

Article

Development Potential Assessment for Wind and Photovoltaic Power Energy Resources in the Main Desert–Gobi–Wilderness Areas of China

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Abstract: The large-scale centralized development of wind and PV power resources is the key to China's dual carbon targets and clean energy transition. The vast desert–Gobi–wilderness areas in northern and western China will be the best choice for renewable energy development under multiple considerations of resources endowment, land use constraints, technical conditions, and economic level. It is urgent to carry out a quantitative wind and PV resource assessment study in desert–Gobi–wilderness areas. This paper proposed a multi-dimensional assessment method considering the influence of the power grid and transportation infrastructure distributions, which includes three research levels, namely, the technical installed capacity, the development potential, and the development cost. Nine main desert–Gobi–wilderness areas were assessed. The wind and PV technical installed capacities were 0.6 TW and 10.7 TW, and the total development potentials were over 0.12 TW and 1.2 TW, with the full load hours of 2513 and 1759 and the average development costs of 0.28 CNY/kWh and 0.20 CNY/kWh. Finally, this paper proposed the meteorological–electrical division distribution. A case study in the Kubuqi and Qaidam Deserts was carried out on wind–wind and wind–PV collaborative development across different meteorological–electrical divisions, which can reduce by 58% the long-term energy storage capacity and decrease the total system LCOE from 0.488 CNY/kWh to 0.445 CNY/kWh.

Keywords: resource assessment of renewable energy; desert–Gobi–wilderness areas; development potential assessment; development cost; meteorological–electrical division



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1. Introduction

The global energy crisis and climate change have accelerated the rapid development of renewable energy (RE) in the world. Vigorously developing and utilizing wind and solar power energy is not only an inevitable choice to promote social sustainable development but also an important measure to achieve the strategic goal of “carbon peaking and carbon neutralization” [1–4]. At present, China continues to accelerate the energy transition, putting the large-scale RE development in a prominent position and actively implementing the clean substitution of low-carbon clean energy such as wind and solar power for high-carbon fossil energy such as coal, oil, and natural gas. In general, China's hydropower resources to be developed are relatively limited, and its biomass resources are not rich and with a relatively high cost. The geothermal and marine energy power generation technology have yet to be broken through. In addition, there are increasingly stringent safety requirements for nuclear power. Therefore, from the perspective of resources endowment, technology maturity, and economic cost, the key to speed up the clean transition is the large-scale centralized development of wind and solar power energy.

In the past decade, China's RE capacities have developed rapidly, and the installed capacity of wind, photovoltaic, and other RE power generation has reached new highs, as shown in Figure 1. It can be predicted that with the generation technology progress and

the scale effect in the future, the cost will drop, forming a positive incentive and further promoting the wind and solar power development in the medium and long term [5,6]. Under multiple considerations of resources endowment, land use constraints, technical conditions, economic level, desertification control, and sustainable development of local society, especially compared with the densely populated central and eastern China, the vast deserts, stone desert, Gobi, and wilderness areas (referred to as “desert–Gobi–wilderness areas”) in northern and western China will be the best choice for the large-scale centralized development of wind and PV resources [7]. The National Development and Reform Commission of China and the National Energy Administration of China have proposed to “achieve the total installed capacity of wind and solar power reach 1200 GW by 2030” [8–11]. Therefore, it is urgent to carry out quantitative assessment and distribution research on the wind and PV resources in the main desert–Gobi–wilderness areas in China and clarify the critical issues of where, how many, and what the cost levels of the wind and PV power resources in such areas are.

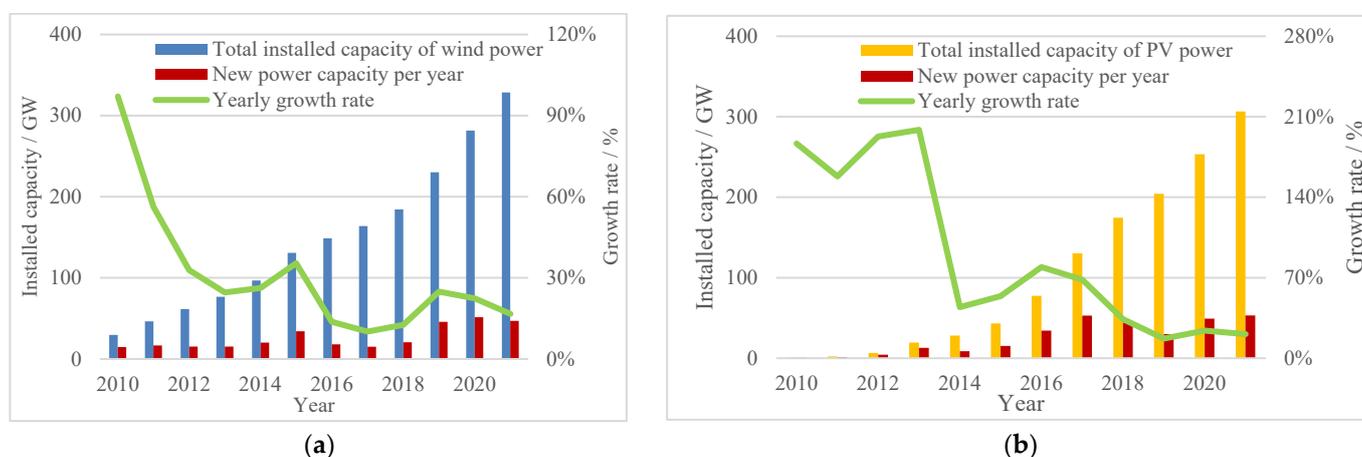


Figure 1. Changes in the installed scale of wind power and photovoltaic power generation in China in the past decade. (a) Wind power generation. (b) Photovoltaic power generation.

However, it is a systematic problem from the concept to the quantitative assessment of resources and then to the actual development: it is not only a power meteorological problem related to the endowment and characteristics of RE resources but also a technical problem that needs to consider the development and utilization conditions and technical progress and a social problem that considers the impact of human social activities and economic benefits. At present, there are few studies on the quantitative assessment of wind and PV power resources under the scenario of vigorously developing the desert–Gobi–wilderness areas. As a result, the development potential, cost analysis, and technical site selection scheme at the practical level are not clear, and it is difficult to provide corresponding support for planning decision and policy making. Among the published papers worldwide, some studies on the development, utilization, and consumption of RE power can be used for reference.

Many research institutions have carried out relevant studies on the assessment models of wind and PV resources and the quantitative calculation for specific or limited areas, which can be divided into two categories from geographical and economic views. From the geographical view, the most important thing is to determine the natural wind/solar conditions near the earth’s surface, as precisely as possible. Usually, field experimental measurements and numerical simulations are adopted for predicting the climate effects for wind/solar conditions [12–14]. Recently, more attention has been paid to building more elaborate regional climate models to evaluate the interactions between power plants and the environment [15–17]. For the specific cases, Rong Zhu from the China Meteorology Administration assessed the distribution of wind energy resources and the technical available amount in the country [18,19] but failed to carry out a quantitative assessment of the

development costs in combination with technical and economic forecasting. Liping Sun of China Energy Investment Corporation carried out the analysis of China's solar energy resource development potential, provided the interval values of PV power generation hours with the optimum tilted angles for each province, and analyzed the interval value of the internal rates of return of the projects' development in each province based on actual data and information [20]. Qiao Zhao of China Power Construction Corporation analyzed the distribution and output characteristics of wind and PV resources in Guizhou Province [21]. However, the above research focused on the characteristics of resource endowment. Next, the technical-related and economic-related factors should be taken into consideration before making policies and constructions, including the restrictions of technical level, land cover, topography, geology, and other factors on development, and attempts have been made on site selections [22–24]. The Commonwealth Scientific and Industrial Research Organization of Australia, the National Renewable Energy center of Spain, the Canadian Meteorological Agency, the Danish Risoe National Laboratory, the National Renewable Energy Laboratory of the United States, and other institutions have carried out national-level wind and solar resources assessments based on the observation data of meteorological stations or numerical simulation data; however, most of the research focuses on the characteristics and distribution of resource endowment, such as wind speed/power density [25–30] or improving processing and analysis methods of resource data [31,32]. IRENA and other institutions have completed the assessment of wind energy resources in Africa [33,34], considering the land covers for excluding unsuitable areas such as cities and farmland. The energy administration of northern Ontario carried out the analysis of environmentally sensitive areas and estimated the technical development areas and amount of installed capacity [35]. However, in general, the assessment of wind and PV resources in the wide area focuses on the analysis of resource reserves and land use and lacks a quantitative calculation of the economy, and no team has yet carried out special research on resource assessment in desert–Gobi–wilderness areas. The existing research on these areas always focuses on analyzing the ecosystem and geomorphic changes or resource characteristics in a single area [36–42].

In view of the deficiencies of the above research, this paper aims to comprehensively consider the natural, technical, economic, and other factors of the desert–Gobi–wilderness areas, starting from the quantitative assessment model, relying on GIS analysis and the platform tool, and through multi-level and multi-criteria quantitative analysis to realize the systematic calculation of wind and PV development potentials in the main desert–Gobi–wilderness areas of China and carry out the case study on the collaborative optimization development of wind and PV energy, so as to fill the above research gap and provide direct support for the planning decision. Specifically, this paper carries out the following three major research innovations:

- (1) The assessment models and principles of wind and PV resources considering the infrastructure distribution in desert–Gobi–wilderness areas are proposed, including three research levels: technical installed capacity, priority development potential, and development cost.
- (2) The definition of the desert–Gobi–wilderness area and the research scope of nine main areas are proposed. Based on GIS technology, the refined technical and economic assessment is realized with a spatial resolution of 500 m.
- (3) The meteorological–electrical divisions of wind and solar resources in China are proposed by analyzing the long-term meteorological data, realizing the case study on the collaborative optimization development of wind and PV power bases.

The above research will help to clarify the wind and PV power potential and economic level of the desert–Gobi–wilderness areas in China, which has certain guiding significance for engineering practice and can provide reference for planning decision and policy making.

2. Research Methods

2.1. Study Scope

From 2021 to now, the National Development and Reform Commission and the National Energy Administration of China have clearly proposed to speed up the planning and development of large-scale wind and solar power bases focusing on the desert–Gobi–wilderness areas. According to the relevant geographical and ecological definitions and main research concerns, this paper proposes the definition of desert–Gobi–wilderness areas: the barren areas that is bare ground or covered by sand and gravel, with dry climate, low precipitation, sparse vegetation, and small biomass, such as the desert, stony desert, salt desert, pebble cobble desert, Gobi, wasteland, and others in general cognition. These areas are mainly distributed in the north and west and often rich in wind and solar energy resources. According to the geographical division, they are mainly located in the Inner Mongolia Plateau, Ordos Plateau, Alxa Plateau, Hexi Corridor plain, and other geomorphic units, which are mainly distributed in Xinjiang, Gansu, Inner Mongolia, Qinghai and other provinces [36].

This paper focuses on seven deserts including the Kubuqi, Ulan Buh, Tengger, Badain Jaran, Gurbantunggut, Kumtag, and Qaidam Deserts and two Gobi regions including Hainan district of Qinghai Province and the north of the Tianshan Mountains, a total of nine main desert–Gobi–wilderness areas in China, to carry out the wind and PV resource assessment and priority development potential evaluation of large-scale bases.

For a long time, there have been some disputes over the geographical boundaries of these nine areas. In this paper, based on the research of the China Geological Survey [37], Longzhen Lin of Beijing Forestry University [38], Peng Jia of Lanzhou University [39], Yiming Feng of the Chinese Academy of Forestry Sciences [40], Jianyu Liu [41], Guolin Yang of Lanzhou Jiaotong University [42], Yujie Xu of the Chinese Academy of Sciences [43], and other institutions and scholars, the main study scope of the nine main desert–Gobi–wilderness areas is provided with high-resolution satellite image data, as shown in Figure 2.

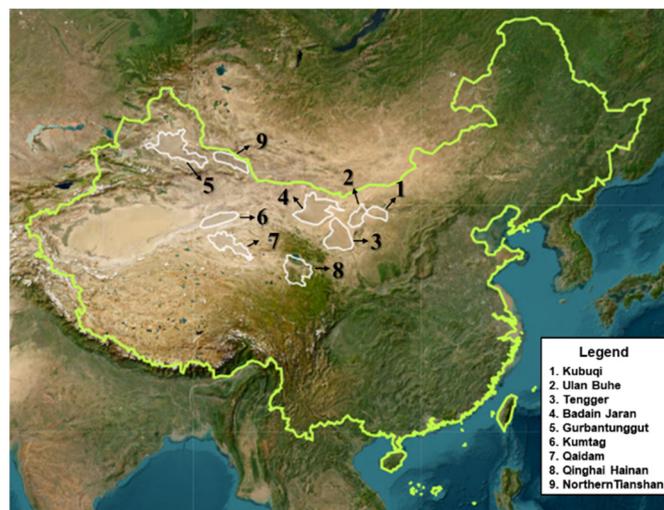


Figure 2. The geographical distribution of nine main desert–Gobi–wilderness areas.

2.2. Assessment Methods

The research team has been engaged in the assessment of RE resources for a long time [2,44,45] and has established quantitative models for the assessment of global wind and solar energy resources by selecting three main indicators, namely, theoretical reserves, technical installed capacity, and development cost, which concern the influence of the power grid and transportation infrastructures distribution. For this study, technical installed capacity and development cost were more suitable and valuable.

2.2.1. Technical Installed Capacity

The key for the assessment was to exclude the undevelopable areas due to resource endowment, conservation areas, altitude and sea depth, land cover, and other restrictions, calculate the available area A_{avl} , then consider the impact of a different land cover, set the land use coefficient, and calculate the effective installed area A_{eft} . The detailed methods and parameters can be seen in the technical monograph in [44,45].

$$A_{eft} = \eta A_{avl} = \eta \left(A_{sum} - \sum_{i=1}^n A_{coni} - \sum_{i=1}^m A_{resi} - \sum_{i=1}^r A_{alti} - \sum_{i=1}^w A_{landi} \right) \quad (1)$$

where η is the land use coefficient, A_{sum} is the total area of the assessment areas, and A_{con} , A_{res} , A_{alt} , and A_{land} are the areas excluded for conservation areas restrictions, poor resources, high-altitude restrictions, and land cover restrictions, respectively.

For the wind energy assessment, the influence of the terrain gradient difference on the installed capacity per unit area was determined by setting the gradient influence factor α . For the technical potential installed capacity $P_{TPGWind}$, it was necessary to calculate the effective installed capacity area and the actual installed capacity of each grid in the area, calculate the annual average wind speed in the standard state as a technical indicator, and calculate the annual hourly power generation sequence according to the typical wind turbine power curve using the interpolation method, so as to obtain the annual power generation $Q_{TPGWind}$. More details of the typical wind turbines' power curves chosen in this study can be found in reference [45], appendix Figure A1.

$$P_{TPGWind} = P_{unit_wind} \sum_{i=1}^n (A_{efti} \alpha_i) \quad (2)$$

$$Q_{TPGWind} = P_{unit_wind} \sum_{i=1}^n \left(A_{efti} \alpha_i \sum_{j=1}^{8760} P_{windj} \right) \quad (3)$$

where, P_{unit_wind} is the wind power installed capacity per unit area, and P_{Windj} is the normalized power generation of a typical wind turbine at the hour j .

For the assessment of PV resources, the area with a terrain gradient greater than 30° was difficult to develop and needed to be excluded. To evaluate the technical developable capacity of P_{TPGPV} , it was necessary to calculate the installed capacity first, that is, to obtain the total capacity power of the photovoltaic power generation modules arranged per unit area based on the equipment parameters and optimal arrangement method under the current technical conditions. The accumulation of the product of the effective installed area and installed density of all grid points in the assessment area is the amount of PV technical installed capacity. Further considering the losses caused by temperature, shelter, equipment loss, and other factors, the hourly photovoltaic power generation can be calculated, and then the annual power generation Q_{TPGPV} can be obtained.

$$P_{TPGPV} = \sum_{i=1}^n A_{efti} \cdot P_{unit_PV} \quad (4)$$

$$Q_{TPGPV} = P_{unit_PV} \sum_{i=1}^n \left(A_{efti} \sum_{j=1}^{8760} P_{PVj} \right) \quad (5)$$

$$P_{PVj} = \frac{GTI}{1000} \cdot k \cdot [1 + \zeta(T - 25)] \quad (6)$$

where P_{unit_PV} is the installed capacity of photovoltaic power generation per unit area, P_{PVj} is the unit installed PV power generator's output after considering reduction and losses in the j th hour, GTI is the global tilted irradiance, ζ is the component power temperature

coefficient with a value of -0.4% , k is the loss coefficient of PV array with a value of 0.85 in this study, and T is the local ambient temperature in degrees Celsius.

2.2.2. Development Costs

The levelized cost of energy (LCOE) was used to evaluate the development cost, which was closely related to the equipment and construction cost, financial parameters, and infrastructure conditions that affected the economy. Each geographical grid was regarded as an independent unit to calculate separately. References [5,6,46,47] introduce the comprehensive multiple linear regression prediction method and the correlation analysis prediction method based on the deep self-learning neural network algorithm to carry out the technical and non-technical cost prediction models, respectively. Among them, it is noteworthy that the research has realized the quantitative analysis of the distribution of the power grid and transportation facilities on the development cost, using the data of 147 national AC and DC backbone transmission networks established by the GEIDCO [44], the dataset of the global highway network released by the socio-economic data and application center of NASA, and the data of the planned road network in China's national highway network planning (2022–2035). Combined with GIS analysis, different transmission mode selections, grid connection distances under different voltage levels, and off-site access road distances at various grid points, the cost impact of grid and off-site traffic connection was quantitatively calculated.

$$LCOE_i = LCOE_{\text{generation}i} + LCOE_{\text{grid}i} + LCOE_{\text{road}i} \quad (7)$$

$$LCOE_{\text{generation}i} = \frac{P_{\text{TPGi}}(C_{\text{EQ}} + C_{\text{INSTL}}) + \sum_{n=0}^N (M_n + F_n) \frac{1}{(1+r)^n} - V_R \frac{1}{(1+r)^N}}{\sum_{n=0}^N Q_{\text{TPGi}} \frac{1}{(1+r)^n}} \quad (8)$$

$$LCOE_{\text{grid}i} = L_{\text{grid}i} \cdot \eta_{\text{grid}} \cdot C_{\text{grid}} \cdot P_{\text{TPGi}} \quad (9)$$

$$LCOE_{\text{road}i} = L_{\text{road}i} \cdot C_{\text{road}} \cdot P_{\text{EPGi}} \quad (10)$$

where $LCOE_i$ is the total LCOE for the i th grid point with the unit of CNY/kWh, which is composed of three parts: the technical cost $LCOE_{\text{generation}i}$ for equipment and construction, the grid connection cost $LCOE_{\text{grid}i}$, and the off-site transportation cost $LCOE_{\text{road}i}$. P_{TPGi} is the technical potential installed capacity, and Q_{TPGi} is the annual power generation. C_{EQ} and C_{INSTL} are the equipment cost and the construction and installation cost per kilowatt, respectively, N is the operation life of the power station, and r is the discount rate. M_n and F_n are the operation and maintenance costs and financial costs of the n th year, respectively. V_R is the residual value of the power station. $L_{\text{grid}i}$ is the nearest distance between the i th grid point and the power grid facilities of each voltage level, and η_{grid} is the nonlinear path coefficient. C_{grid} is the grid connection cost per unit installed capacity unit distance after the transmission mode selection with the unit of CNY/(kW·km). $L_{\text{road}i}$ is the distance between the i th grid point and the nearest highway facilities, and C_{road} is the traffic cost per unit installed capacity unit distance with the unit of CNY/(kW·km).

2.2.3. Digital Platform Tool

The Global Renewable-Energy Exploitation Analysis Platform (GREAN) established by the research team was based on the global resource–geographic–social database and the multi-dimensional refined assessment model, which can realize the systematic assessment and rapid online calculation of hydropower, wind power, and photovoltaic power generation resources worldwide.

Reference [2] introduces the research on the cost increment of carbon neutrality in China's power system based on the GREAN platform, which is carried out in cooperation with Tsinghua University and Harvard University. Reference [48] introduces the research on

the green hydrogen development potential and economic analysis in China. Reference [49] introduced that the GREAN platform, as a typical global meteorological energy service case, can promote the development of RE and was included in the global annual report of the World Meteorological Organization in October 2022.

2.3. Assessment Principles of Desert–Gobi–Wilderness Areas

At present, there is no unified standard for the classification and geographical boundaries of the desert–Gobi–wilderness areas. In addition, these areas are distributed in different provinces and regions in the vast northern part, with obvious geomorphic differences. It is necessary to put forward the specific areas, assessment principles, and relevant quantitative parameters according to the local conditions on the basis of the abovementioned RE resources assessment model. Therefore, this paper puts forward three research levels, namely, the technical installed capacity assessment of the whole region, the development potential, and the cost assessment of the priority regions.

(1) Technical Installed Capacity Assessment Principle

According to the differences of surface characteristics and development conditions of desert–Gobi–wilderness areas, it is necessary to consider different influencing factors, such as resource endowment, land cover, conservation areas, altitude restriction, and so on, and put forward the assessment principles. Table 1 provides the main indicators and recommended parameters.

Table 1. Main indicators and recommended parameters used in wind and PV resource assessment model of technical potential installed capacity in desert–Gobi–wilderness areas.

Type	Restriction	Threshold Value	Land Use Coefficients η	
			Wind	PV
Resource restrictions	Annual average wind speed	>5 m/s	-	-
	Global horizontal irradiance	>1000 kWh/m ²	-	-
Technical development restrictions	Wind land elevation	<4000 m	-	-
	PV land elevation	<4500 m	-	-
Conservation area restrictions	Natural ecosystem	Unsuitable	0%	0%
	Wildlife	Unsuitable	0%	0%
	Natural relics	Unsuitable	0%	0%
	Natural resources	Unsuitable	0%	0%
	Others	Unsuitable	0%	0%
Land cover restrictions	Bare ground	Suitable	100%	100%
	Shrub	Suitable	100%	100%
	Grassland	Unsuitable	0%	0%
	Forest	Unsuitable	0%	0%
	Cultivated land	Unsuitable	0%	0%
	Wetland and swamp	Unsuitable	0%	0%
	Cities and urban areas	Unsuitable	0%	0%
Ice and snow	Unsuitable	0%	0%	
GIS Slope	-	>30°	0%	0%

- ① Eliminate the areas with unsatisfactory resource endowment. Due to the increasing large-scale level of wind turbines and the continuous improvement of hub height, the wind speed resource data at two elevations of 100 m and 150 m height were used in the assessment. The total horizontal radiation GHI was used for the photovoltaic assessment. Combined with the engineering construction practice, the areas with annual average wind speeds less than 5 m/s or areas with GHIs less than 1000 kWh/m² were regarded as low-resource areas, which are not suitable for large-scale development.

- ② Eliminate all types of national conservation areas, including natural ecology, wildlife, and natural resources conservation areas.
- ③ Exclude the high-altitude areas that are not suitable for development under the current technical level and the plateau with an altitude of more than 4000 m; the air is thin, the wind power density is reduced, and most of them are distributed with glaciers and permafrost. The construction of the power generation base is difficult, which may seriously affect the natural environment and is not suitable for development.
- ④ Bare ground and sparse low shrubs are the two typical land covers in the desert–Gobi–wilderness areas, and the recommended land use coefficient is 100%. Grassland, forests, cultivated land, wetlands, swamps, cities, ice, and snow are not suitable for centralized development.
- ⑤ Considering the distribution and mobility characteristics of desert–Gobi–wilderness areas in China, the mobile sandy land and semi-mobile sandy land are difficult for engineering construction and should be excluded. As the most widely distributed category, the desert can be divided into four types according to its mobility characteristics: mobile sandy land, semi-mobile sandy land, semi-fixed sandy land, and fixed sandy land [50]. The surface landscape characteristics of mobile and semi-mobile sandy land are shifting dunes and sand, which is distributed continuously in a large area and generally causes it to be difficult to construct power bases.
- ⑥ The area with a terrain gradient greater than 30° is not suitable for development due to its difficulty and poor economy under the current technical level and should be excluded.
- ⑦ In combination with the detailed investigation and data collection of the specific desert–Gobi–wilderness areas, the mineral areas, scenic spots, military-sensitive areas, and other areas that are not suitable for development can be further excluded.

(2) Priority Development Potential Assessment Principles

Take the region located in the edge of desert–Gobi–wilderness areas, along the crossed highway, around the villages and other populated areas as the priority development areas, and assess the development potential of wind and photovoltaic power. The assessment principles are as follows. Tables 2 and 3 show the composition and the recommended parameters of the initial development investment and the recommended values of the financial parameters.

Table 2. Main investment parameters for wind and PV resource assessment in desert–Gobi–wilderness areas.

Number	Investment Composition for Wind Resources	Total Cost (CNY/kW)	Investment Composition for PV Resources	Total Cost (CNY/kW)
1	Equipment and installation cost	4144	Equipment and installation cost	3087
1.1	Generator and blade	2912	PV module	1400
1.2	Tower	525	Support bracket	357
1.3	Installation	182	Installation	749
1.4	Others	525	other	581
2	Construction and others	1393	Construction and others	161
2.1	Foundation and other buildings	665	Management costs	14
2.2	Management costs	161	Design fee	35
2.3	Others	567	Others	112
	Total	5537	Total	3248

Table 3. Main financial parameters for development cost study of wind and PV resources in desert–Gobi–wilderness areas.

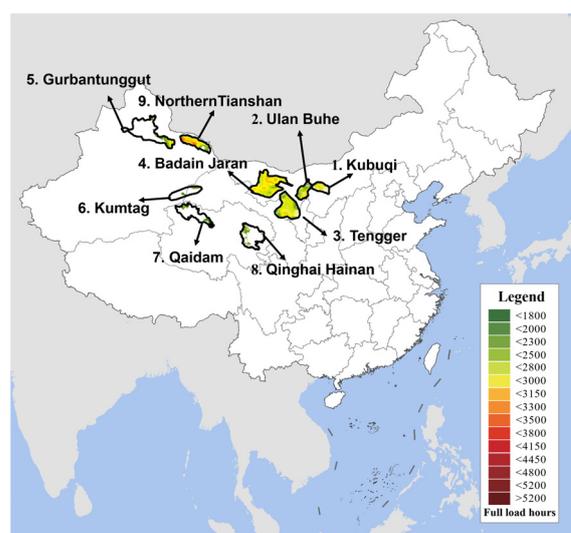
Number	Financial Parameters	Wind	PV
1	Loan term	7 years	7 years
2	Loan proportion	70%	70%
3	Loan rate	3%	3%
4	Construction period	1 year	1 year
5	Service life	20 years	20 years
6	Residual value proportion	0%	0%
7	Operation and maintenance proportion	3.5%	1.5%

- ① According to the principle of easy to difficult and phased development, 5 km, 10 km, and 20 km were selected as the distance thresholds to determine the scope of the priority development areas and then assess the technical installed capacity of wind and photovoltaic power in the area as the priority development potential.
- ② Focusing on the technical costs of the equipment and infrastructure, combined with the situation of existing projects, and considering the reasonable non-technical costs (mainly including land use, up-front costs, etc., accounting for 10–15%), the comprehensive development and construction costs in 2025 were predicted.
- ③ The off-site transportation costs and grid connection costs of the power bases were included in the total development cost, and the LCOE under level year was calculated.

3. Wind and PV Assessment

3.1. Development Potential Assessment of Wind Resources

The annual average wind speed in nine major desert–Gobi–wilderness areas was about 5.7 m/s at 100 m height. The total amount of technical installed capacity was more than 600 GW, with a full load hour of 2600. The distribution of technical available areas for wind power development and full load hours is shown in Figure 3. Mainly affected by the wind resource endowment, the four deserts including the Badain Jaran, Ulan Buh, Kubuqi, and Tengger Deserts and the Gobi region at the northern foot of the Tianshan Mountains had a wider space distribution with full load hours generally higher than average level, up to more than 2800. Based on the wind speed data at 150 m height, the technical installed capacity was increased to 750 GW, and the average full load hours exceeded 3070.

**Figure 3.** Distribution of technical available areas for wind power development and full load hours in the nine main desert–gobi–wilderness areas.

The technical available areas located in the edge of desert–Gobi–wilderness areas, along the crossed highway, around the villages and other populated areas with a distance less than 5 km can be regarded as the priority development areas. The nine desert–Gobi–wilderness areas had priority development areas of 27,000 km², accounting for 9% of the total area, with the priority development potential of about 120 GW and full load hours of 2513. According to the investment economic level in 2025, the average cost was 0.28 CNY/kWh.

According to the phased development principle from easy to difficult, 5 km, 10 km, and 20 km were selected as the distance thresholds to determine the scope of priority development areas, which accounted for 9%, 16%, and 27%, respectively. The development potentials were 120, 210, and 350 GW. Table 4 shows the detailed potential assessment results.

Table 4. Wind development potential assessment results in the nine main desert–Gobi–wilderness areas.

	Name	Total Area (km ²)	Wind Speed (m/s)	Technical Installed Capacity (GW)	Priority Development with Distance of 5 km			LCOE (CNY/kWh)
					Development Area (km ²)	Development Potential (MW)	Full Load Hours	
1	Kubuqi	12,518	6.4	31.3	1404	6808	2428	0.26
2	Ulan Buh	15,525	6.04	58.5	3666	16,615	2487	0.27
3	Tengger	42,678	6.2	164.2	3066	14,380	2426	0.28
4	Badain Jaran	51,614	6.48	170.1	6657	29,031	2760	0.28
5	Gurbantunggut	50,536	4.84	45.0	2336	10,784	2274	0.3
6	Kumtag	22,688	4.99	11.3	519	2060	2230	0.34
7	Qaidam	35,007	5.25	27.5	2400	10,216	2051	0.34
8	Qinghai Hainan	43,559	5.38	15.2	2196	6540	2049	0.33
9	Northern Tianshan	20,308	6.42	80.6	4361	19,078	2824	0.25
	Total	294,433	5.7	603.6	26,605	1,155,112	2513	0.28

3.2. Development Potential Assessment of Photovoltaic Resources

The GHI in the nine main desert–Gobi–wilderness areas was 1677 kWh/m². The total scale of PV technical installed capacity was more than 10.7 TW, and the full load hour was 1747, which was significantly higher than the 1650 value of all desert–Gobi–wilderness areas in China. The distribution of technical available areas for PV power development and full load hours is shown in Figure 4.

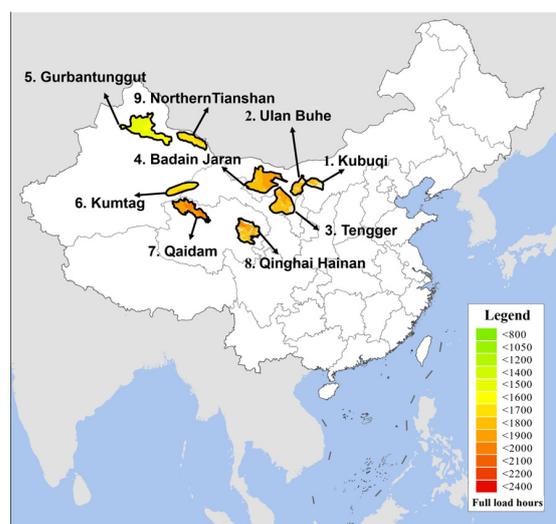


Figure 4. Distribution of technical available areas for PV power development and full load hours in the nine main desert–Gobi–wilderness areas.

The PV priority development areas with 5 km distance thresholds in nine desert–Gobi–wilderness areas was 36,000 km², accounting for 12% of the total area, with the priority development potential of about 12 TW and full load hours of 1759. According to the investment economic level in 2025, the average cost was 0.20 CNY/kWh. Moreover, 5 km, 10 km, and 20 km were selected as the distance thresholds, and the priority development areas accounted for 12%, 21%, and 28%, respectively. The development potential was 12, 21, and 30 TW, respectively. Table 5 shows the detailed PV development potential assessment results.

Table 5. PV development potential assessment results in the nine main desert–Gobi–wilderness areas.

Name	GHI (kWh/km ²)	Technical Installed Capacity (GW)	Priority Development with Distance of 5 km			LCOE (CNY/kWh)	
			Development Area (km ²)	Development Potential (MW)	Full Load Hours		
1	Kubuqi	1711	280	1404	8630	1770	0.19
2	Ulan Buh	1739	548	2129	90,850	1781	0.19
3	Tengger	1730	1690	1038	47,530	1783	0.20
4	Badain Jaran	1760	1930	2593	102,870	1793	0.22
5	Gurbantunggut	1463	1550	8442	83,700	1491	0.24
6	Kumtag	1679	900	1313	51,990	1691	0.24
7	Qaidam	1821	1670	4307	210,520	1876	0.18
8	Qinghai Hainan	1672	1520	10,104	445,440	1801	0.19
9	Northern Tianshan	1637	642	4797	148,510	1674	0.22
Total		1677	10,730	36126	1,190,040	1759	0.20

3.3. Development Suitability Evaluation of Large-Scale Wind and PV Power Bases

The layout planning and site selection of large-scale wind and PV power bases in the desert–Gobi–wilderness areas need to consider many aspects of influence. This paper carries out a comprehensive comparative analysis to evaluate the suitability in six aspects: the wind and PV power resource endowment, economic and social development, desertification level, base construction conditions, power grid, and road network infrastructure conditions. The development suitability radar maps are shown below.

(1) Wind Power Endowment

There were great differences of wind resources in these nine areas. The average wind speeds in the Kubuqi and Badain Jaran Deserts with good resource conditions were more than 6.4 m/s, while the average wind speed in the Gurbantunggut Desert was less than 5 m/s, which led to a small technical available area and relatively low equipment utilization hours. For wind development, the Tianshan Mountain Gobi had the highest full load hours, reaching 2824, and the average development cost was 0.25 CNY/kWh. The four regions of the Kubuqi Badain Jaran, Ulan Buh, and Tengger Desert had full load hours of 2400 and above, and the costs were less than CNY 0.28, which had excellent economy. For Kumtag, Qaidam, and Hainan Gobi, due to the limitations of high altitude, poor resources, and other conditions, the costs were higher than 0.33 CNY/kWh with relatively poor economy. As an example, the distribution map of the wind speed, the probability histogram of the wind speed, and the LCOE distribution in the priority development areas with a 20 km distance threshold of the Kubuqi Desert are shown in Figure 5.

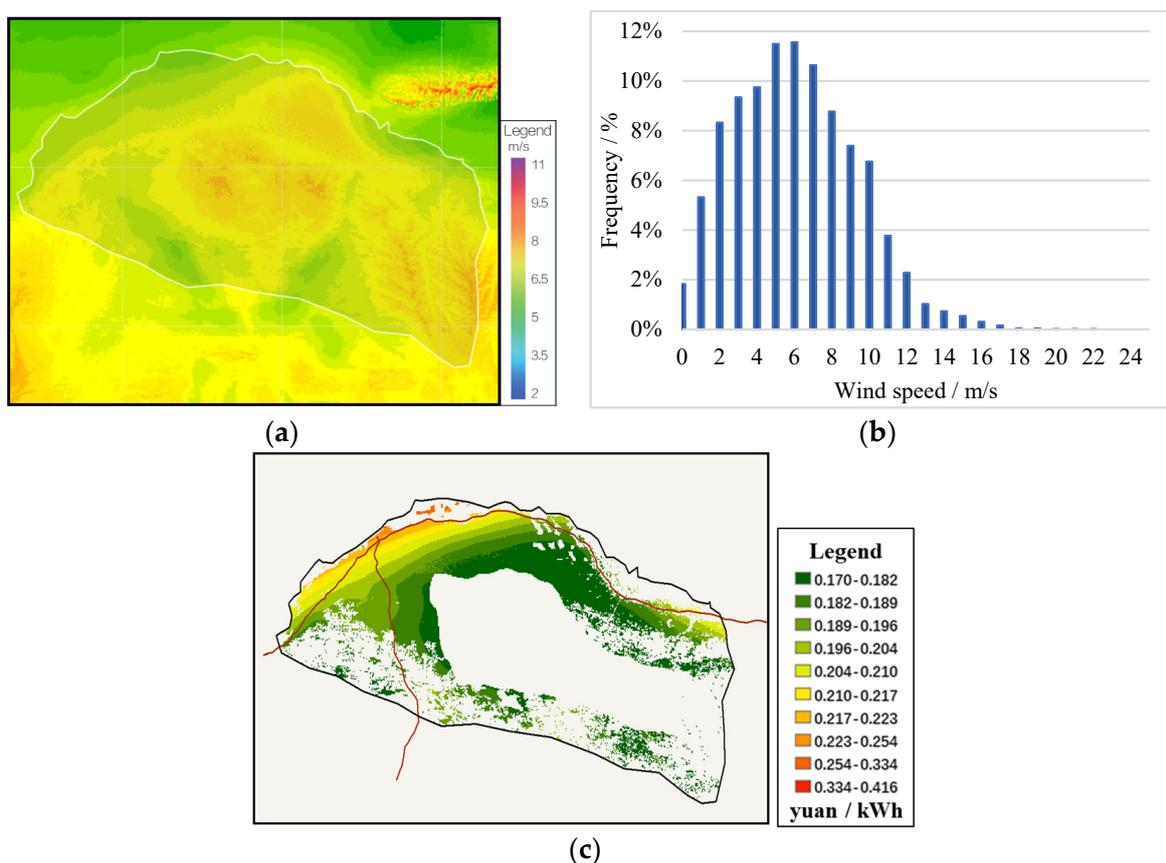


Figure 5. Wind power endowment analysis in the Kubuqi Desert. (a) Wind speed. (b) Probability histogram of wind speed. (c) LCOE distribution in the priority development areas with 20 km distance threshold.

(2) PV Power Endowment

In terms of PV resources, the average annual GHIs were 1463–1821 kWh/m², which were significantly higher than the national average. Among them, the GHI of the Qaidam Desert, the Badain Jaran Desert, the Ulan Buh Desert, and the other five regions was more than 1710 kWh/m², with good resource endowment. The average GHI in the Gurbantunggut Desert was relatively low, less than 1500 kWh/m². For PV development, the full load hours in the Qaidam Desert reached 1876, but limited by the general infrastructure conditions, the LCOE was 0.18 CNY/kWh. The full load hours of the Kubuqi, Ulan Buh, and Tengger Deserts exceeded 1770, and the costs were less than 0.19 CNY/kWh. Restricted by poor resources and traffic conditions, the LCOEs in Kumtag and Gurbantunggut were higher than 0.24 CNY/kWh. As an example, the distribution map of GHI, the average daily GHI histogram, and the LCOE distribution in the priority development areas with a 20 km distance threshold of the Qaidam Desert are shown in Figure 6.

(3) Economic and Social Development

The nine desert–Gobi–wilderness areas are located in Inner Mongolia, Xinjiang, and Qinghai Province. These administrative regions are inhabited by ethnic minorities, mainly including the Mongolian, Kazak, Tibetan, Uygur, and Hui. The main local pillar economic industries include tourism, minerals, and energy development. Due to the small population, the per capita GDP and per capita disposable income of the administrative regions are mostly higher than the national average. However, from the perspective of urbanization development, the urbanization level of the two Gobi areas is relatively low, at about 34–44%, while the urbanization rate of other areas has basically reached a relatively high level of about 60% with the promotion of poverty alleviation and desertification control. In the

future, with the large-scale development of renewable resources in these areas, the land resources with no economic value at present can be fully utilized and turned into energy oases. This will not affect the lives of local people and the production of animal husbandry but can provide more employment opportunities for local people bring tax and other fiscal revenue to the local government.

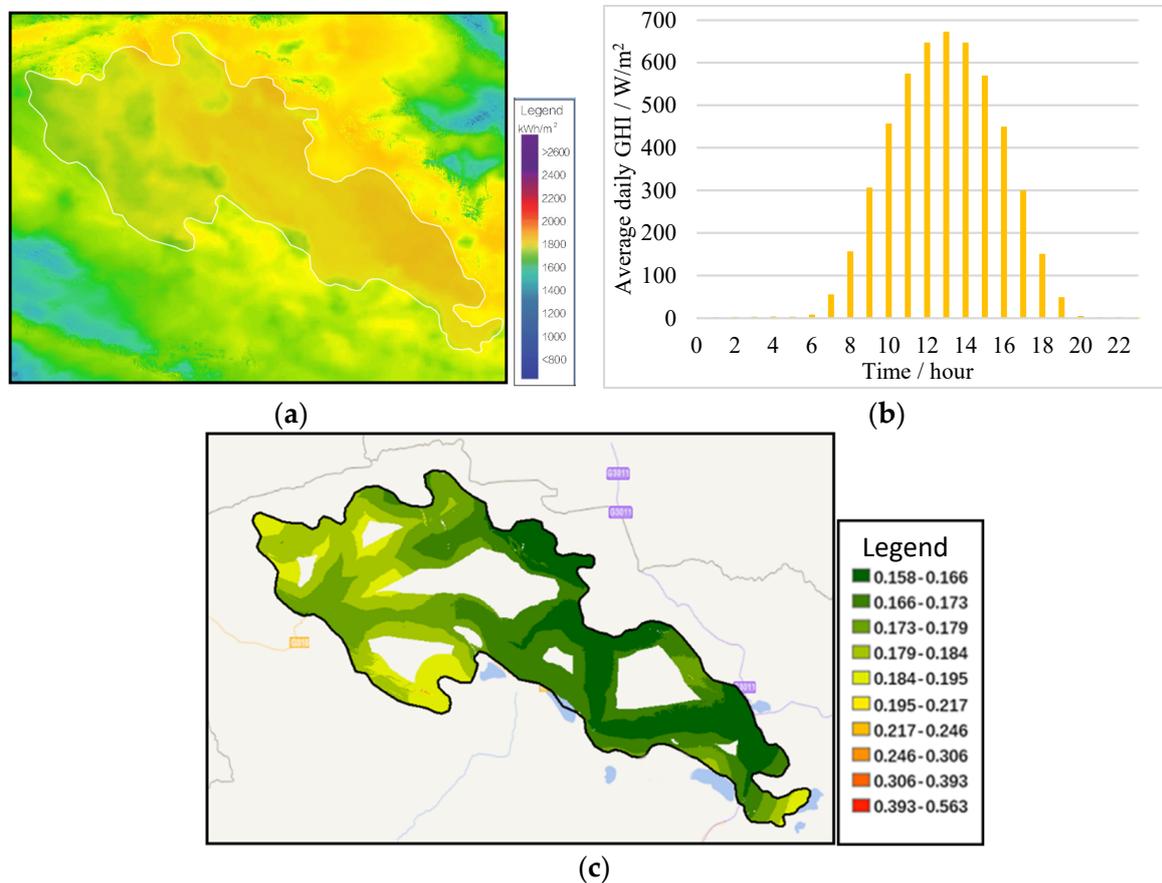


Figure 6. PV power endowment analysis in the Qaidam Desert. (a) GHI. (b) Histogram of average daily GHI. (c) LCOE distribution in the priority development areas with 20 km distance threshold.

(4) Desertification Level

According to the type and distribution of land covers, the percentage of desert, Gobi, and other bare ground in the total area is taken as the key index to quantitatively analyze the desertification level. In general, the larger the proportion of bare land, the higher the degree of desertification, and the impact of large-scale development on human production and life is smaller. However, at the same time, the construction will experience more difficulty, the operation and maintenance costs will be higher, and they will always face a difficult ecological restoration.

The nine desert–Gobi–wilderness areas are mainly covered by bare ground, with a total area of 200,000 km², accounting for 67% of the total. Sparse shrubs cover an area of about 840 km², which is also suitable for wind and PV development. Grassland is also widely distributed, covering an area of 87,000 km², accounting for about 30%. However, taking the Gurbantunggut Desert as an example, further combined with satellite image analysis, it can be seen that the grassland identified by remote sensing in the region is actually sparse and short-lived desert plants, which are very different from the general beautiful grassland scenery and are also suitable for large-scale development. In general, the desertification levels of Kumtag, Badain Jaran, Qaidam, and the northern Tianshan

Mountains are almost 100%, and the desertification levels of Ulan Buh and Tengger are also more than 80%, as can be seen in Figure 7.

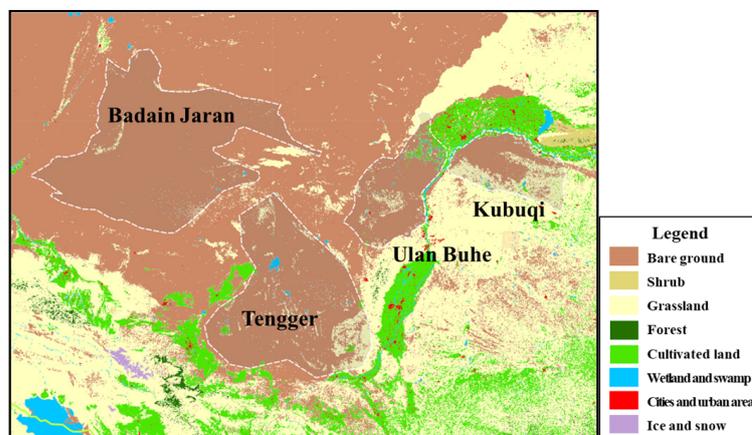


Figure 7. Land cover distribution in typical deserts.

(5) Base construction conditions

The site selection of bases needs to avoid several restrictive factors, such as populated areas, conservation areas, steep mountains, active earthquake regions, high-altitude areas, unstable strata, etc. Overall, none of the nine areas are located in conservation areas. All areas are sparsely populated and on generally flat terrain, with an average population density of less than 10 people/km². Kubuqi, the northern Tianshan Mountains, and the Qaidam Desert have good ground flatness. As the northern Ulan Buh Desert is adjacent to Langshan Mountain in Inner Mongolia and the Danxia landform ridge in Qinghai, the maximum terrain gradient is more than 40°. The strata are mainly composed of loose sedimentary rocks and siliciclastic sedimentary rocks. Except for the occasional historical earthquakes in Hainan prefecture, Qinghai, Kubuqi, and the adjacent areas around the Tengger, there are no historical earthquake records, and the geological structure is stable. It is preliminarily judged that there are no disruptive technical factors affecting the large-scale development.

(6) Power Grid and Road Infrastructure

One or more 220 kV and above AC transmission lines pass through Ulan Buh, Qaidam, Kumtag, Gurbantonggut, and other deserts, as well as Hainan Prefecture, with good grid conditions. The Kubuqi, Tengger, and Badain Jaran Deserts and the northern Tianshan Mountains Gobi are adjacent to 220 kV and above AC transmission lines within 70 km. In terms of road network infrastructure, one or more provincial and national roads have been built across the nine desert–Gobi–wilderness areas except the Kumtag Desert, and several highways have been built across Kubuqi, Gurbantonggut, and Badain Jaran and the northern Tianshan Mountains Gobi, laying a good foundation for base construction. The distribution of power grid and transportation infrastructure in the Kubuqi Desert and surrounding areas is shown in Figure 8.

(7) Comprehensive Analysis of Radar Maps

According to the following radar maps, as shown in Figure 9, Kubuqi and Ulan Buh have been evaluated highly in many aspects, such as showing a high level of economic and social development, excellent resource endowment, and good construction conditions. The northern Tianshan Mountain Gobi is suitable for large base construction. However, the surrounding power grid and road network infrastructure conditions need to be improved, and compared with PV, the wind resources in the region are excellent. The above three areas have good development suitability and are suitable for priority development.

The Tengger Desert has good resources, a high desertification level, and good base construction conditions, but the regional economic and social development is not good. In

the Badain Jaran Desert, the economic and social development level is high, the wind and PV resource endowment is excellent, and the ground exposure is high, but the surrounding infrastructure conditions need to be improved. The Qaidam Desert has good construction conditions, relatively good infrastructure conditions, and excellent photovoltaic resources but poor wind resources. The development suitability of the above three areas is good.

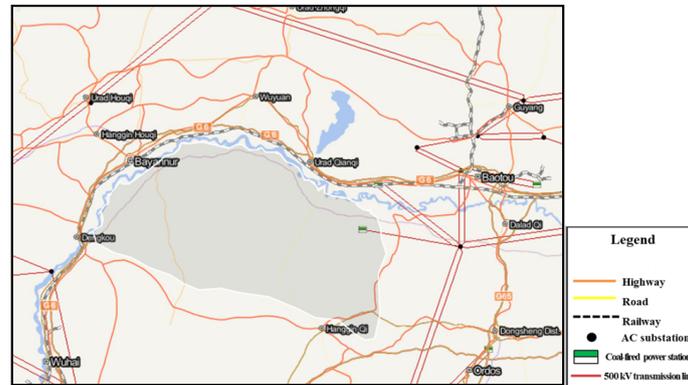


Figure 8. Distribution of power grid and transportation infrastructure in the Kubuqi Desert and sur-rounding areas.

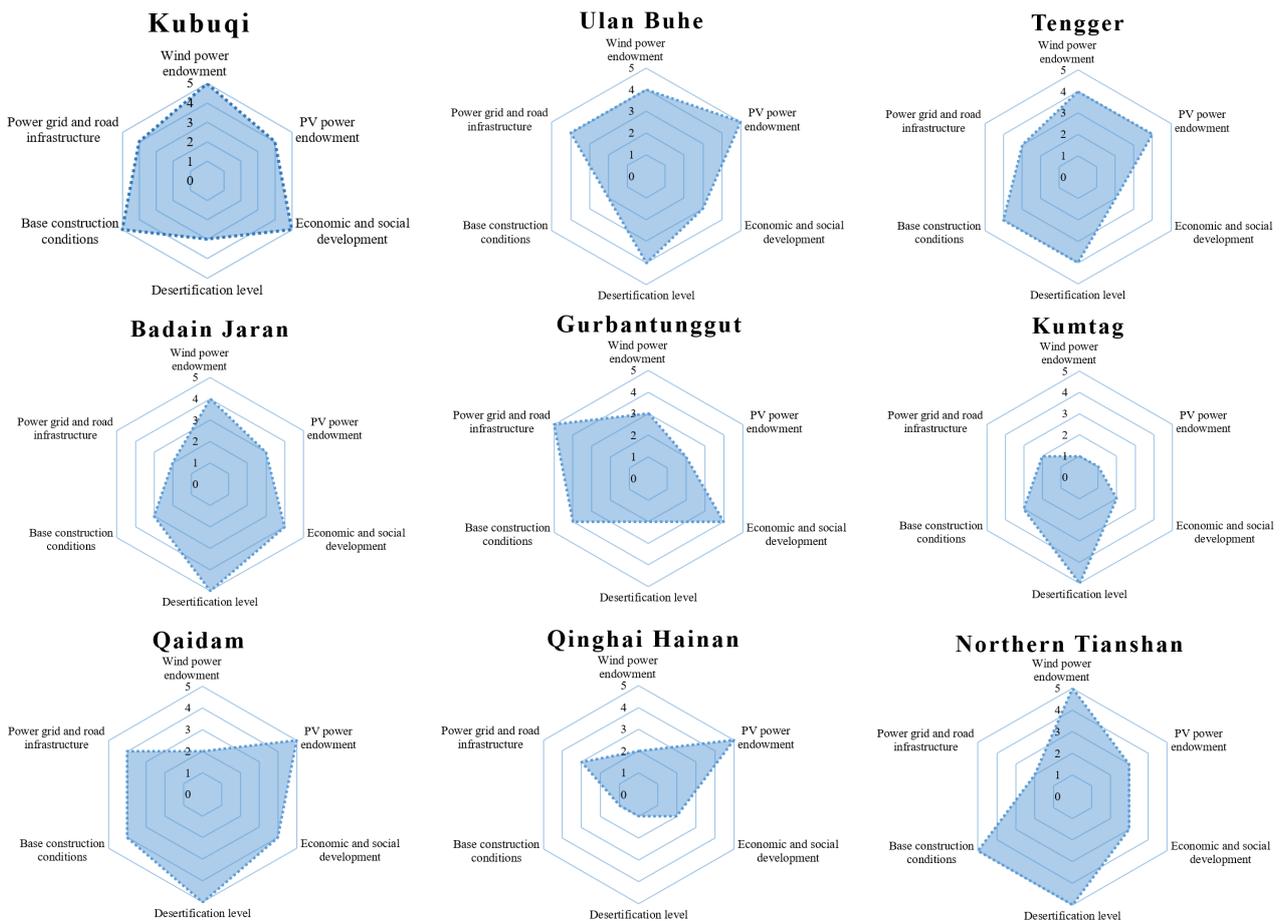


Figure 9. Evaluation of suitability radar maps of the nine main desert-Gobi-wilderness areas.

4. Wind–PV Collaborative Development Considering Meteorological Characteristics

4.1. Necessity of Wind–PV Collaborative Development

As we know, wind and PV power resources have strong volatility and unpredictability due to the randomness of natural factors (temperature, air density, wind speed, solar radiation, etc.) [51,52], which require a large capacity of energy storage (ES) equipment to stabilize the fluctuations and achieve stable power output, leading to a high investment cost level of the total system [2]. However, in the wide space area, the output curve of large-scale RE power generation clusters has certain rules. In other words, in addition to the two dimensions of resource variety and time, the renewable power output characteristics also have the regularity of geographical distribution. If the output complementary characteristics of wind–wind and wind–PV in different regions, which show seasonal and intra-day features, can be characterized and used, it can improve power generation quality and promote RE consumption [53]. References [54–56] point out that it is an important way to improve the security and economy of the power system with a high proportion of renewable energy in the future by cooperating with large-scale base optimization layout, energy storage, and power grid plan and giving play to their complementary benefits. Therefore, how to visually and graphically represent the temporal and spatial distribution characteristics of wind and PV power generation will help to carry out reasonable and efficient wind–PV collaborative development, reduce the overall volatility of power generation, mitigate the impact of wind solar grid integration, reduce the demand for flexible resources, and improve the economic level.

4.2. Meteorological–Electrical Division

The typical annual data were reconstructed from the global ERA5 reanalysis data (40 years, 1979–2018) and the global ISD meteorological station data (120 years, 1901–2021), and the monthly average wind speed and monthly average solar radiation were used to carry out the RE meteorological analysis. Based on the climate zoning concept in atmospheric physics and meteorology research, combined with the empirical orthogonal function method and spatial clustering analysis method, this paper analyzes the temporal and spatial distribution characteristics of China's wind and solar resources, clarifies the distribution laws contained in the massive long-term meteorological data, and obtains the meteorological–electrical division, as shown in Figure 10.

According to the correlation analysis of the wind speed time series data, on the monthly average time scale, China's land region presented the regular distribution of four typical modes, which were characterized by strong summer–light winter, light summer–strong winter, strong spring–light autumn, and light spring–strong autumn. For example, the Qaidam Desert in Xinjiang Province is divided by the tectonic belt at the Qilian Mountain southern foot into two regions with different wind characteristics, as strong summer–light winter and strong spring–light autumn. The two regions are only more than 50 km apart in space. If the large-scale wind power base layout can cover these two regions at the same time, the considerable wind–wind collaborative development benefits can be obtained. Moreover, the Gansu and Qinghai provinces span three different divisions within 200 km. When planning the renewable bases, the consideration of cross-division layout will achieve great benefits.

As for solar energy, the annual variation of surface irradiance in China had a high consistency, which increased or decreased seasonally. However, considering the spatial distribution correlation, there were three typical meteorological–electrical divisions of PV power. Most of the central and northern regions were characterized by strong summer–light winter. The southwest boundary showed strong spring–light autumn characteristics, which were related to the local cloudy weather all year round. The southeast region showed a strong negative correlation, as the light spring–strong autumn characteristics.

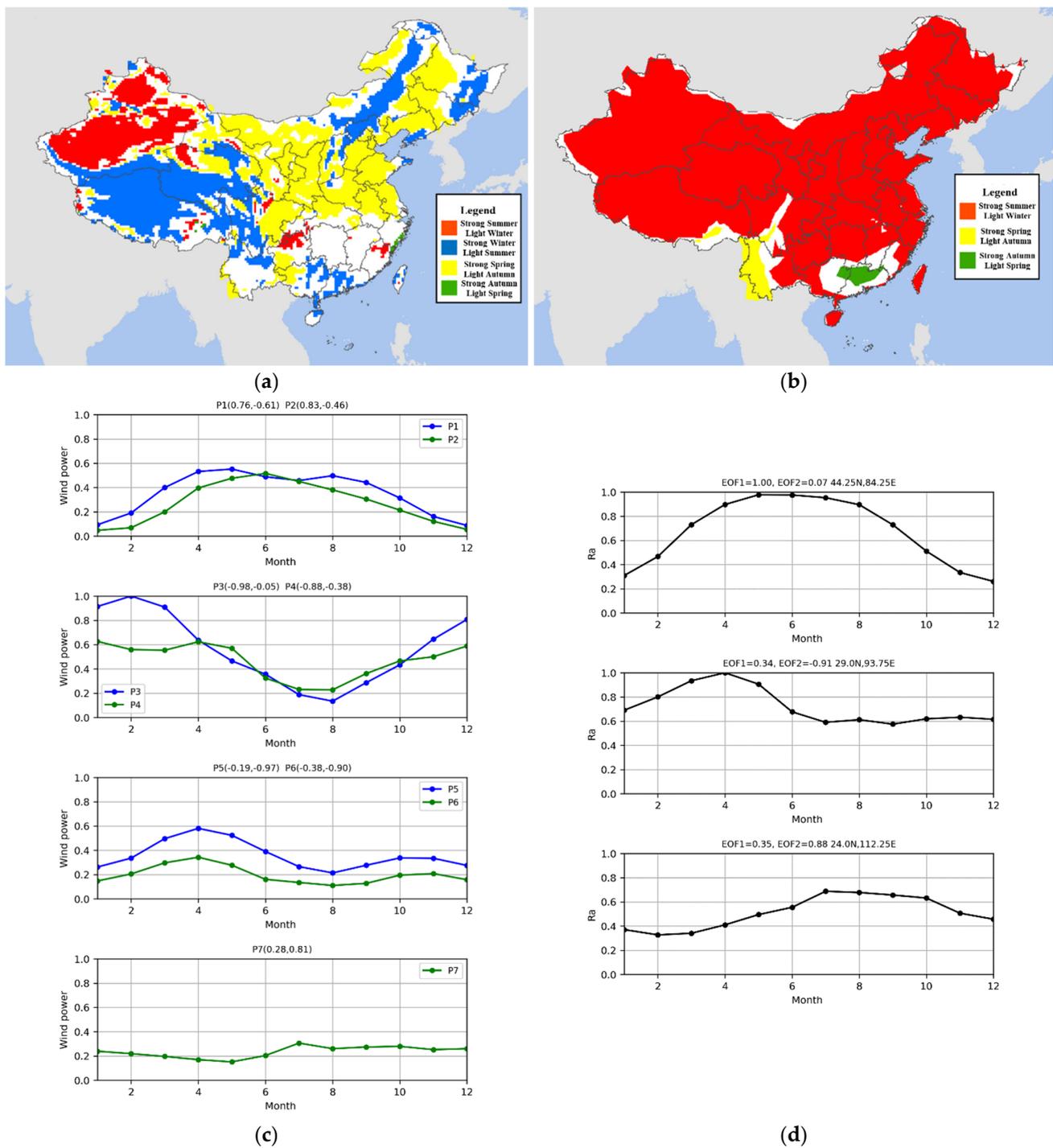


Figure 10. Distribution of meteorological–electrical divisions of China’s wind and PV resources. (a) Wind resource meteorological–electrical divisions in China. (b) PV power resource meteorological–electrical divisions in China. (c) Four typical monthly wind power output curves. (d) Three typical monthly PV power output curves.

4.3. Case Study of Across-Division Development

The Kubuqi Desert is located in the wind meteorological–electrical division characterized as strong spring–light autumn, which was selected for wind and PV development while allocating the suitable capacity of ES equipment as plan 1. The Qaidam Desert is located in the strong summer–light winter division. The comparative research will be carried out to develop a certain wind power replacing part of the wind power in the Kubuqi

Desert as plan 2. At the same time, the PV power in Kubeqi will develop continually, and ES equipment will be also allocated. In this study, the power generation and transmission system model named GOPT was used, and the detailed function description can be seen in reference [2,44,57]. Based on the analysis completed by the GREAN platform and the GOPT model, the optimization calculations of two plans were carried out, as shown in Table 6, which compared the power system’s comprehensive cost for different wind–PV collaborative development plans across different meteorological–electrical divisions. The calculation results are shown as follows. Figures 11 and 12 show the typical weekly and annual power balance results of plan 1 and plan 2.

Table 6. Calculation results of the wind and PV collaborative development plans across meteorological–electrical divisions.

Collaborative Development Plans		Plan 1: Wind and PV in Kubeqi, with Energy Storage (4 h, 90% Efficiency)	Plan 2: Wind and PV in Kubeqi, Wind in Qaidam, with Energy Storage (4 h, 90% Efficiency)	
Technical indicators	Transmission scale (MW)	10,000	10,000	
	Transmission full load hours	6000	6000	
	Guarantee rate	95%	95%	
	Curtailement rate	10%	10%	
Capacity (GW)	Renewable energy	13 GW wind and 28 GW PV in Kubeqi	6 GW wind in Qaidam and 7.2 GW wind and 28.3 GW PV in Kubeqi	
	Energy storage capacity	Short term	8.5	9
		Long term	1.815	0.755
Cost and full load hour	LCOE (CNY/kWh)	0.488	0.445	
	Energy storage cost (CNY/kWh)	0.669	0.590	
	Energy storage hours	Short term	1057	994
		Long term	3849	3898
	Annual cost of wind and PV power (billion CNY)	14.95	15.08	
	Annual cost of energy storage equipment (billion CNY)	12.60	8.81	

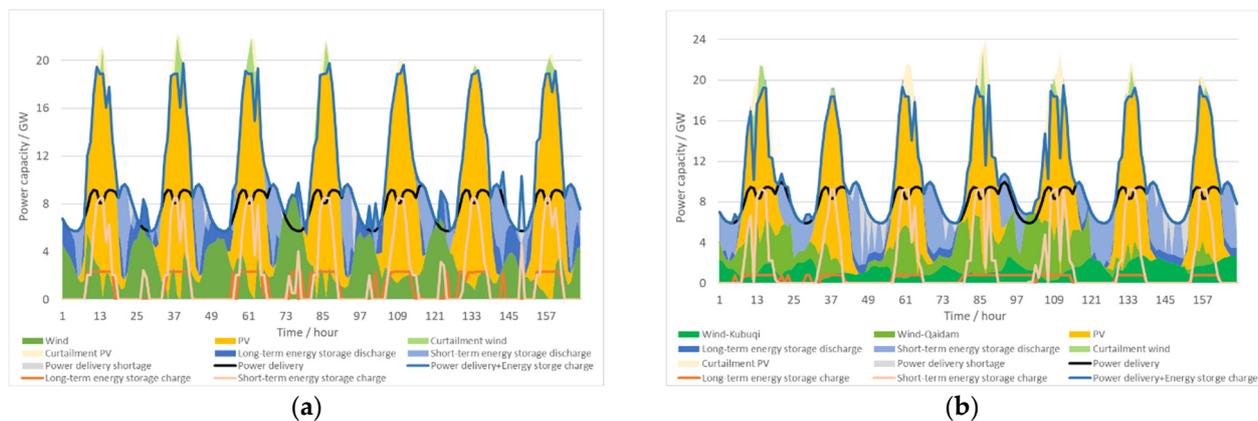


Figure 11. Typical weekly power balance results of plan 1 and plan 2. (a) Plan 1: 13 GW wind and 28 GW PV power in Kubeqi. (b) Plan 2: 6 GW wind in Qaidam, and 7.2 GW wind and 28.3 GW PV in Kubeqi.

On the premise of the same power transmission demand and the total installed RE capacity, when 6 GW of wind power from the Qaidam Desert in the strong summer–light winter meteorological–electrical division was developed to replace the wind power in the Kubeqi Desert in the strong spring–light autumn division, the demand for ES capacity was effectively reduced, from 10.315 GW to 9.755 GW, especially for the long-term ES, only 42% of the original. As can be seen in Figure 11, the orange line represents the charge of long-term ES, and its maximum value in annual power balance results decreased more obviously than the typical weekly power balance. Moreover, the annual cost was significantly reduced from CNY 12.7 billion to CNY 8.8 billion, a decrease of about 40%,

and the LCOE of total system was reduced from 0.49 CNY/kWh to 0.45 CNY/kWh, which effectively improved the economy of RE development and realized significant wind–wind and wind–PV collaborative development benefits. The results show that the collaborative development of wind and solar energy across different meteorological–electrical divisions can reduce the volatility of the output and the capacity demand of long-term ES equipment. This case study can verify the correctness and rationality of the meteorological–electrical division results in China provided in this paper.

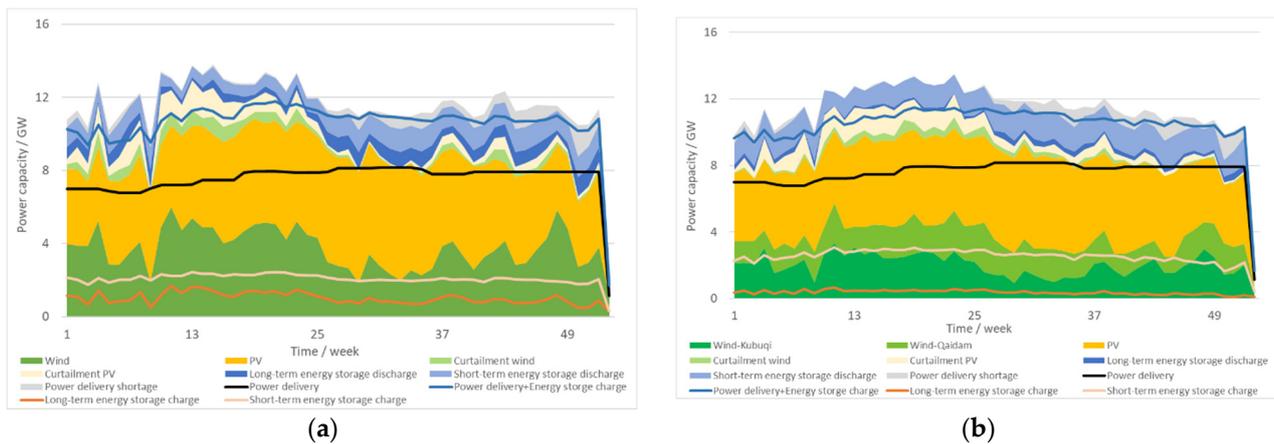


Figure 12. Annual power balance results of plan 1 and plan 2. (a) Plan 1: 13 GW wind and 28 GW PV power in Kubuqi. (b) Plan 2: 6 GW wind in Qaidam and 7.2 GW wind and 28.3 GW PV in Kubuqi.

5. Discussion and Conclusions

- (1) Renewable energy development in desert–Gobi–wilderness areas is the best choice under multiple considerations. First, the key to accelerating the clean transformation in China is the large-scale development of RE, while the wind and solar resources are mainly concentrated in the northern and western areas, especially in the vast desert–Gobi–wilderness areas. Second, with the continuous progress of power generation technology, the cost is falling rapidly. Third, the energy density of the unit land area for wind or PV power generation is low, so the base construction needs a large area. In particular, the land occupation area of a PV power station with the same power generation is about five to 10 times that of wind farms and 200–300 times that of thermal power plants. As the population and economic activities in eastern and central China are concentrated, land resources specially provided for wind and PV bases are very limited. The vast desert–Gobi–wilderness areas have high wind speed, strong irradiances, and no limitations of forestry, cultivated land, mining, water, and other restrictions, which can provide sufficient land space, while achieving efficient land use, promoting local economic development and helping desert control.
- (2) The desert–Gobi–wilderness areas are rich in wind and PV resources and will be the key development areas in the near future. In this paper, seven deserts including Kubuqi, Ulan Buh, Tengger, Badain Jaran, Gurbantunggut, Kumtag, and Qaidam and two Gobi regions in Hainan prefecture of Qinghai Province and the northern foot of the Tianshan Mountains were selected to carry out resource assessment and development potential calculations. The total amount of wind technical installed capacity was more than 600 GW, and the total amount of PV was more than 10,700 GW. Considering the edge of the desert area, along the highway, villages, and other densely populated areas as the priority development area, the wind energy development potential was about 120 GW, with full load hours of 2513, and the PV development potential was about 1.2 TW, with full load hours of 1759. According to the economic level in 2025, the average costs of wind and PV power development were 0.28 CNY/kWh and 0.20 CNY/kWh. Furthermore, with the development of large-scale and low-speed wind turbines and the improvement of operation and maintenance technology in

desert–Gobi–wilderness areas, the full load hours especially in the low-wind areas will increase, and the LCOE will decline obviously.

- (3) The influence of meteorological–electrical divisions will effectively enhance the collaborative benefits of RE development. Therefore, the rational layout of large-scale wind and PV power bases in vast spaces could reduce the volatility of power generation. So, the intuitive and visual understanding of resource characteristics and geographical distributions is key. In this paper, based on the massive long-term meteorological data, combined with the EOF and spatial clustering analysis methods, the wind and PV resource meteorological–electrical characteristic divisions in China were proposed for the first time. Moreover, with a case study in the Kubuqi and Qaidam Deserts, the collaborative development of wind–wind and wind–PV resources across different meteorological–electrical divisions reduced the capacity requirement of long-term energy storage from 1.815 GW to 0.755 GW, with a decline of 58%, and the total system LCOE decreased from 0.488 CNY/kWh to 0.445 CNY/kWh, nearly 10%.

In general, the development potential assessment results of wind and PV resources in China’s main desert–Gobi–wilderness areas provided by this paper can provide decision support for related provinces to develop these advantageous RE resources and formulate clean energy transition plans. The meteorological–electrical divisions in China can provide new ideas and decision-making references for the large-scale base planning in relevant regions.

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