

Study on green power supply modes for heavy load in remote areas

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Abstract: In this study, the present situation and characteristics of power supply in remote areas are summarized. By studying the cases of power supply projects in remote areas, the experience is analyzed and described, and the applicability of related technologies, such as grid-forming storage and power load management, is studied, including grid-connection technologies, such as grid-forming converters and power load management. On this basis, three power-supply modes were proposed. The application scenarios and advantages of the three modes were compared and analyzed. Based on the local development situation, the temporal sequences of the three schemes are described, and a case study was conducted. The study of the heavy-load power supply mode in remote areas contributes to solving the problem of heavy-load green power consumption in remote areas and promoting the further development of renewable energy.

Keywords: Remote area; Renewable energy; Grid-forming storage; Power load management; Power supply mode

0 Introduction

Remote areas mainly refer to islands, deserts, Gobi, rain forests, etc., which are often rich in natural resources

and renewable energy, with a certain potential for future development, but are usually less populated, poor in power electricity infrastructure with low power capacity, have poor reliability, and face difficulty in connecting to the main grid.

Heavy loads in remote areas are mostly related to natural resource development, such as oil field exploitation in the deserts of the Middle East and Africa's forests, copper and gold mining in South America and the Gobi in Oceania, and lithium mining in salt lakes in South America. Presently, the power supply in these areas relies on diesel, gasoline, natural gas, and other fossil fuels, with only a small amount of renewable generation. This pattern not only results in a high cost of electricity and endangers the local natural environment, but also fails to meet power development requirements.

Received: 29 November 2023/Revised: 18 February 2024/Accepted: 19 March 2024/Published: 25 August 2024

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Relying on the development of renewable technologies and the experience of global energy interconnection, case studies for more safe, green, and affordable power supply modes for remote areas based on high proportions of renewable energy generation become possible. The results of this study could be applied to remote areas, such as islands, borders, deserts, and Gobi in various countries, effectively promoting the construction of global energy interconnection across the world.

1 Typical power supply cases in remote areas

1.1 Degrussa power supply project in Australia

The Degrussa copper mine, approximately 900 km from Perth, is wholly owned by Australia's Sandfire Resources. The copper mine has been in operation since 2012 with an annual output of approximately 300,000 tons of copper and an annual electricity consumption of approximately 105 GWh.



Fig. 1 Degrussa Mine with its power supply

Originally, the mine was supplied only with diesel power generation, with an installed capacity of 19 MW. In 2015, 10.6 MW solar photovoltaic panels and 6 MW lithium battery energy storage were installed, with an annual generating capacity of approximately 21 GWh, and the project investment was approximately 25 million US dollars. The project began in July 2015 and was completed and entered operation in June 2016. Currently, the Degrussa Power Supply project is an off-grid project that integrates solar, diesel, and battery energy storage. The electricity used by the copper mine is completely provided by this project.

Although the specific contract price of the project has not been disclosed, according to research conducted by

CSA Catapult in 2020, the levelized cost of energy (LCOE) for the Degrussa Power Supply project system in full investment (discount the grant) is approximately 0.322 A\$/kWh, while the LCOE for a diesel-only system is 0.351 A\$/kWh [1].

1.2 West Australia Agnew gold mine power supply project

The Agnew Gold Mine is located in a desert area approximately 800 km from Perth and is wholly owned by Australian Gold Fields, Ltd. The mine has been in operation since 1980, with an annual output of about 6.52 tons (about 230 thousand ounces) of gold.



Fig. 2 Agnew micro-grid power supply project

The average load of the mining area is approximately 15 MW, and the annual electricity consumption is approximately 120 GWh. The power supply project is an off-grid microgrid project that integrates gas and diesel power (23 MW), solar energy (4 MW), wind energy (18 MW), and gas and battery energy storage (13 MW/4 MWh). This project provides the electricity consumed by the gold mine. The project was built, owned, and operated by Energy Development Limited (EDL) and put into operation in April 2020 under a 10-year power purchase agreement (PPA). This fully met the electricity demand of the mining area, and the operational safety of the system was 99.99%. Renewable power generation accounts for approximately 56% of the total power generation [2, 3].

1.3 Chile Zaldivar Copper Mine power supply

The Zaldivar Copper Mine is located in northern Chile, approximately 196 km from Antofagasta. The Barrick Gold and Antofagasta mining companies each own 50% of the mine. The Zaldivar Mine produced approximately 103,000 tons of copper in 2017, with an estimated remaining reserve of 13 years and an annual electricity consumption of approximately 550 GWh.



Fig. 3 Zaldivar Copper Mine

Power to the mine is supplied by the main grid owned by the Chilean power company COLBUN under a 10-year PPA. In 2018, it achieved 100% renewable power supply [4]. According to the research results of the Renewable Energy Research Institute, the LCOE of the photovoltaic power supply system in Chile is approximately 0.02–0.06 US dollars/kWh. The LCOE of Chile's wind power supply system is approximately 0.04–0.05 US dollars/kWh. The LCOE of the Zaldivar copper power supply should be somewhere in between these values [5].

1.4 Lihir Gold Mine project in Papua New Guinea

Located on Lihir Island, Papua New Guinea, approximately 900 km from Port Moresby, the Lihir Gold Mine is wholly owned by Lihir Gold Limited and has been operating since 1997, with an annual production capacity of 6.8 tons (240,000 ounces) of gold and an annual electricity consumption of approximately 319 GWh.

The total investment in the Lihir Gold Mine power-supply project is approximately 76 million US dollars, and the installed capacity of the geothermal project is 56 MW. The geothermal power plant and 70-MW diesel power generation meet the electricity demand of mining. When the project is in operation, the geothermal power station can satisfy 75% of the mining electricity demand while providing electricity to the residents of the island [6]. The specific contract price of the project has not been announced, but the National Renewable Energy Laboratory (NREL) agency analyzed and calculated the LCOE of the power supply system of Lihir Gold Mine, and the results showed that the LCOE of the geothermal power generation system is approximately 0.065–0.067 US dollars/kWh. The LCOE of the pure diesel power generation system is approximately 0.109–0.185 US dollars/kWh. Geothermal power generation offers significant economic advantages [7].



Fig. 4 Lihir Gold Mine and its power supply

1.5 Insight into typical cases

Regarding the typical cases, several experiences can be summarized as follows:

1. To some extent, off-grid power supply systems using diesel or other fossil fuels can satisfy the demand for heavy loads in remote areas at a high cost.
2. Certain amounts of renewable generation combined with fossil fuel generation can be considered as an efficient way to limit the cost of off-grid power supplies without endangering the stability of the system. They are also more environmentally friendly than fossil fuels.
3. An on-grid power supply is more stable and economical than an off-grid power supply.

2 Challenges for power supply in remote areas

The power grid is weak. Limited by the geographical environment and climatic characteristics of remote areas, the local population is typically small, leading to a low appliance load and generation capacity. Owing to a lack of power infrastructure and weak local power grids, it is often difficult to extend the main grid to remote areas. When a heavy load appears in a local area, it is typically impossible to connect to the main grid within a short time.

High reliability is required by heavy-load power supply. Depending on the overall scale and annual output of natural resource exploitation, the scale for heavy loads in remote areas ranges from tens to thousands of megawatts. After completion, the load is classified as a first-level load, requiring continuous power supply throughout the year, and the reliability of the power supply should be high.

The cost of heavy-load power supply in remote areas is high. Presently, the power supply in remote areas mainly relies on diesel, gasoline, natural gas, and other

fossil fuels. The cost of electricity, the uncertainty of heavy-load construction timing, and the investment risk for power companies are relatively high.

The demand for green power supply is urgent. The ecology and environment in remote areas are fragile, and diesel, gasoline, natural gas, and other fossil fuel power-generation sources can easily endanger the local natural environment. Renewable generation can effectively alleviate the pressure on environmental protection, and with the progress of technology, renewable power generation can effectively reduce the cost of power supply compared with diesel and other fossil fuel power-generation sources.

3 Key factors for power supply in remote areas

Dealing with the challenges of power supply in remote areas requires technological advancements. Fortunately, key technologies have emerged with the widely accepted concepts of green energy and global energy interconnection.

3.1 Green power supply

Fossil-fuel power generation, which is the main generation method in remote areas, suffers from fuel price volatility, supply uncertainties, and potential regulation risk. Renewable generation and green power supplies have become increasingly competitive and attractive for heavy-load applications in remote areas. Owing to innovations in renewable technology, the cost of renewable energy generation has decreased rapidly. Since 2010, the LCOE of solar photovoltaic (PV) energy has decreased by 85%. For concentrating solar power (CSP), the LCOE decreased by over 68%, and for wind power, it decreased by over 56% (onshore) and 48% (offshore) [8].

Green power supplies have the potential to decrease the LOCE of heavy-load generation in remote areas. Based on estimates, deploying renewable generation can reduce the energy cost of off-grid heavy loads, such as mining, by 25% for existing operations and up to 50% for new ones [9]. The LCOE for power generation can be expressed as:

$$LCOE = \frac{C_{gf}}{C_{te}} \quad (1)$$

where C_{gf} is the total lifetime cost and C_{te} is the total energy produced. For the power solution of a specific mine, the LCOE can be identified as [10]:

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (2)$$

where I_t is the investment cost in year t , M_t is the maintenance cost in year t , F_t is the fuel cost in year t , E_t is the energy generated in year t , n is the life of the system, t is the time of the year, and r is the discount rate.

Equation (2) indicates that the LCOE is affected by many factors, such as investment, maintenance, and fuel costs. Investment and operational costs are significantly dependent on energy sources. Compared with fossil fuels, the cost of renewable energy generation is lower [11], as shown in Table 1.

Table 1 Cost comparison for different energy sources

Name	I_t	M_t	F_t
Coal	Extremely high	Extremely high	High & volatile
Heavy fuel oil	High	High	High & volatile
Gas	Medium	High	High & volatile
Diesel	Medium	High	High & volatile
Renewable	High	Extremely low & stable	Zero & stable

3.2 Grid-forming energy storage (GFES)

Energy storage or renewable generation can be simulated as a voltage source through grid-forming converter technology, so energy storage can actively support grid reliability, such as providing potential, inertia, and damping, which helps to improve the stability of weak power grids, such as microgrids for heavy-load power supply in remote areas. A circuit diagram of the grid-forming energy-storage system is shown in Fig. 5.

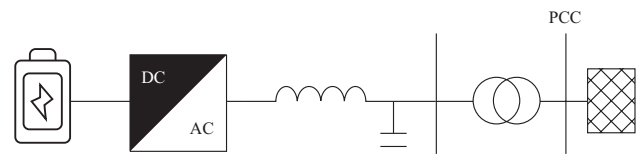


Fig. 5 Equivalent circuit diagram of grid-forming energy storage [12]

The grid-forming energy storage can flexibly control the output power by controlling the phase and amplitude of the internal potential. The equations for the active power P and reactive power Q of the storage are [12]

$$P = \frac{E^2}{Z} \cos \theta - \frac{EU}{Z} \cos(\theta - \varphi) \quad (3)$$

$$Q = \frac{E^2}{Z} \sin \theta - \frac{EU}{Z} \sin(\theta - \varphi) \quad (4)$$

where E, U are the virtual internal potential of grid-forming

energy storage and the voltage of the external power grid, respectively, Φ is the phase angle difference between grid-forming energy storage and the external power grid, and Z, θ are the amplitude and angle of the connection impedance between the grid-forming energy storage and the synchronous generator, respectively.

GFES can support the system voltage and frequency independently, improve the short-circuit capacity and inertia of the system, improve the impedance characteristics of the power grid, and suppress broadband oscillations. It can not only efficiently charge and discharge, but can also play the role of the “regulator” of the power grid and effectively improve renewable energy integration. In addition, with black start capability, the GFES can operate in both off-grid and grid-connected modes, as well as strong and weak power grid-wide adaptive capabilities.

Taking a lithium mine as an example, sensitivity analysis of system stability is carried out through the comparative analysis of GFES. The generation scheme is shown in Table 2, grid diagram is shown in Fig. 6, and power flow for this case is shown in Fig. 7.

Table 2 Lithium mine power supply scheme configuration

Load/MW	CSP/MW	PV/MW	Storage/(MW/MWh)
40	40	35	20/40

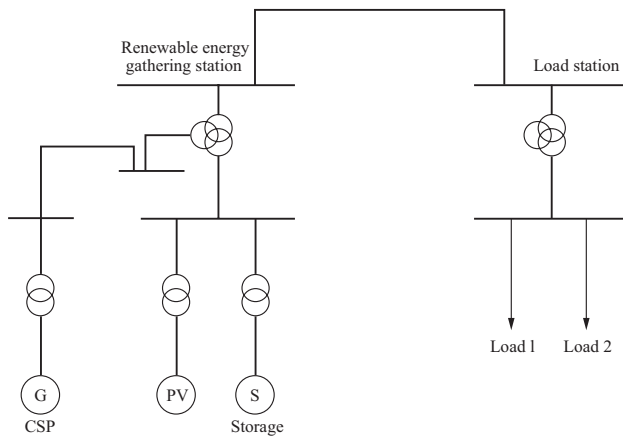


Fig. 6 Grid diagram for power supply to one lithium mine

Assuming that the CSP transmission line suffers a line fault (N-1), the active power of the system will be unbalanced, leading to a voltage drop and frequency instability. The system voltage status is illustrated in Fig. 8. The system voltage status when the energy storage is changed to GFES is shown in Fig. 9. The results show that the GFES can help maintain system stability.

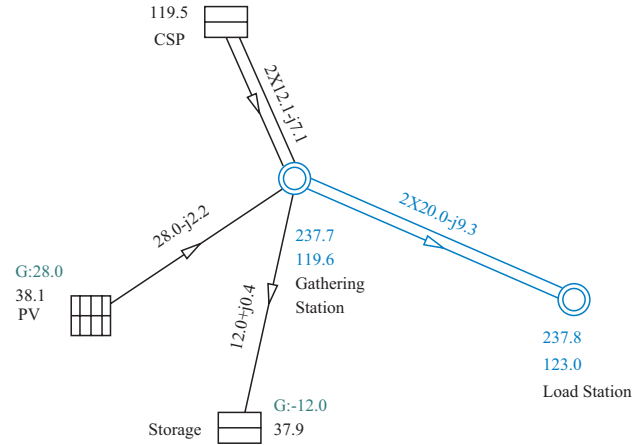


Fig. 7 Power flow diagram for lithium mine power supply

The advantages of grid-forming energy storage for steady-state and transient stability under a weak grid were simulated and demonstrated. In terms of engineering applications, grid-forming energy storage has been applied in a small number of demonstration projects, and the operating results of these projects have confirmed the theoretical results. However, the transient stability analysis of multimachine systems has just begun, and there is no unified conclusion on how to determine the reasonable proportion and access location of such equipment [13].

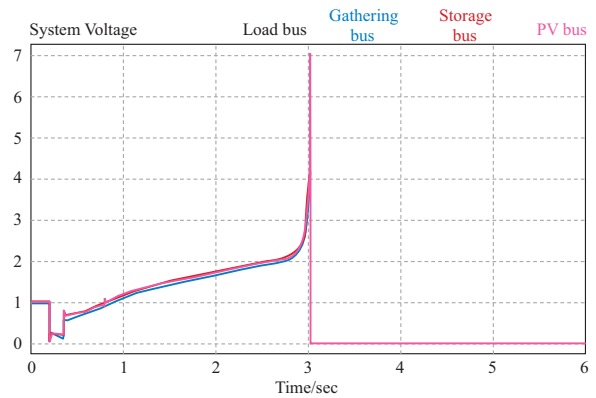


Fig. 8 System voltage status without GFES

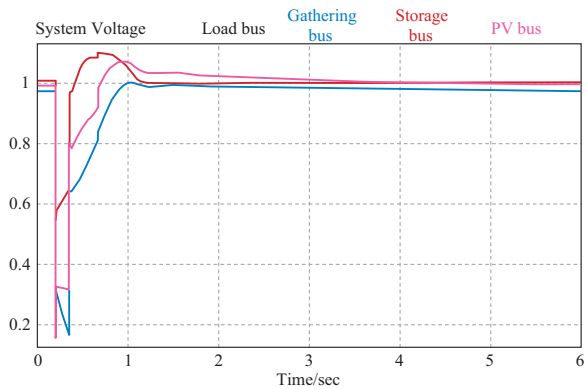


Fig. 9 System voltage status with GFES

Application Case: Grid-forming Storage Demonstration Project in Ejina Region

The project comprises a 25 MW/25 MWh grid-forming energy storage system, four sets of 1.8 MW diesel generators, and four renewable generation stations with an installed capacity of 110 MW. The total installed capacity was 142.2 MW. This project involved three voltage levels: 110, 35, and 10 kV, contains 17 substations, 28 main transformers, 25 transmission lines, and 77 distribution lines, with a total power supply region of approximately 114000 km².



Fig. 10 Grid-forming power storage station in Ejina

This project employed a grid-forming energy-storage system instead of conventional reserves as a black-start power supply. It has achieved seamless in-grid/off-grid switching and 49 consecutive hours of safe and stable operation of Ejina Banner's power system, with an ultrahigh proportion of renewable generation. It can operate for over 22 consecutive hours with 100% renewable and 100% power electric equipment [14].

3.3 Power load management (PLM)

Power load management (PLM) refers to the management of power load regulation, control, and operation optimization through the comprehensive use of economic, administrative, and technical means to ensure the safe and stable operation of power grids, maintain a stable order of power supply and consumption, promote the consumption of renewable energy, and improve the energy use efficiency, including measures such as demand response and orderly electricity consumption [15].

PLM can effectively alleviate the tension in the system power supply, reduce the pressure on the power grid, prevent voltage drops, and ensure the safety of the power grid. It can also tap into the potential of the equipment, reduce or eliminate capacity expansion, and reduce equipment investments. PLM can also reduce line losses and electricity consumption.

With the advancement of renewable technology, power supply in remote areas in the future will be dominated by renewable generation, which requires higher requirements for the flexible adjustment of resource construction and allocation and can further drive the potential of load-side management regulation.

Taking one copper mine as an example, the load ratio of each piece of electrical equipment deployed during operation is shown in Fig. 11. Among the main pieces of electrical equipment, the electricity load of the ore grinder accounts for the highest proportion (approximately 60%) and has a certain adjustment potential. The electricity loads of the other links are superimposed to participate in the adjustment, and the depth of the copper mine load adjustment is approximately 30%.

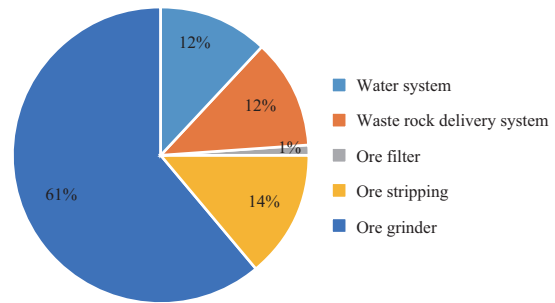


Fig. 11 Load ratio of each piece of electrical equipment

The maximum load of the copper mine was assumed to be 100 MW. The adjustments were considered to be 0% and 30%, and the adjustment period was at night and in the renewable generation low-output stage. The copper mine had no heating demand, and the generation combination was configured as solar PV, wind, and energy storage. The energy storage duration was 12 h, and the round-trip efficiency (RTE) was 85%. The RTE is defined as follows:

$$RTE = \frac{\sum_1^i W_{Di}}{\sum_1^i W_{Ci}} \times 100\% \quad (5)$$

where i is the charging cycle time, W_{Di} is the energy output at the rated power, and W_{Ci} is the power charged into the battery.

Using grid optimization planning tools (GOPTs), an operational comparison was conducted. The results are presented in Figs. 12 and 13.

When the copper mine load was not involved in the adjustment, daytime power support was mainly provided by photovoltaic, and nighttime power support was provided by energy storage. When the copper mine load was involved in the adjustment, the adjustment period was 16 times from 19:00 to 11:00 the following day, and the load was adjusted

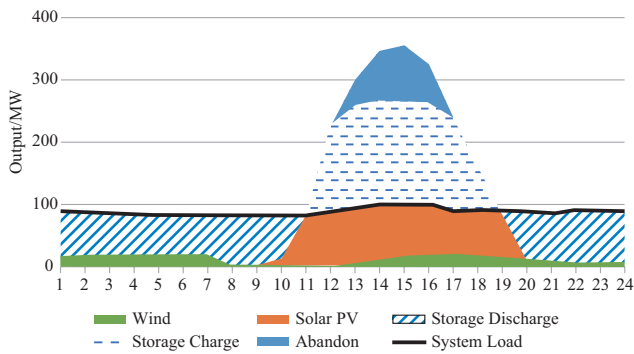


Fig. 12 System operation process without load management

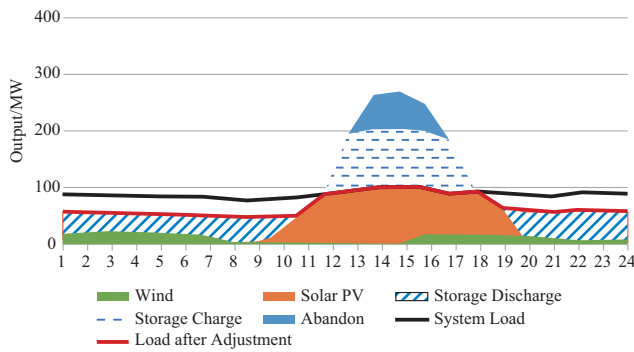


Fig. 13 System operation process with load management

downward with the maximum adjustment depth (30%), which reduced the electricity consumption by approximately 5 GWh, accounting for 24% of the total electricity demand. Regardless of whether the copper mine load participated in the adjustment, the renewable energy power abandonment rate was 20%, which reached the upper limit of the power abandonment rate.

The influence of different load adjustment depths on the allocation scale of the power supply and electricity price of the copper mine was also analyzed. The load adjustment depths were 10%, 20%, and 30%, respectively. The results are presented in Table 3.

With load management, the total installed power

Table 3 Generation scale and electricity price of copper mine under different load adjustment depths

Load adjustment depth	Wind	Solar	Storage	Total generation /MW	Price /(CYN/kWh)
0%	90	484	178	752	0.97
10%	80	428	156	664	0.86
20%	80	397	140	617	0.82
30%	80	380	126	586	0.79

Application case: Electric Heating Load Flexible Control Demonstration Project in Hetian

capacity is 586 MW, which is 22% less than when load management is not involved, and the scale of energy storage decreases from 178 to 126 MW, which is a 29% reduction. With reductions in generation and storage capacity, the total investment decreases and the price of electricity is then reduced by 18% from 0.97 to 0.79 CYN/kWh.

This project was based on an in-depth analysis and exploration of load regulation resources in Hetian. More than ten control modes and technical solutions for electric heating equipment have been developed. A total of 884 centralized and 507 decentralized electric heating users were included in the regulation resource pool. A total of 1108 sets of flexible load control devices were installed on the centralized electric heating equipment, while 1137 sets were installed on the decentralized equipment. An electric heating flexible load control platform was established with a load pool of 175 MW and a load adjustment depth of up to 70%.

Different dispatching patterns have been designed for various electric heating load groups, targeting power supply, grid security, and renewable energy consumption. “Flexible regulation” strategies were proposed for electric heating load control. An electric heating load flexible control platform was constructed, which can achieve organic unity of “centralized control + decentralized control”. A user rating system was established by integrating various grids and user factors. The load control can be implemented while ensuring users’ heating needs, achieving “zero perception” for users participating in accurate peak shaving of the power grid during morning and evening peaks, promoting users’ energy conservation and consumption reduction and clean energy consumption, enabling sustainable interactions between electric heating equipment and the power grid [6].

4 Green power supply modes in remote areas

The previous sections analyzed typical cases of power supply in remote areas and identified the applicable key technologies with application cases. This section presents three modes of heavy-load green power supply in remote areas, analyzes the advantages and application scenarios of the three modes, provides practical suggestions, and presents a case study of the three power supply modes.

4.1 Modes Description

Renewable energy off-grid (REO) mode

Relying on renewable energy resources in remote areas, solar PV, wind power, and other renewable energy sources can be treated as the main sources of electrical power, supported by a certain capacity of energy storage or CSP

systems. An off-grid micro-grid system can be formed without connecting it to the main grid.

Solar PV and wind power technologies are relatively mature and can be used as the primary power supply in remote areas. Owing to the intermittent characteristics of renewable energy, a certain amount of energy storage should be provided; however, the effect and life of electrochemical energy storage are greatly affected by extreme weather. It has been suggested that diverse energy storage methods should be considered for application. CSP power generation can be treated as power supply and energy storage simultaneously. It can also participate in the peak regulation and frequency modulation of the system while maintaining a stable power supply and provide great support to the isolated grid. However, the current costs of CSP systems are relatively high. Grid-forming storage should be applied to form a more stable power supply system, and connections with the local main grid must be considered for planning in advance.

Renewable energy in-grid/off-grid (REIO) mode

In the REO mode, for certain heavy loads, a power line can be set up nearby to form a connection with the main grid. The special power line and local renewable generation jointly satisfy the power demands of heavy loads and provide support to the micro-grid power supply system.

Renewable energy in-grid (REI) mode

In this mode, the power grid is strengthened in heavy load regain, power transmission lines are built, and the demand for heavy loads was met by electricity transmission from the main power grid. This mode is applied with mature power grid technology; the main concerns should be the coordination of power grid and mining planning. The different application scenarios, advantages, and disadvantages are summarized in Table 4.

In reality, the development progress of heavy loads in remote areas is different, and the grid coverage of remote areas is also different. Most of the time, there is a mismatch between the cycles of heavy-load development and grid construction. Therefore, when choosing the power supply mode, it is necessary to choose an appropriate mode according to the construction sequence based on the actual power grid and heavy load demand.

It is suggested that the REO mode should be selected in the early stage of heavy-load construction, the REIO mode should be selected in the middle stage, and the REI mode should be selected in the long term. The above suggestions assume that the heavy-load power supply has undergone the entire development process, but do not rule out that some heavy loads always choose one of the modes. Therefore, it

is necessary to make a comprehensive judgment based on the actual situation, technical economy, and other factors.

Table 4 Different application scenarios for different modes

Mode	Typical Scenarios	Pros	Cons
REO	1. Far from the main grid 2. No excessive requirements for power supply reliability 3. Open for load adjustment	Short construction period	1. Large investment 2. Relatively low reliability
REIO	1. Far from the main grid 2. Require high power supply reliability	1. Lower investment 2. Higher reliability	1. Long construction period 2. Low utilization rate for the special line
REI	All	1. Lower investment 2. Higher reliability	1. Long construction period 2. High investment for grid operators

4.2 Evaluation of power supply mode

The evaluation mainly includes the comprehensive power supply cost (CPS), renewable energy utilization rate (NER), and power supply guarantee rate (PSR), among which the CPS and PSR are particularly important.

CPS:

$$CPS = \frac{\sum_i^n P \cos t_i + \sum_i^n \sum_{j=1}^T P_{O\&Mi,j} + \sum_j \sum_{i=1}^T P_{taxi,j} - \sum_i^n P_{valuei}}{\sum_i^n \sum_{j=1}^T P_{power,j}} \quad (6)$$

where P_{cost_i} is the initial investment for i_{th} equipment in the generation system, $P_{O\&Mi,j}$ is the maintenance cost for i_{th} equipment in j year, $P_{taxi,j}$ is the annual financial expenses for i_{th} equipment in j year, and P_{valuei} is the residual value for i_{th} equipment.

NER:

$$NER = \frac{\sum_i^n \sum_{j=1}^N P_{outsj}(i,j)}{\sum_i^n Q_{need}(i)} \quad (7)$$

where $P_{outsj}(i,j)$ is the output of i_{th} equipment in the generation system at time j and $Q_{need}(i)$ is the demand for i_{th} equipment in the generation system at time j .

PSR:

$$P(i) = P_{outyc}(i,j) - Q_{need}(i) \quad (8)$$

$$number(i) = \begin{cases} 1, P(i) \geq 0 \\ 0, P(i) < 0 \end{cases} \quad (9)$$

$$PSR = \frac{\sum_i^n \sum_j^N \text{number}(i) \times P_{outyc}(i, j)}{\sum_i^N Q_{need}(i)} \quad (10)$$

where $P_{outyc}(i, j)$ is the usable output of i_{th} equipment in the generation system at time j , and $Q_{need}(i)$ is the demand for i_{th} equipment in the generation system at time j .

4.3 Case study

This case study was conducted in a remote highland area with rich renewable generation potential, lithium resources, and poor local infrastructure. In the short-term, the peak load is around 135 MW, and the REO mode is more suitable. The solar and wind potential is shown in Figs. 14–17.

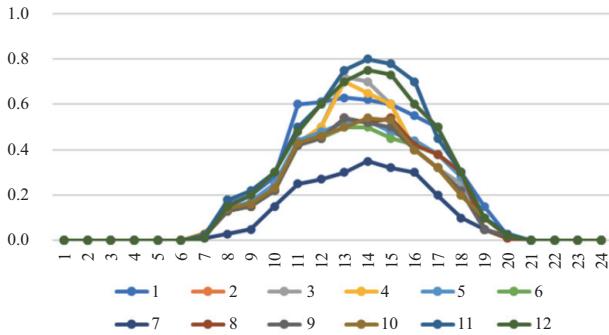


Fig. 14 Typical daily variation curve of monthly solar output

In the study area, for PV, the maximum output occurs from 13:00 to 16:00. From the perspective of annual output characteristics, peak power generation occurs from November to April. The average annual utilization of solar power is approximately 1,944 h. The wind power output is highest from 18:00 to 05:00 the next day, and from the perspective of annual output characteristics, the peak power generation is from November to April. The average annual utilization of wind power is approximately 3450 h.

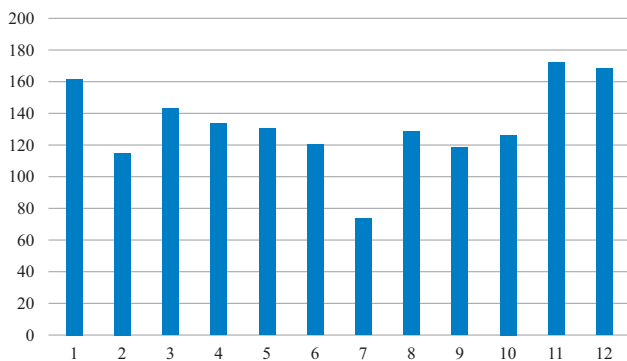


Fig. 15 Utilization hours per month (Solar)

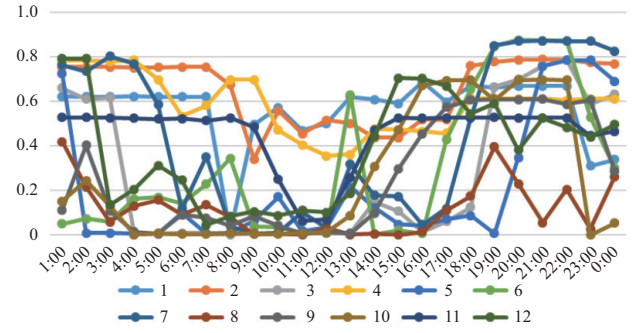


Fig. 16 Typical daily variation curve of monthly wind output

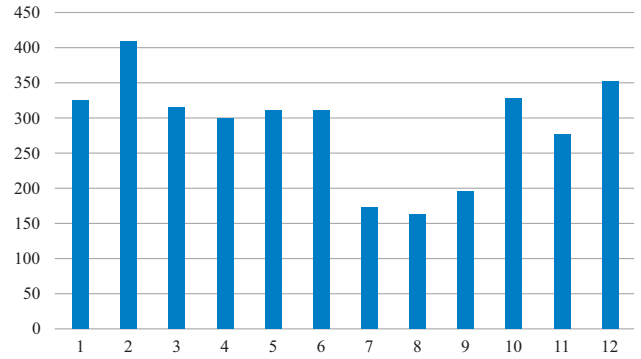


Fig. 17 Utilization hours per month (wind)

Based on the renewable resources in the study area, PV, wind, CSP, and energy storage were selected as the main sources. Owing to the characteristics and high cost of CSP, it was considered as the base load supply and peaking power supply, and the minimum output was set at 15%. The daily load characteristics of lithium ore are relatively consistent and, combined with the complementary characteristics of wind and solar power, the appropriate allocation of wind power can effectively smooth the output of the power supply system, enhance the power supply capacity at night, and reduce the installed capacity of energy storage and solar power concentration.

PV utilization hours were considered to be 2100 h, and the comprehensive cost of photovoltaic power is 4200 yuan/kW. Wind power utilization hours were considered to be 2500 h, the comprehensive cost of wind power is 7000 yuan/kW, and the power generation cost of the CSP is closely related to the technical route. To simplify the calculation at this stage, the CSP was temporarily considered in accordance with 3000 power generation utilization hours, and the comprehensive cost of the CSP was 25000 yuan/kW. Based on different conditions, upper and lower limits of different power supplies were proposed. The evaluation index of the scheme was calculated after 8760 h of production simulation. The installed capacity of the initial power-supply combination scheme was updated,

the evaluation index under the new scheme was calculated, the scheme indices were compared, and the optimal scheme configuration was retained until the optimal configuration scheme was obtained. This process is illustrated in Fig. 18.

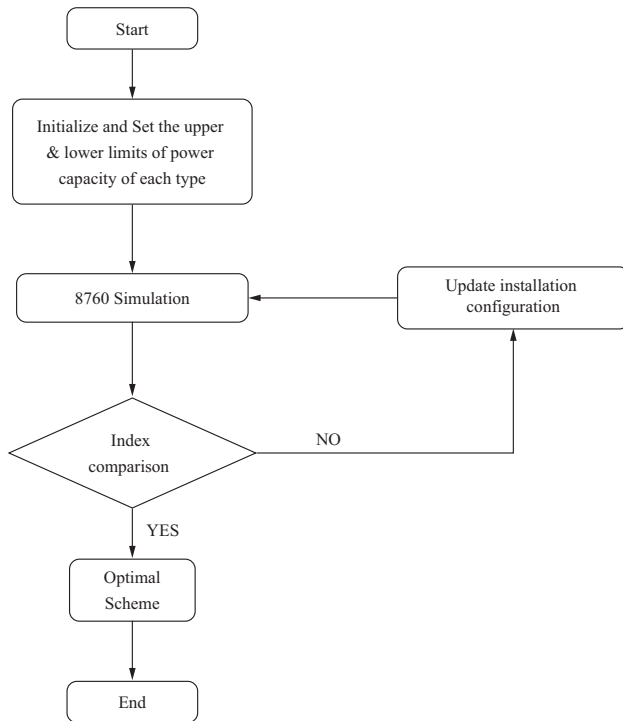


Fig. 18 Process for obtaining the optimal configuration

The feasible schemes with typical daily power balance results are as follows:

Table 5 Different schemes for the studied case

Generation/ (MW, MWh)	Scheme 1	Scheme 2	Scheme 3
Wind	300	320	220
PV	400	120	220
CSP	0	160	130
Storage	1660	0	640

Table 6 Evaluation factors for different schemes

Evaluation/(Billion yuan, yuan/kWh)	Scheme 1	Scheme 2	Scheme 3
Investment	6.104	6.744	6.61
CPS	0.732	0.805	0.774
NER	60.30%	63.10%	70.40%
PSR	94.10%	94.10%	93.90%

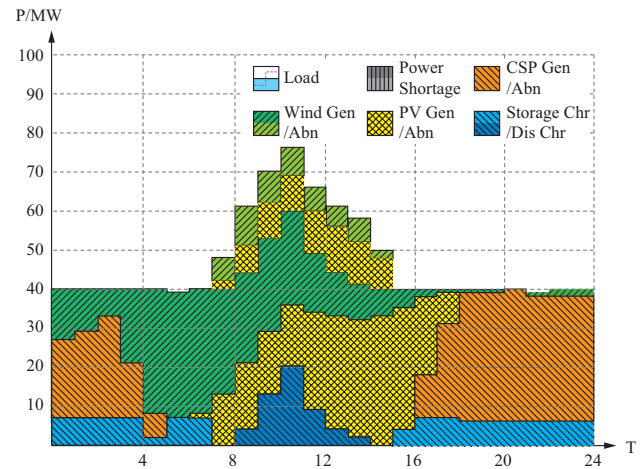


Fig. 19 Schematic diagram of typical daily power balance results

As shown in Table 5 and 6, in Scheme 3, the installed capacity of the total power supply was small, and the photothermal turbine can provide the moment of inertia and voltage support for the off-grid power supply. Through coordinated control, “CSP + energy storage” can improve the frequency modulation ability and improve the frequency stability level and system stability. Although the total investment of scheme 1 was low, the stability and flexibility of the system operation were poor. Therefore, it is recommended that Scheme 3 be used as a short-term mining power supply plan.

5 Conclusions

In this study, practical power supply cases for heavy loads in remote areas were investigated, and the insights are summarized as follows: Three key technologies for improving the reliability of renewable generation are discussed, along with application cases. Three power supply modes were introduced, and evaluation methods were identified and simulated. The following conclusions were drawn.

(1) Grid-forming storage and power load management can increase the stability and safety of off-grid power supply systems with a high proportion of renewable generation.

(2) With the recent development of renewable energy and energy storage technologies based on the three modes identified in this study, 100% renewable generation can be recognized as a reliable power supply pattern for heavy loads in remote areas.

Declaration of Competing Interest

We declare that we have no conflict of interest.

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