q_{i,t}^*$	Newly installed capacity of self-use/external power unit i in period t
Parameters	
A_t/A_t^*	Average self-use/external load in period t
G_t/G_t^*	Total self-use/external demand in period t
$H_{i,max}/H_{i,max}^*$	Theoretical utilization hours of self-use/external power unit i
$P_{i,t}/P_{i,t}^*$	Installation cost of self-use/external power unit i in period t
S_i/S_i^*	Break-even utilization hours of self-use/external power unit i
$\alpha_{i,t}/\alpha_{i,t}^*$	Minimum utilization rate of self-use/external power unit i in period t
$\beta_{i,t}/\beta_{i,t}^*$	Utilization rate of self-use/external power unit i in period t for adding new power plants
γ_t/γ_t^*	Maximum penetration rate of self-use/external power unit i in period t
$\theta_{loss}/\theta_{loss}^*$	Comprehensive line loss rate of self-use/external transmission channels
λ	Power delivery ratio
η/η^*	Reserve capacity coefficient of self-use/external thermal power
$\delta_{i,t}/\delta_{i,t}^*$	Operating cost of self-use/external power unit i in period t
ϑ/ϑ_t^*	Non-hydropower renewable energy weights in period t

Declarations

Ethics Approval and Consent to Participate

Not applicable.

Consent for publication

Not applicable.

Availability of supporting data

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

LY contributed to the design of the work, acquisition of data, analysis and interpretation of data, drafting of the work, and management work. DM contributed to the design of the work, acquisition of data, analysis and interpretation of data, drafting of the work, and management work. HST and LDG contributed to the design of the work, interpretation of data, and drafting of the work. QG contributed to the design of the work, interpretation of data, and drafting of the work. LGQ and XGL have contributed equally to the writing and contributed to the revising and finalizing of the article. The authors read and approved the final manuscript.

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Figures

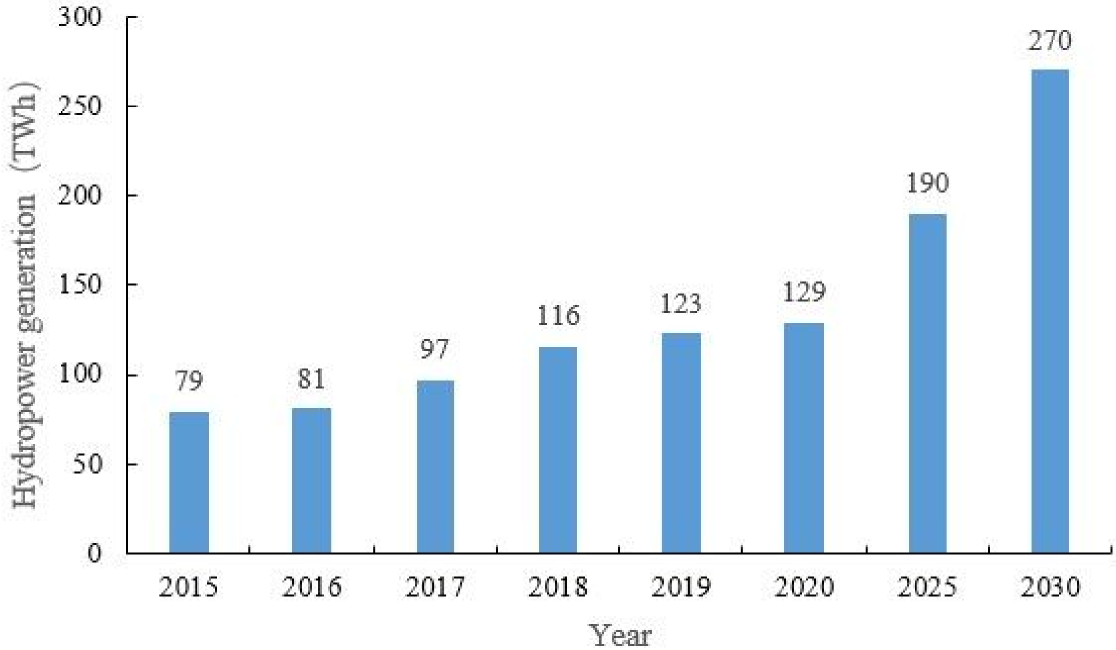

Figure 1

Self-use demand in Xinjiang during the planning period

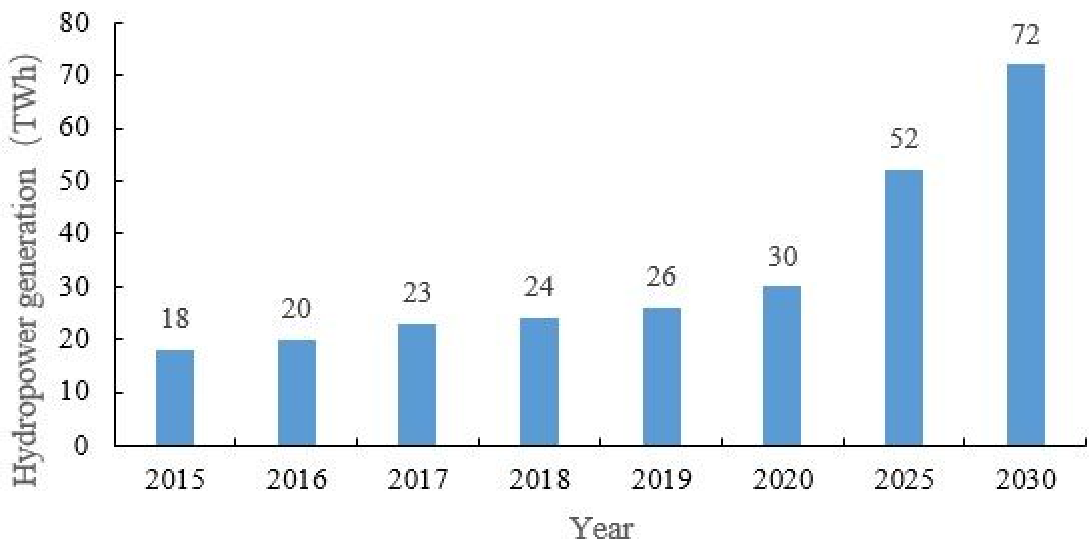

Figure 2

Hydropower generation amount during the planning period

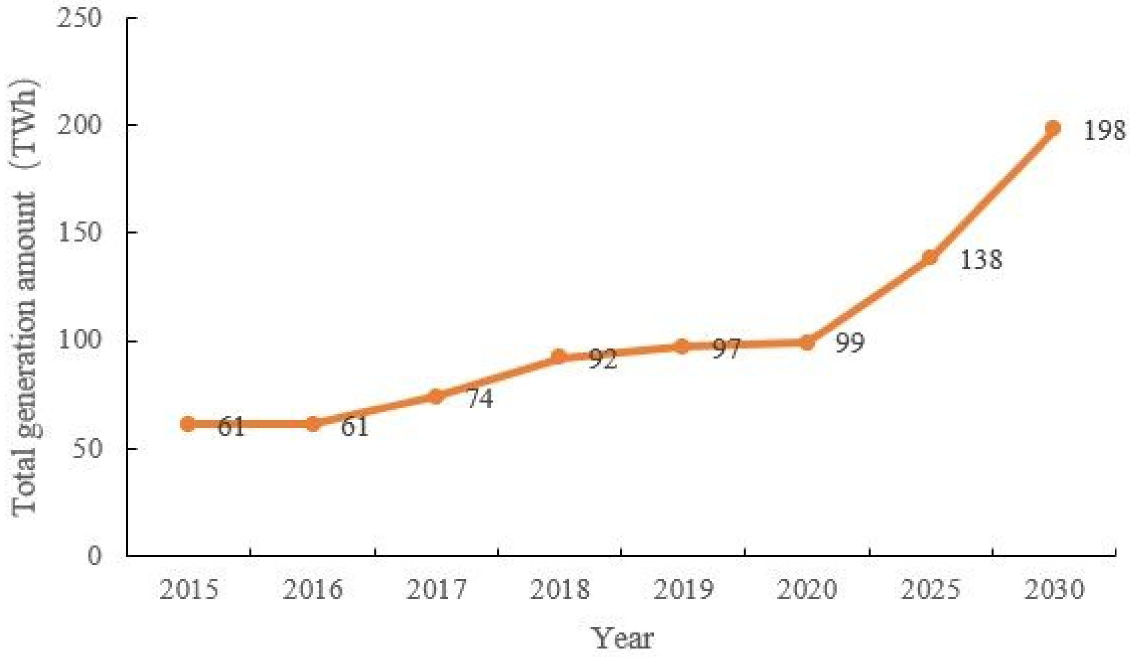

Figure 3

Total generation amount of three power resources

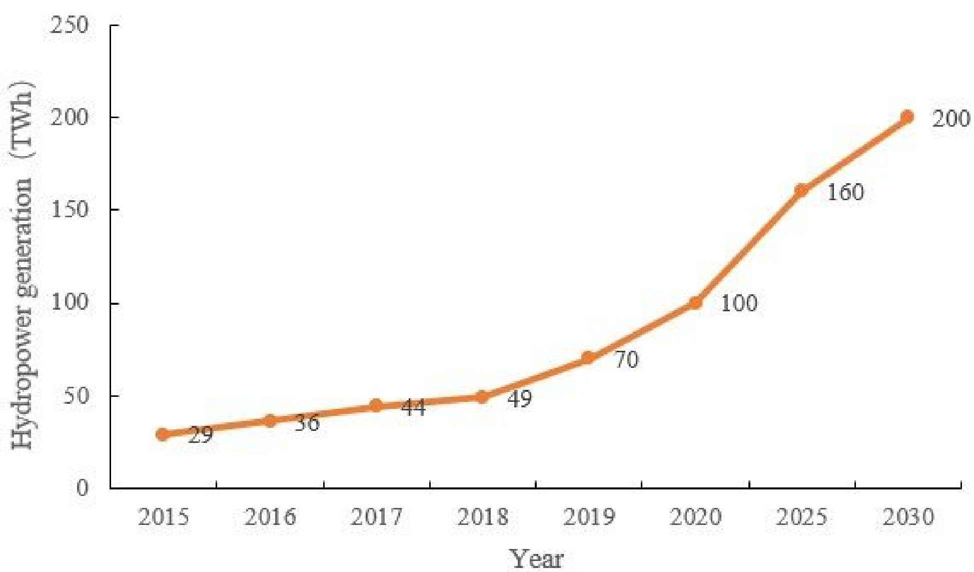

Figure 4

Total external power demand during the planning period

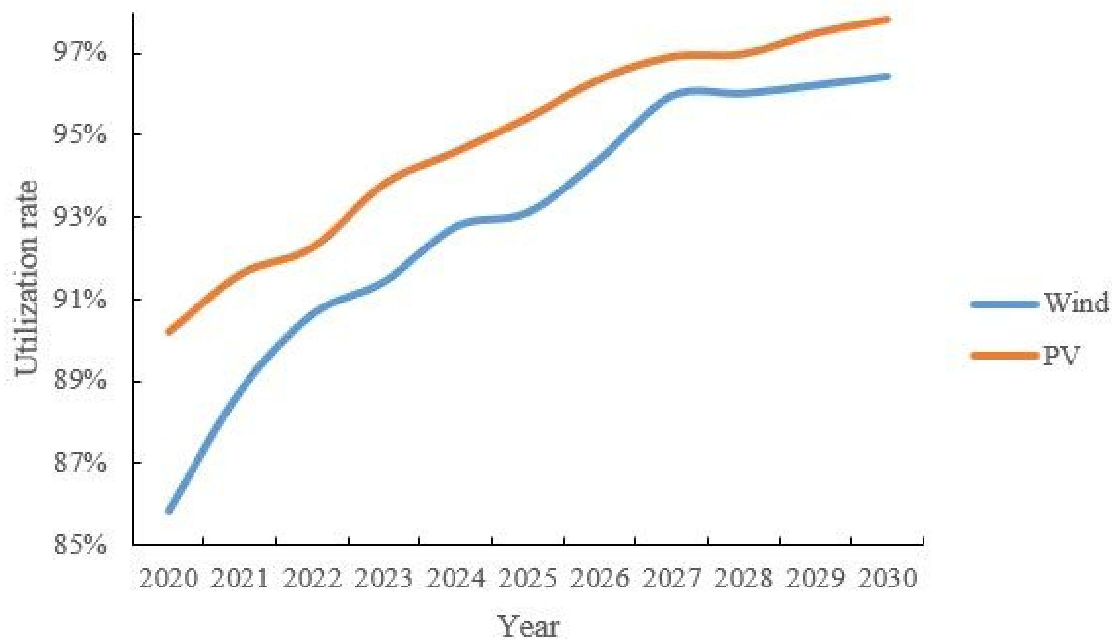

Figure 5

Utilization rate of renewable from 2020 to 2030

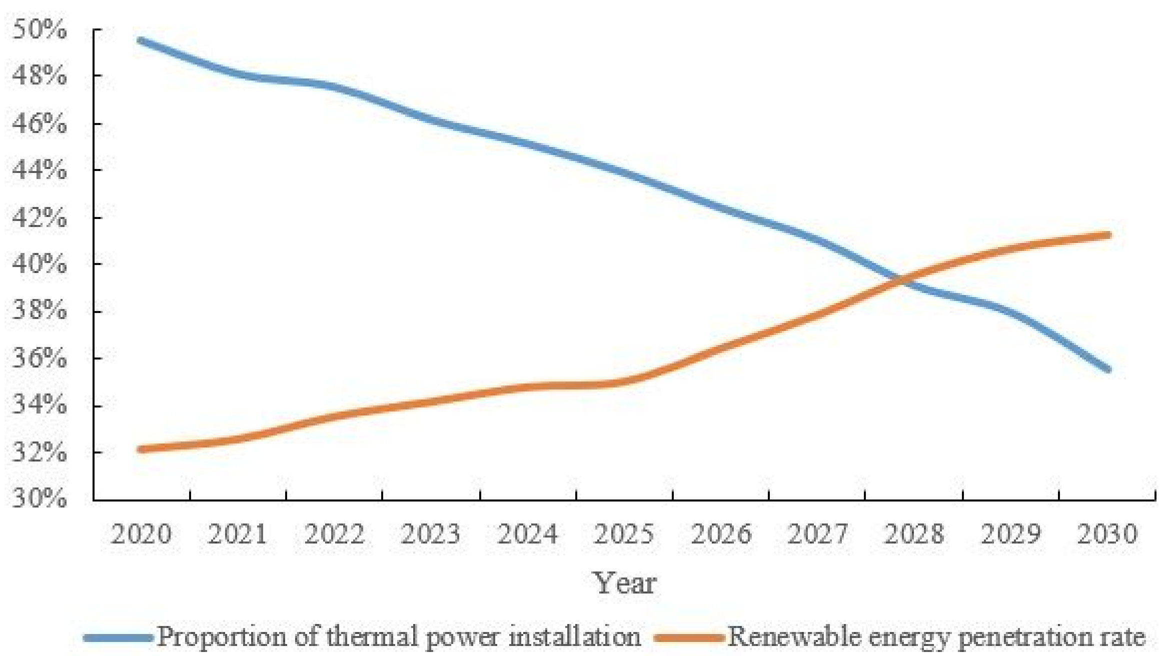

Figure 6

The power structure of Xinjiang

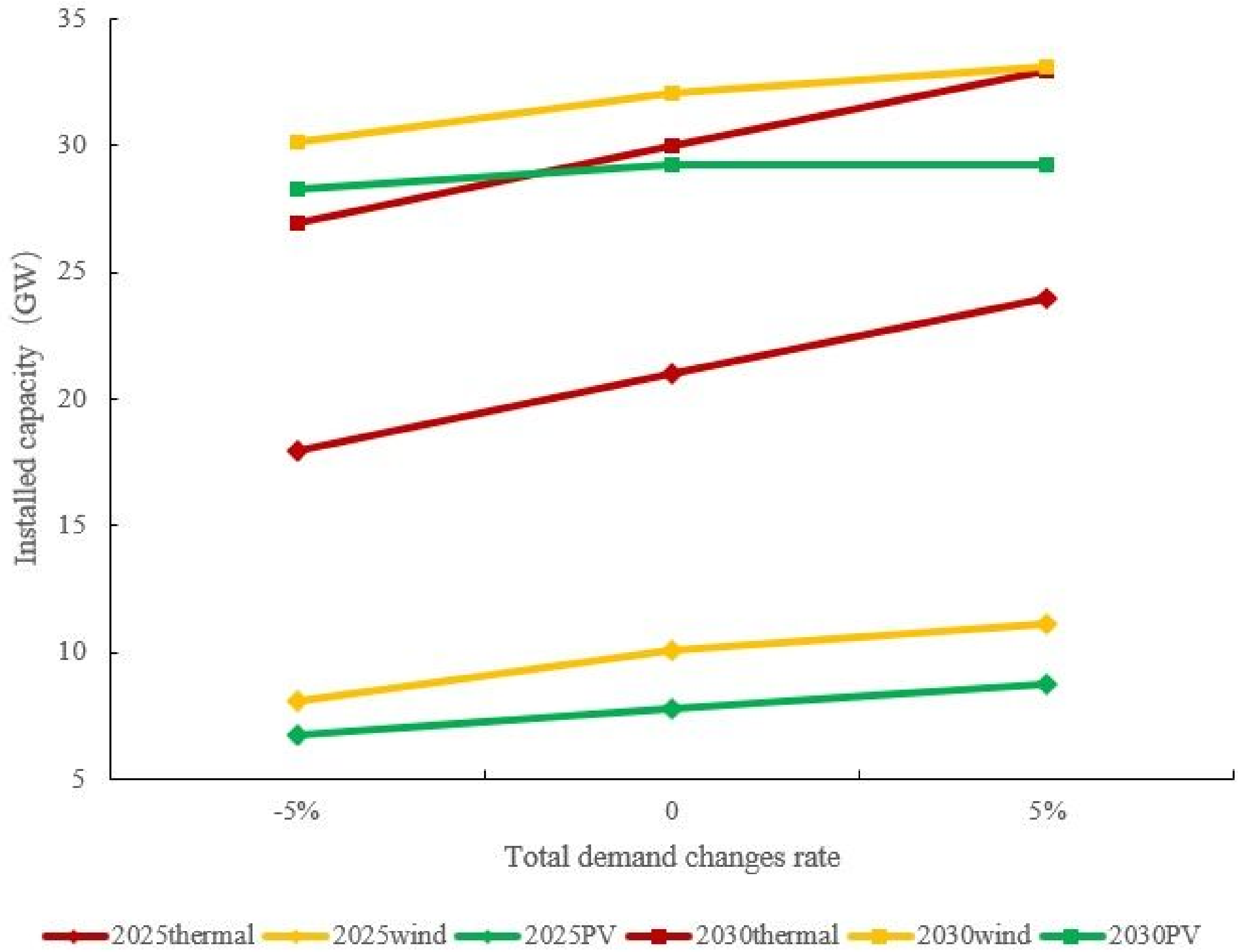

Figure 7

Sensitivity analysis result of optimization model (excluded the external power plants)