Research on capacity allocation optimization of a wind-photovoltaic -hybrid-battery power generation system with multi-energy complementary

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Abstract: The output of complementary energy is the core of power generation system planning, and researching its configuration is the basis for realizing safe, reliable, economical and stable operation of the system throughout total life cycle. This paper comprehensively considers the constraints of power supply reliability and battery energy storage operation, and proposes a capacity optimization method for wind-photovoltaic-hydro-storage system aiming at life cycle cost and unit cost of electricity. Take the Northwest Region as an example, the optimization problem was solved by HOMER software, the optimal capacity allocation result was obtained. Compared with other solutions, the life cycle cost was reduced by 12.1%, the unit cost of electricity was reduced by 11.9%, and the load power shortage rate probability was relatively reduced. The result prove that the complementary system helps to reduce power generation cost and improve power supply stability.

Key words: complementary energy; wind-photovoltaic-hydro-storage; capacity configuration; HOMER software; life cycle cost.

1. Introduction

Since the output power of wind and solar resources is greatly affected by weather factors, no single energy source can provide stable and reliable power. In order to improve the reliability of power supply, it is usually necessary to combine and configure two new energy sources to form complementary output[1-3]. In the northwest region, the hydropower, wind energy and solar energy have multiple complementarities. The abundance and dryness of water power and the complementary wind energy and solar energy of day and night form seasonal complementary advantage[4-6]. Using hydropower with low operating cost and rapid start-stop, taking into account the tracking load and bidirectional charging characteristics of energy storage devices, it provides key technologies for adjusting the output power characteristics of wind and solar output and forming a multi-energy complementary power generation[7-10].

This paper will consider the factors of economy, reliability and technical feasibility, establish the capacity configuration optimization of the wind-photovoltaic-hydro-storage multi-energy complementary generation system with the system life cycle cost and unit cost of electricity as the optimization object, taking into account the reliability of power supply and the operation constraints of the battery. For the wind-solar hybrid power generation system, the multi-energy hybrid optimization model is built and simulated by the HOMER software developed by the United States National Renewable Energy Laboratory. After optimization, the capacity configuration results that meet different constraints are obtained, and the optimal results are analyzed.

2. Structure of Wind-photovoltaic-hybrid-battery Multi-energy Complementary Generation System

As shown in Figure 1, the main power generation part includes photovoltaic array and wind turbine, hydroelectric generator and battery in the system to assist in generating electricity. The system initially sets the wind and solar utilization to the limitation, that is, the photovoltaic array and wind turbine work at the maximum power point. Firstly the system provide electric energy to the load, and quickly charge the battery when the electrical energy provided by the system has excess energy. If the electric energy generated by the main power source is not enough to the load demand of the user, the auxiliary power supply is supplied by the backup power source; if the electric energy of the user is not met, the electric energy is purchased from the grid to meet the load demand of the complementary system.

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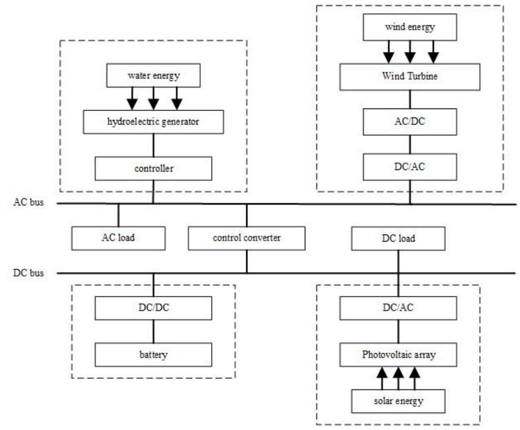


Fig. 1 Structure of wind-photovoltaic-hybrid-battery multi-energy complementary generation system

3. Capacity Configuration Optimization Model

3.1 Objective Function

In the planning of the complementary power generation system, the operation investment cost should be reduced as much as possible on the premise of ensuring the feasibility and reliability of the system[11]. Therefore, considering the system status and actual requirements, choose the life cycle cost and unit power generation cost of the overall system as the optimization goals to meet the safe, stable, reliable and economical power demand of users, and finally the optimal capacity allocation of photovoltaic cells, wind energy, hydropower and energy storage. Select the wind power capacity N_{wind}, photovoltaic capacity N_{pv}, hydropower capacity N_H and battery capacity N_{bat} in wind-photovoltaic-hybrid-battery complementary generation system as optimization variables. Variable as:

$$N = \left[N_{wind} \quad N_{pv} \quad N_H \quad N_{bat} \right] \tag{1}$$

3.1.1 Life Cycle Cost

The life cycle cost is the net present value of the system, which refers to all costs incurred during the overall system life cycle due to installation and operation, minus the present value of the earning revenue during the cycle. The cost mainly include initial investment cost, replacement cost, operation and maintenance cost, cost of fuel and pollution, and cost of purchasing electricity from the grid when electricity is insufficient. Since this system only considers renewable energy power supply, excluding the cost of fuel and pollution. Since the research has not considered the connection with the power grid and has not generated funds with the power grid, the present value of the power grid income is temporarily recorded as zero income.

Therefore, the life cycle cost of the research system can be expressed as:

$$C_{NPC} = C_{I.invest} + C_{R.reset} + C_{O\&M} - C_{income} \tag{2}$$

1) Equipment Investment Cost

$$C_{I.invest} = C_{I.wind} N_{wind} + C_{I.pv} N_{pv} + C_{I.bat} N_{bat} + C_{I.H} N_H \tag{3}$$

where $C_{I.wind}$ is the initial investment costs of wind turbines; $C_{I.pv}$ is the initial investment costs of photovoltaic arrays; $C_{I.H}$ is the initial investment costs of battery packs; $C_{I.bat}$ is the initial investment costs of hydroelectric generator.

2) Equipment Replacement Cost

$$C_{R.reset} = \sum_{1}^{k=n} \left(C_{R.wind} N_{wind} + C_{R.pv} N_{pv} + C_{R.bat} N_{bat} + C_{R.H} N_H \right) * \frac{1}{(1+i)^{(k-1)*Y}} \tag{4}$$

where n is reset time, take its value as the ratio of the system life cycle Y_{system} to the equipment life Y_A and round up, A is any device in the system; $C_{R.wind}$, $C_{R.pv}$, $C_{R.H}$, $C_{R.bat}$ are the replacement investment costs of wind turbines, photovoltaic arrays, hydroelectric generators, and battery packs, respectively; i is the annual real discount rate, can be calculated by $i = \frac{i' - f}{1+f}$, where i' is nominal discount rate, f is expected inflation rate.

3) Equipment Operation and Maintenance Cost

$$C_{O\&M} = \sum_{1}^{k=n} \left(C_{O\&M.wind} N_{wind} + C_{O\&M.pv} N_{pv} + C_{O\&M.bat} N_{bat} + C_{O\&M.H} N_H \right) * \frac{1}{(1+i)^{(k-1)}} \tag{5}$$

where $C_{O\&M.wind}$ is operation and maintenance costs for wind turbines; $C_{O\&M.pv}$ is operation and maintenance costs for photovoltaic arrays; $C_{O\&M.H}$ is operation and maintenance costs for hydroelectric generators; $C_{O\&M.bat}$ is operation and maintenance costs for battery packs.

3.1.2 Unit Cost of Electricity

The unit cost of electricity characterizes the average cost of a system to generate 1kWh of active electrical energy, can be expressed as:

$$C_{COE} = \frac{C_{annual}}{E_{ELE}} \tag{6}$$

where

$$C_{annual} = \frac{i(1+i)^N}{(1+i)^N - 1} C_{NPC} \tag{7}$$

where C_{annual} is the total cost of annual power generation conversion of the system; E_{ELE} is annual total power load of the system; N is system life cycle.

3.2 Power Supply Reliability Permit Model

Due to the periodic characteristics of new energy power generation, ensuring the safety and reliability of the power supply system is a basic requirement. The evaluation criteria of power supply reliability include load power shortage rate and energy waste rate. The loss of power supply probability $LPSP$ represents the probability of a shortage of system capacity demand, and the loss of renewable energy rate $LRER$ represents the ratio of the annual curtailment of wind power and photovoltaics to the total annual wind power generation. When optimizing the system capacity, give the two equal weights to record a new index power deviation PD [12], which can be expressed as:

$$PD = 0.5LPSP + 0.5LRER \tag{8}$$

1) The Loss of Power Supply Probability

$$LPSP = \frac{\sum_{t=1}^{8760} P_{lack}}{\sum_{t=1}^{8760} P_{load}} \tag{9}$$

where

$$P_{lack} = P_{load} - P_{pv} - P_{wind} - P_H - P_{bat} \tag{10}$$

where P_{lack} is the system of lacks power at time t ; P_{load} , P_{pv} , P_{wind} , P_H , P_{bat} are the output power of the load, the output power of the photovoltaic array, the output power of wind turbines, the output power of the hydroelectric generators and the output power of the battery.

2) The Loss of Renewable Energy Rate

$$LRER = \frac{\sum_{t=1}^{8760}\left(P_{loss.pv} * \Delta t + P_{loss.wind} * \Delta t\right)}{\sum_{t=1}^{8760}\left(P_{pv} * \Delta t + P_{wind} * \Delta t\right)} \tag{11}$$

where $P_{loss.pv}$, $P_{loss.wind}$ are the load-loss power of photovoltaic and wind power when the load is not met respectively; P_{pv} , P_{wind} are the photovoltaic and wind power outputs at time t under ideal conditions respectively.

3.3 Constraint Condition

3.3.1 Power Balancing Constraints of the System

When renewable energy generation is sufficient to support the load,

$$P_{pv} + P_{wind} + P_H = P_{load} + P_{bat} + P_{loss} \tag{12}$$

When renewable energy generation is insufficient to the load demand,

$$P_{load} = P_{pv} + P_{wind} + P_H + P_{bat} + P_{lack} \tag{13}$$

3.3.2 Every Equipment Output Constraint

For any kind of power output at time t, it is subject to constraints:

$$0 \le P_i(t) \le P_i^{\max} \tag{14}$$

where $P_i(t)$ is the actual output power value of a certain power supply at time t; $P_i^{\max}$ is the maximum output power value of each power supply.

3.3.3 Battery Operating Constraints

The use of battery energy storage needs to ensure its service life and operating limitations, and the battery needs to consider two constraints during the charging and discharging process:

$$SOC_{\min} \le SOC \le SOC_{\max} \tag{15}$$

$$\begin{cases} P_{ch}(t) \le 0.2E_{bat} / \Delta t \\ P_{dch}(t) \le 0.2E_{bat} / \Delta t \end{cases} \tag{16}$$

where SOC is battery charge and discharge status; $P_{ch}(t)$ is charging power per hour; $P_{dch}(t)$ is discharge power per hour; E_{bat} is the available power of the battery at the moment. The use time of the battery is limited by the charging and discharging power. Excessive charging and discharging rate will detract from its use time. Therefore, the upper limit of the charging power per hour cannot exceed $SOC/5$, Δt which is taken as 1h[12].

3.3.4 System Power Supply Reliability Constraints

$$PD \le \lambda_{\max} \tag{17}$$

where $\lambda_{\max}$ is the maximum acceptable power deviation for the power supply system.

4. Case Analysis

4.1 Simulation Basic Data

4.1.1 Basic Components

Optimization and sensitivity analysis of HOMER allows to evaluate the economic and technical feasibility of a large number of technology options, taking into account changes in technology cost and energy availability[9]. Therefore, it is necessary to consider the geographical conditions of the study site, natural resource conditions, meteorological data, local power grid data, and required loads to determine the type, capacity and power of various equipment in the current power generation system, so as to ensure that multi-energy complementary power generation system remain as optimal as possible. In this paper, the economic parameters of related equipment are set as shown in Table 1 by referring to papers and related materials and considering the premise of parallel economy and reliability.

Tab. 1 The economic parameters of each equipment in the system

Device parameters	Component type				
	Photovoltaic	Wind Turbines	Hydroelectric generator	Battery	Control converter
Equipment capacity（kW）	1	10	100	1kWh	50
Initial investment cost（￥）	5000	48000	105500	1500	2100
Replacement cost（￥）	4800	45000	75000	1190	2000
Operation and maintenance cost（years/￥）	100	1400	8000	100	120
Service life（years）	25	20	30	15	15

The design life of the research system is assumed to be 25 years. It can be seen from the table that the photovoltaic cell and hydroelectric generator do not need to be replaced during the overall system life cycle. In addition to the parameters described in the table above, other parameters need to be set as follows:(1) When photovoltaic cells generate electricity, there will be a demand for land occupation. This article sets the upper limitation of the allowable photovoltaic installed capacity to 500 kW. (2) The nominal number of 10kW wind turbines is set to 0,10, 20, 30, 40. (3) The 100kW hydroelectric generator is limited by the head H and flow Q, the parameters are set in the system. (4) The battery used is a 1 kWh lithium-ion battery and the SOC limitation is 30% to 100%. Usually, the maximum battery is 90% in practical applications. (5) The rectification efficiency and inverter efficiency of the converter are both set to 95% and the capacity variable of the converter is set to 0/50/100 kW.

4.1.2 Resource Data Setting

In the HOMER software, after determining the latitude and longitude coordinates of a certain place, you can directly download the wind energy resources, solar energy resources and water resources data of the research area from the meteorological resources website database.

1） solar and wind data

The research takes a region in northern China (34°15'N, 108°54'E) as the research object. According to the geographic coordinates of the region, solar and wind energy data are downloaded from the homer energy website or obtained from the National Meteorological Information Center website. The required historical meteorological data for 2016-2020 and take the monthly average of the data. Table 2 shows the monthly average radiance S , the corresponding clarity index k and the wind speed data at a height of 10m used for meteorological measurement. According to the statistical results, it is obvious that the wind energy and solar energy resources are relatively abundant.

Tab. 2 Meteorological data at the study site

Month	Clearness index(k)	solar radiation S (kWh/m^2/day)	Speed v (m/s)
January	0.543	5.460	6.320
February	0.557	5.780	5.190
March	0.569	5.980	5.690
April	0.612	6.240	3.670
May	0.655	6.320	4.380
June	0.690	6.420	2.620
July	0.692	6.530	3.210
August	0.681	6.750	3.450
September	0.622	6.430	5.390
October	0.601	6.230	3.530
November	0.527	5.230	6.450
December	0.517	5.120	6.340

Enter the resource data results obtained by statistics in the corresponding resource tab of HOMER. In order to simulate the output curve as accurately as possible, many factors need to be considered. Therefore, 4, 6, and 8 (kWh/m2/day) are used for the average solar radiation in the selected base year. Similarly, the average annual wind speed in the wind power resource components is 4, 6, and 8 (m/s). When the average radiance value of the year is 6, the distribution curve of solar energy resources is shown in Figure 2; when the average wind speed value is 8, the distribution curve of wind energy resources is shown in Figure 3. The selection of annual average is related to the simulation results.

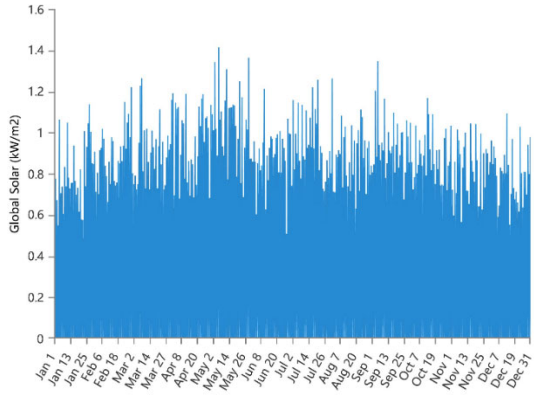


Fig. 2 The local hourly solar radiation data for the whole year after separation

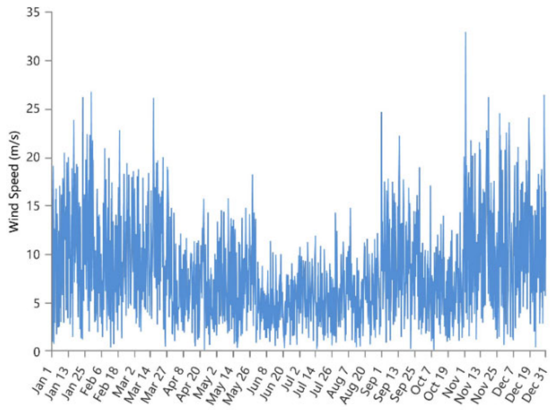


Fig. 3 Local hourly wind speed data throughout the year after separation

2） water resource data

The local water resources are abundant throughout the year. The annual average water flow is about 172.5L/s, and the maximum flow could reach 200L/s. The monthly average water flow in this area is shown in Table 3 through long-term observation.

Tab. 3 The average monthly water flow in the local area throughout the year

month	1	2	3	4	5	6
annual average stream flow L/s	190	195	200	200	190	185
month	7	8	9	10	11	12
annual average stream flow L/s	160	125	135	145	160	185

3） load data

Assuming that only AC load is considered, according to the existing load model in the software, combined with the load demand of a certain region, the load model of this study can be obtained. By entering the corresponding information into the corresponding load tabs related to the load demand and adding daily variability and time variability, a load distribution of 8760 hours in 12 months of the year could be generated, as shown in Figure 4. The model is a load based on "Community Load", which conforms to the normal law of residential electricity consumption. The peak of the load curve appears at 18:00-21:00, and the trough period is in the early morning.

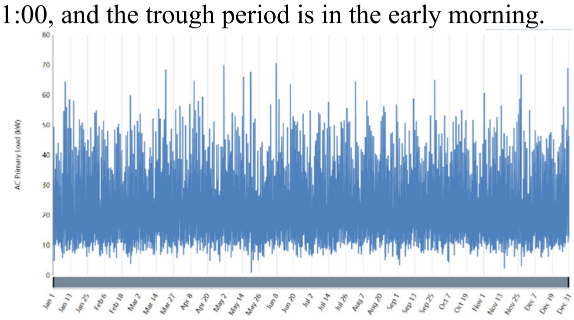


Fig. 4 Annual load data in the study area

4.2 System modeling and simulation result analysis based on homer software

Compared with other optimization software, the advantage of HOMER software developed by the National Renewable Energy Laboratory is that it can quickly and accurately help users to obtain configuration results. During the simulation process, the software will internally judge whether the design is feasible and compare various configuration results. In this paper, the simulation and optimization are carried by HOMER software, the optimization goal is to minimize the life cycle cost of the power generation system and the lowest unit power generation cost. According to the conditions of the selected research area, a model of a hybrid power generation system with wind-solar-water-storage is established. The model established in the software is shown in Figure 5. As can be seen from the figure, the main power generation parts of wind turbine and photovoltaic cell, including hydroelectric generator, are arranged on the AC side, and the battery is connected to the DC bus. The two are connected by an AC-DC converter to facilitate energy flow conversion and battery charging and discharging.

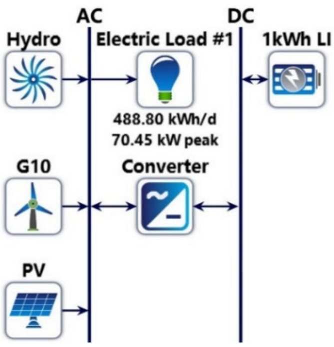
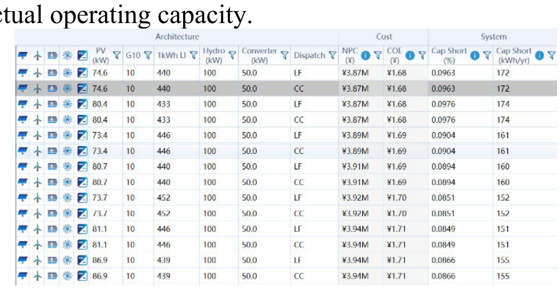


Fig. 5 Research system model diagram

The basic service life of the system is set to 25 years, the expected expansion rate is 2%, the nominal discount rate is 8%, and the maximum allowable power outage probability is 5%, resulting in an actual discount rate of 5.88%. The control strategies are selected as load following strategy (LC) and cyclic charging (CC) strategy. The parameters of the design selection and various resource and load data are entered into the model.

4.2.1 Analysis of Simulation Results

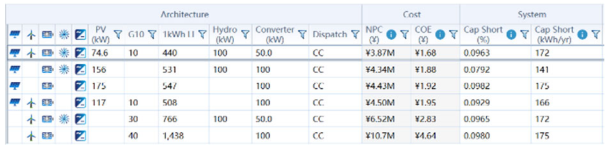
Press the "calculate" button to simulate according to the set basic data and constraints. The simulation outputs an operable capacity configuration plan, and the obtained configurations are arranged in order of life cycle cost from low to high. A part of the configuration scheme of the optimized configuration results is shown in Figure 6. It can be clearly seen from the figure that the smaller total net present value of the system, the smaller power generation cost; on the contrary, the greater load power shortage rate will be, that is, the required operating capacity that the system can provide will not meet the actual operating capacity.



Architecture						Cost		System	
PV (kW)	G10	1kWh LI	Hydro (kW)	Converter (kW)	Dispatch	NPC (¥)	COE (¥)	Cap Short (%)	Cap Short (kWh/yr)
74.6	10	440	100	50.0	LF	¥3.87M	¥1.68	0.0963	172
74.6	10	440	100	50.0	CC	¥3.87M	¥1.68	0.0963	172
80.4	10	433	100	50.0	LF	¥3.87M	¥1.68	0.0976	174
80.4	10	433	100	50.0	CC	¥3.87M	¥1.68	0.0976	174
73.4	10	446	100	50.0	LF	¥3.89M	¥1.69	0.0904	161
73.4	10	446	100	50.0	CC	¥3.89M	¥1.69	0.0904	161
80.7	10	440	100	50.0	LF	¥3.91M	¥1.69	0.0894	160
80.7	10	440	100	50.0	CC	¥3.91M	¥1.69	0.0894	160
73.7	10	452	100	50.0	LF	¥3.92M	¥1.70	0.0851	152
73.7	10	452	100	50.0	CC	¥3.92M	¥1.70	0.0851	152
81.1	10	446	100	50.0	LF	¥3.94M	¥1.71	0.0849	151
81.1	10	446	100	50.0	CC	¥3.94M	¥1.71	0.0849	151
86.9	10	439	100	50.0	LF	¥3.94M	¥1.71	0.0866	155
86.9	10	439	100	50.0	CC	¥3.94M	¥1.71	0.0866	155

Fig. 6 Partial capacity configuration results

In different combinations in the optimal configuration plan, the electric energy is selected to be provided by one or both of the three energy sources of wind energy, solar energy and water energy, or the electric energy is provided by the three together. The optimal allocation results of different combination schemes are shown in Figure 7, and the specific allocation and investment costs of each scheme are shown in Table 4.



Architecture						Cost		System	
PV (kW)	G10	1kWh LI	Hydro (kW)	Converter (kW)	Dispatch	NPC (¥)	COE (¥)	Cap Short (%)	Cap Short (kWh/yr)
74.6	10	440	100	50.0	CC	¥3.87M	¥1.68	0.0963	172
156		531	100	100	CC	¥4.34M	¥1.88	0.0792	141
175		547		100	CC	¥4.43M	¥1.92	0.0982	175
117	10	508		100	CC	¥4.50M	¥1.95	0.0929	166
	30	766	100	50.0	CC	¥6.52M	¥2.83	0.0965	172
	40	1,438		100	CC	¥10.7M	¥4.64	0.0980	175

Fig. 7 Optimal configuration results for each scenario

Table 4. The specific allocation and investment costs of each scheme are shown

Configuration	1	2	3	4	5	6
PV (kW)	74.6	156	175	117	/	/
Wind Turbines (kW)	100	/	/	100	300	400
Hydroelectric generator (kW)	100	100	/	/	100	/
Battery (kWh)	440	531	547	508	766	1438
Converter (kW)	50	100	100	100	50	100
Life cycle cost (mil)	3.87	4.34	4.43	4.50	6.52	10.7
Unit cost of electricity (￥)	1.68	1.88	1.92	1.95	2.83	4.64
Capacity shortage fraction (%)	0.096	0.079	0.098	0.092	0.096	0.098
Capacity Shortage(kW)	172	141	175	166	172	175

It can be seen from Figure 7 and Table 4 that the configuration schemes listed in the software are obtained after the optimized operation results of the given capacity configuration are in line with the power supply reliability settings. Therefore, from the configuration results, when the life cycle cost is 3.87 million yuan and the unit power generation cost is the lowest 1.68 yuan/kWh, the optimal solution is the solution 1 in the table. Compared with other solutions, the whole life cycle cost is at least reduced 12.1%, the unit cost of power supply decreased by 11.9%. The specific allocation of capacity is as follow: wind turbine capacity is 100kW, hydroelectric generator capacity is 100kW, photovoltaic cell capacity is 74.6kW, battery capacity is 440kWh, and bidirectional converter capacity is 50kW.

At this time, the annual load power shortage rate of the optimal configuration result can be obtained through the formula $LPSP=\frac{E_{CS}}{E_{demand}}$. Among them, E_{CS} is the annual capacity shortage; E_{demand} is the total electricity demand. The calculated result is 0.096%. According to the HOMER software, the comparison curve between the total annual load demand and the annual load shortage of 8760 hours a year can be generated, as shown in Figure 8. It can be seen from the figure that there is a significant capacity shortage during the peak load months.

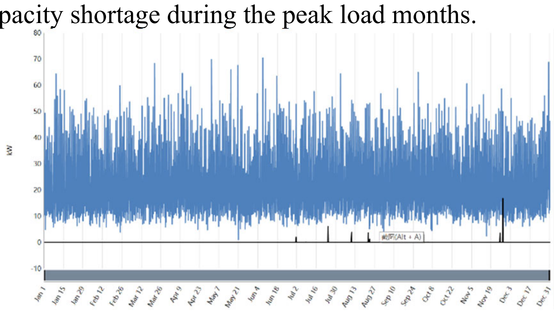


Fig. 8 The comparison curve of the total annual load demand and the annual load shortage

When the wind-solar-hybrid-battery power generation system is optimally configured, according to the data in Table 5, it can be seen that in the determined configuration results, wind power accounts for 49.6% occupying the backbone of annual power generation. The sources of renewable energy power generation for 12 months of the year are shown in Figure 9. It can be seen that the output of hydroelectric generator is mainly concentrated from December to June; In April, June and July (the wind speed is small), the output is relatively small.

Tab. 4 System renewable energy power generation data

Renewable energy	power generation (kWh/year)	Proportion of power generation (%)
Photovoltaic	131143	17.5
Wind turbine	372806	49.6
Hydroelectric generator	247401	32.9
Total	751350	100

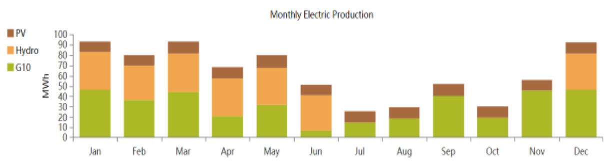


Fig. 9 Distribution of renewable energy generation in the system

5. Conclusions

In this paper, the HOMER software for optimizing the power generation system is used to establish a wind-solar-hydro-storage power generation system with multi-energy complementary in the rich resources research area. According to the selected parameter data of each equipment, the data of renewable energy resources in a certain place and the load demand, the constraints such as the relevant parameters of the research system, sensitive variables and the range of capacity variables of each part are determined. Based on the relevant conditions, the simulation of the whole life cycle of the research object in hours is carried out. Under the premise of the lowest life cycle cost, the optimal configuration combination of wind-solar-water-storage that meets the requirements of designing a complementary power generation system is obtained, so costs and load shortage rates are significantly optimized. Therefore, it is proved that the wind-solar-water-battery system containing a variety of renewable energy has broad development prospect and contributes to the sustainable development of the energy system in the future.

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