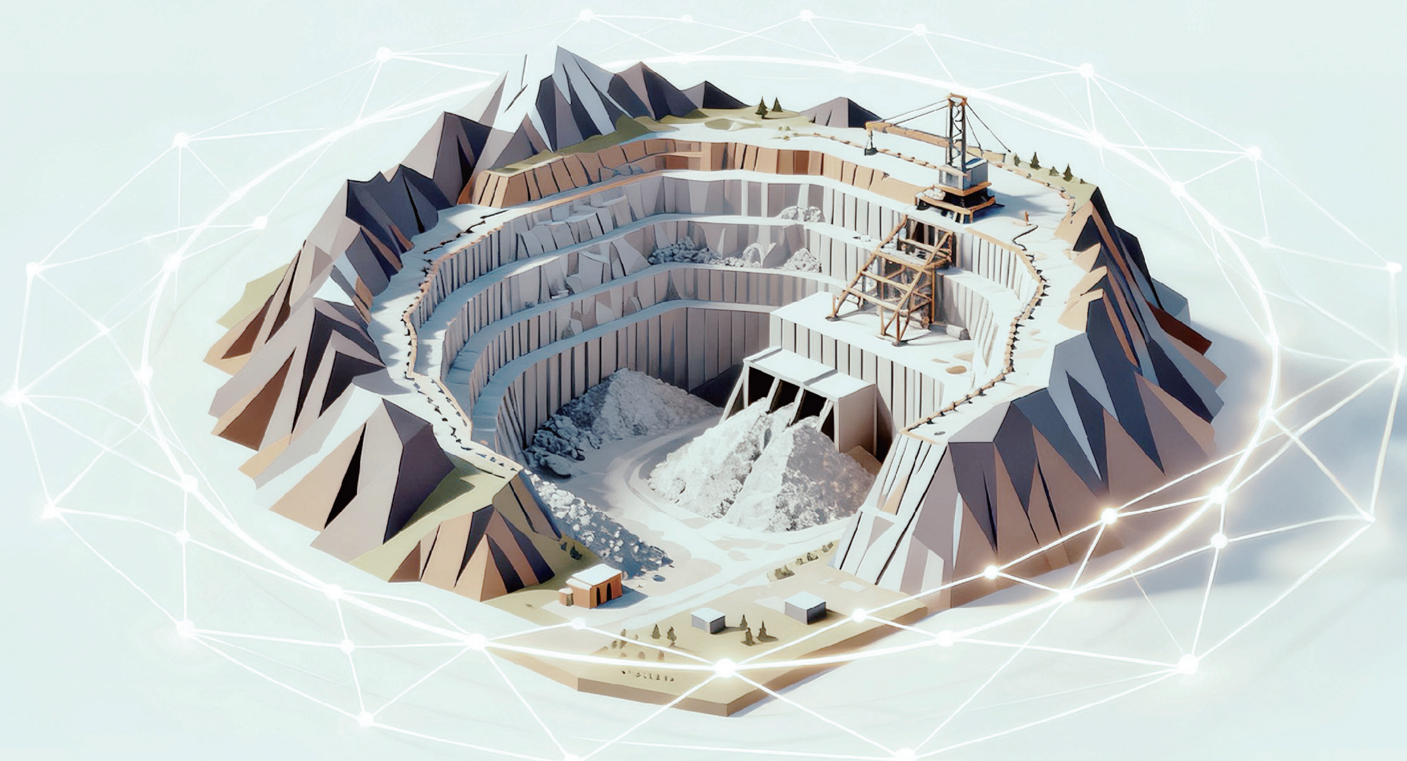
HUAWEI

Technical White Paper on Smart Microgrid Solution

(Mining Scenario)



Contents

Introduction

The mining industry faces two challenges in sustainable development: power supply stability and economic efficiency. Traditional gensets, with high costs, unreliable performance, and heavy carbon emissions, struggle to meet the demands of green and intelligent transformation.

Huawei's Smart Microgrid Solution, centered on a grid-forming energy storage system (ESS), effectively integrates multiple energy sources to deliver highly reliable power for mining operations. This approach reduces the levelized cost of electricity (LCOE) by over 50% while cutting carbon emissions. Having been validated through multiple large-scale international mining projects, it has established a replicable benchmark for energy transition in the sector.

Mining microgrids are evolving from "auxiliary power systems" into "core infrastructure for zero-carbon mining." By 2030, wind-PV-ESS microgrids are expected to become mandatory for newly built mines, marking a shift from mines as "energy consumers" to "energy producers." Early adopters of this transformation will gain significant advantages in cost control, environmental, social, and governance (ESG) rating, and market access, reshaping the global competitive landscape of mineral resources.

Chapter I

Industry Background and Development Drivers

1. Characteristics of Electricity Demands in the Mining Industry

The mining industry's energy demands—marked by high consumption, stringent reliability, and complex challenges—underscore the limitations of traditional power supply models.

The explosive growth of the renewable energy industry has driven a surge in demand for key metals such as copper and lithium. By 2030, copper demand in the renewable energy industry is expected to increase from 1.82 million tons in 2021 to 7.2 million tons (a 295% increase), lithium from 110,000 tons to 810,000 tons (a 660% increase), and cobalt and nickel by more than 170%.

The growth of metal demand has driven the expansion of mining capacity. The electricity consumption of global mineral development has accounted for 11% of the total energy consumption and increased by 5% year by year.

Table 1-1: Global renewable energy industry's demand for metals and demand increase from 2021 to 2030

Metal	2021 Demand (10,000 tons)	2030 Estimated Demand (10,000 tons)	Estimated Increase
Copper	182	720	295%
Lithium	11	81	660%
Cobalt	10	29	178%
Nickel	23	115	410%
Manganese	10	56	454%
Zinc	54	175	222%

Electricity costs are the core burden of mining enterprises, and the proportion varies greatly among different types of mines. The proportion of power costs in mechanized coal mining is 20% to 30%, that in major metal mines such as iron and copper mines is 20%, and that in rare metal mines such as lithium extraction from salt lakes and tungsten mines is 25% to 35%. Take a 10,000-ton/year open-pit copper mine in Congo-Kinshasa as an example. The annual electricity consumption is about 200 million kWh, and the power of a single ball mill is at least 10 MW. The electricity expenditure directly affects the profit.

Table 1-2: Proportion of electricity costs to operating costs of different minerals

Mineral Category	Mineral Subcategory	Electricity Cost Proportion
Coal	Mechanized coal mining	20%–30%
Major metal minerals	Iron, copper, etc.	20%
Non-metallic minerals	Limestone, gypsum	10%–20%
Rare metal minerals	Tungsten, molybdenum, lithium extraction from salt lakes, etc.	25%–35%

More than 80% of the world's large mines are over 200 km away from the main power grids. The cost of extending a power grid is as high as CNY2 million/km, and the economic feasibility is low.

In addition, extreme environments such as high altitude and extreme cold reduce the efficiency of traditional power generation equipment by more than 40%, increasing the power supply pressure. Traditional diesel generators are the main power supply mode for remote mines,

but they are difficult to adapt to industry development. Globally, mines consume about 40 million tons of diesel fuel annually and emit over 120 million tons of CO2. In Africa, 70% of mines rely on diesel fuel, consuming 18 million tons annually. [(1)] [(2)]

Diesel power generation faces inherent technical limitations. Compared to national power grids or grid-forming BESS, it has weaker frequency and voltage stability; its emergency response is slow and difficult to meet millisecond-level requirements—for instance, a copper mine in Africa experienced frequency instability due to fluctuations in PV /load, resulting in an efficiency drop of over 15%, with annual losses exceeding USD10 million. Environmental adaptability is weak: Power output degrades by 30–50% at high altitudes, efficiency drops in extremely cold regions, and noise and emissions fail to meet regulatory standards. Operations and maintenance (O&M) are complex, with short fault intervals. In regions with underdeveloped infrastructure, such as parts of Africa and Latin America, diesel fuel transport relies heavily on road networks, which are vulnerable to disruption—for example, road closures caused by rainstorms—posing a direct threat to production continuity.

More critically, diesel power generation incurs high direct and hidden costs. At a copper mine in Congo-Kinshasa, generation costs exceed USD0.40/kWh—significantly higher than those of the PV-ESS solution. In remote mines, diesel is often transported over a distance exceeding 500 km, with logistics accounting for 15%–20% of total fuel costs. Storage requires dedicated explosion-proof facilities, driving up safety-related capital investment.

As wind-PV-ESS technologies mature, diesel power generation is no longer the main power source but the emergency backup power supply. Its technical and cost disadvantages make it less competitive compared to renewable energy solutions.

The unique characteristics of mining production determine highly complex and stringent power requirements, summarized as follows:

Reliability	Power supply interruption may cause equipment damage, production suspension, or safety accidents. For example, if a ball mill halts for over 10 minutes, the grinding medium solidifies, requiring several days of cleanup. A one-hour shutdown of the underground drainage system can result in well flooding. If a coal mine blower stops for just 10 minutes, gas concentrations may exceed safety thresholds. To prevent such risks, the power supply system must operate continuously and respond to faults within milliseconds.
Stability	Frequent startup and shutdown of heavy-load motors (such as crushers and ball mills) can cause voltage fluctuations and harmonic interference, requiring dynamic reactive power compensation (SVG) and voltage regulators to maintain stability. In a weak grid, spinning reserves or ESSs are needed; in off-grid operation, stability relies on coordinated control between ESSs and gensets.
Flexibility	Power systems must adapt to temporal and spatial variations. Electricity demand fluctuates significantly across different production stages over time. Spatially, open-pit mines require mobile substations, while underground mines need grid expansion. Additionally, systems must support short-term equipment overloads and optimize power usage across operational processes.
Large capacity	The entire process requires high power. The power of electric hydraulic shovels and mining trucks in the mining process is high, and the power of semi-autogenous grinding mill motors in the processing process reaches 5 MW to 10 MW. Large mines often necessitate dedicated substations rated at 110 kV or even 220 kV, along with multiple high-capacity transformers.
Cost efficiency	Electricity expenses account for 15% to 40% of operational costs. A mere 1% reduction in electricity expenses can significantly boost profitability. To achieve this, power sources must be optimized, energy efficiency improved, and intelligent dispatching implemented. In mining, cost advantage is critical to survival.
Energy conservation and environmental protection	Under the carbon goals, emission reduction is imperative. Driven by policies, technologies, and shifts in the energy mix, energy conservation and environmental protection directly impact mining license acquisition and brand value. They are central to the industry's sustainable development agenda.

2. Policy and Regulation Drivers

The global carbon neutrality goal and microgrid incentive policies of countries are working together to promote the green and low-carbon transformation of mining energy systems. This trend, coupled with increasingly stringent carbon trading mechanisms, is restructuring the competition rules of global mining industry. Take the European Union (EU) as an example. Its carbon price under the Emissions Trading System (ETS) has risen to EUR80 per ton in 2025. Congo-Kinshasa produces 2.6 million tons of copper each year. If all the copper is sold to the EU, the country needs to pay a carbon tax of EUR400 million,

accounting for more than 2% of its operating revenue. Carbon costs have turned from potential risks into substantial financial pressure.

Top mining enterprises have accelerated their efforts to reduce emissions: BHP plans to cut 30% of carbon emissions by 2030 (compared to 2020 level) and achieve net zero emissions by 2050. Rio Tinto has invested USD5 billion to USD6 billion in renewable energy development, aiming to reduce emissions by 50% by 2030. Zijin Mining plans to peak carbon emissions by 2029, one year ahead of the national target (see table 1-3).

Table 1-3: Carbon emission reduction targets of top mining enterprises worldwide

Enterprise	Country	Target
BHP	Australia	Reduce emissions by 30% by 2030 (compared to 2020 level), achieve net zero emissions by 2050, invest in electric transportation, and use clean energy to generate electricity; (3)
Rio Tinto	United Kingdom	Reduce emissions by 50% by 2030 (compared to 2018 level), achieve net-zero emissions by 2050, and invest USD5–6 billion in renewable energy, aluminum anode technology, and alumina processing;(4)
Zijin Mining	China	Peak carbon emissions by 2029—one year ahead of China's commitment. By then, carbon intensity per CNY10,000 of industrial output will be reduced by 34.9% compared to 2020 levels. Achieve carbon neutrality by 2050;(5)
Glencore	Switzerland	By 2035, reduce total emissions by 40% (compared to 2019 level)and cut carbon emission intensity of coal mining by 50%. By 2050, achieve carbon neutrality;(6)
Vale	Brazil	Reduce emissions by 33% by 2030 (compared to 2020 level), and achieve carbon neutrality by 2050;(7)
Anglo American	United Kingdom/ South Africa	Reduce greenhouse gas (GHG) emissions by 30% by 2030 (compared to 2016 level),and achieve carbon neutrality for all mining operations by 2040;(8)
FMG	Australia	Invest USD6.2 billion to achieve scope-zero emissions in onshore operations in Australia by 2030 and reduce carbon emissions by 3 million tons annually.(9)

The carbon neutrality goal is driving stricter ESG regulations and raising barriers to capital access. The EU's Carbon Border Adjustment Mechanism (CBAM) and standards set by the International Council on Mining and Metals (ICMM) are pressuring companies to reduce emissions. Otherwise, companies will face export restrictions and rising financing costs. Financial institutions such as Goldman Sachs and JPMorgan have made emission reduction progress a key criterion for loan approval, significantly increasing financing challenges for high-carbon emission mining enterprises. (10)(11)

3. Economic and Technical Drivers

The declining cost of renewable energy and the maturity of microgrid technologies provide both feasibility and economic support for energy transition in mining operations.

The price of monocrystalline silicon modules has dropped from USD0.60/Wp in 2015 to USD0.11/Wp in 2025. After 2025, the mass production of perovskite cells is expected to further reduce costs by 30% compared to monocrystalline silicon. By 2030, the LCOE for PV systems may fall as low as USD0.02/kWh. Lithium-ion battery costs have declined from USD350/kWh in 2015 to USD80/kWh in 2025, with life exceeding 8,000 cycles. By 2030, costs may drop further to USD58/kWh, driving down the LCOS of ESSs.
The continued decline in PV and ESS costs is driving down the cost of PV-ESS microgrid power generation. It is expected that the "accelerated grid parity" phase will begin after 2025, and PV+ESS microgrids will be able to compete with coal and gas power plants in most regions around the world, becoming the mainstream choice of distributed energy. (12)

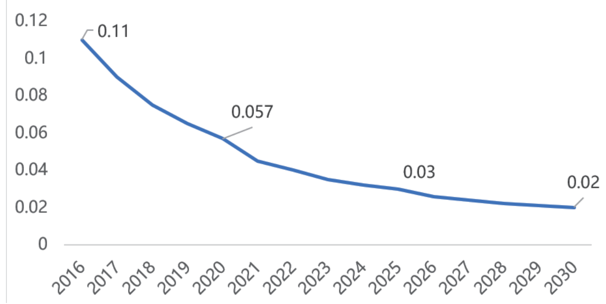


Figure 1-1: PV system LCOE trends (2015-2030) (Unit: USD/kWh)

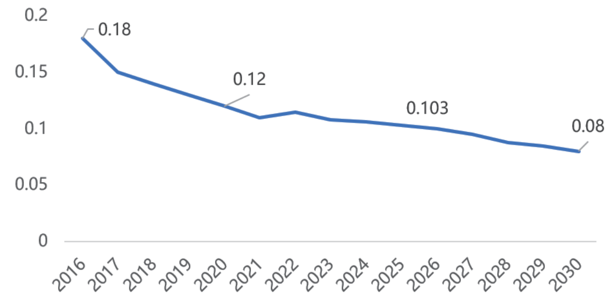


Figure 1-2: ESS levelized cost of storage (LCOS) trends (2015-2030) (Unit: USD/kWh)

Microgrid technology has gone through three development phases and has evolved from a "backup system" to a "core infrastructure."

Exploration and verification	In the early stage, a microgrid mainly provides power supply in islanded mode (such as for remote rural areas and border outposts), with a scale of only tens to hundreds of kilowatts. The system architecture consists of a basic PV-ESS-genset configuration, featuring simple dispatching logic.
Demonstration	The virtual synchronous generator (VSG) technology is mature and grid forming power conversion systems (PCSs) are widely used, providing grid support capabilities comparable to synchronous generators. Model predictive control (MPC) enhances dispatching by enabling multi-objective coordination. The IEC 61850 protocol has been extended to microgrids, addressing interoperability challenges among heterogeneous devices.
Large-scale promotion	Thousands of PCSs can be synchronized and connected in parallel, supporting the construction of 100 MW-level microgrid plants. Microgrids are upgraded from a single power supply to a multifaceted platform integrating energy efficiency management, carbon emission management, and electricity trading—shifting from a subsidiary of the main grid to a cornerstone of modern power system stability.

4. Challenges of Mining Microgrid Development

The promotion of renewable-ESS mining microgrids faces multi-dimensional challenges in terms of technology, economy, and mode, and needs to be systematically addressed.

Technology: Intermittent power generation by renewables conflicts with stable energy consumption demands in mines. ESS applications are limited by costs, service life, extreme environment adaptability, and system integration complexity. Old power grids cannot support grid connection, and the durability and efficiency of devices in special environments are also a problem.

Capital: The mismatch between project duration and facility lifespan hinder cost amortization, while high upfront investment intensifies financial pressure. Regional disparities inflate financing costs, ESS expenses prolong the payback period, and supply-demand mismatches in renewable energy further adds to overall costs.

Construction and O&M: It is difficult and costly to construct projects in remote mining areas due to the shortage of technical personnel, high requirements on system O&M, and difficulties in intelligent collaborative dispatching.

Business model: Mining enterprises and energy developers often diverge in investment entities, lacking a mature risk-sharing model. As a result, third-party investments encounter multiple challenges.

Policy: There are large differences in policies of different countries, with frequent changes and lengthy approval processes. Projects also face risks related to land use, ecological impact, community acceptance, and geopolitical factors.

Chapter II

Key Technologies of Mining Microgrids

1. Solution Overview

A microgrid is a small power system consisting of distributed energy sources, ESSs, loads, and control devices. It has a clear electrical boundary and can operate in on-grid or islanded mode (defined in IEEE 2030.7-2017). The application scenarios are as follows:

Off-grid scenario: Without connection to the main power grid, the PV system, ESS, gensets, and loads operate together as an islanded microgrid.
Key features include:

① Loads are completely powered by internal power sources in the microgrid to achieve self-consumption; The
② microgrid provides the plant-wide black start capability to implement minute-level synchronous black start with loads;
③ The microgrid central controller (MCGG) implements secondary and emergency voltage and frequency regulation;
④ The microgrid energy management system (EMS) implements economical operation through generation-grid-load-storage interaction;
⑤ The ESS can operate independently in grid forming mode;
⑥ The ESS and genset can work coordinately in grid forming mode, improving the loading capability of the microgrid and increasing renewable energy integration.

On/Off-grid scenario: The main power grid often imposes electricity rationing or experiences frequent outages.
Key features include:

① The microgrid connects to the power grid via the point of interconnection (POI) and supports both on-grid and off-grid modes;
② The microgrid supports planned on/off-grid switching;
③ The microgrid supports unplanned seamless on/off-grid switching;
④ The microgrid supports demand control and zero feed-in control at the POI;
⑤ The microgrid supports time-of-use (TOU) control at the POI;
⑥ The microgrid supports frequency/voltage stability control in off-grid mode and PV+ ESS+ genset synergy.

Based on the project scale, the PV-ESS system can be coupled in medium-voltage (MV) AC mode (coupling point voltage: 10 kV to 35 kV) or high-voltage (HV) AC mode (coupling point voltage: ≥ 110 kV). Different coupling voltage levels correspond to distinct microgrid control architectures.

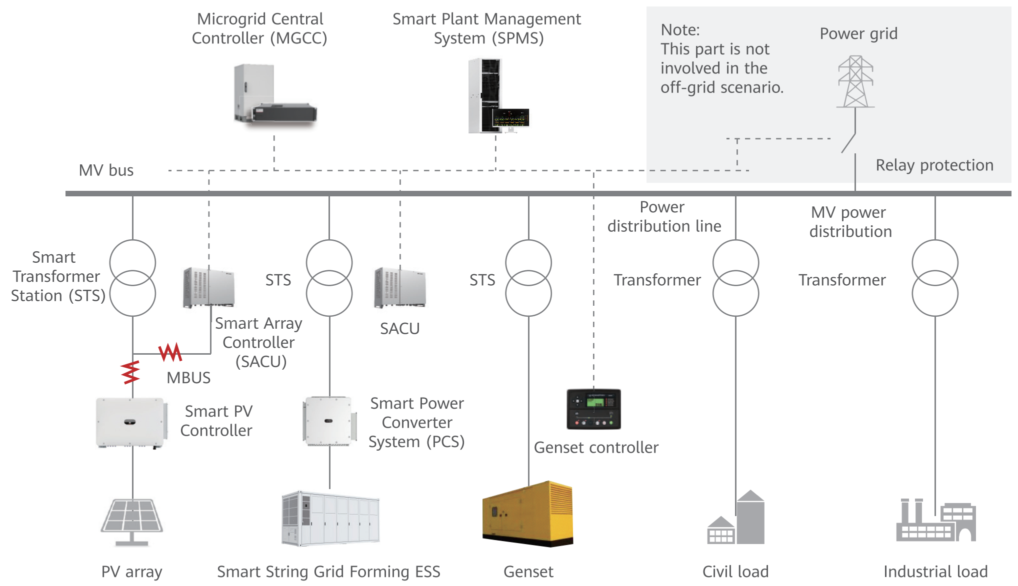


Figure 2-1: AC-coupled PV+ESS microgrid system architecture (off-grid & on/off-grid)

2. Microgrid Operation Modes

The Institute of Electrical and Electronics Engineers (IEEE) defines two stable microgrid operation modes and four switching processes.

Stable operation modes

① On-grid mode: The microgrid is connected to the main power grid and can exchange power with the power grid. The PV system and ESS operate in current source PQ mode (preset output power), and the genset is usually in cold standby mode.

② Off-grid mode: The microgrid operates independently. The internal voltage source (such as the ESS in VSG mode or genset in VF mode) supports the voltage and frequency. The PV system operates in PQ mode.

Switching processes

① Planned islanding: The switching is manually triggered. The power can be pre-controlled before the switching, and the inrush current is small.
② Unplanned islanding: The switching is caused by a grid fault, and the inrush current is high. Seamless switching needs to be implemented with the cooperation of protective relays and the microgrid controller.
③ Grid reconnection: It is classified into seamless (quasi-synchronous grid connection) and seamed (grid connection after the power supply is shut down) modes.
④ Black start: After a system power outage, a power source with black start capability (such as the ESS) rebuilds voltage and gradually restores power supply.

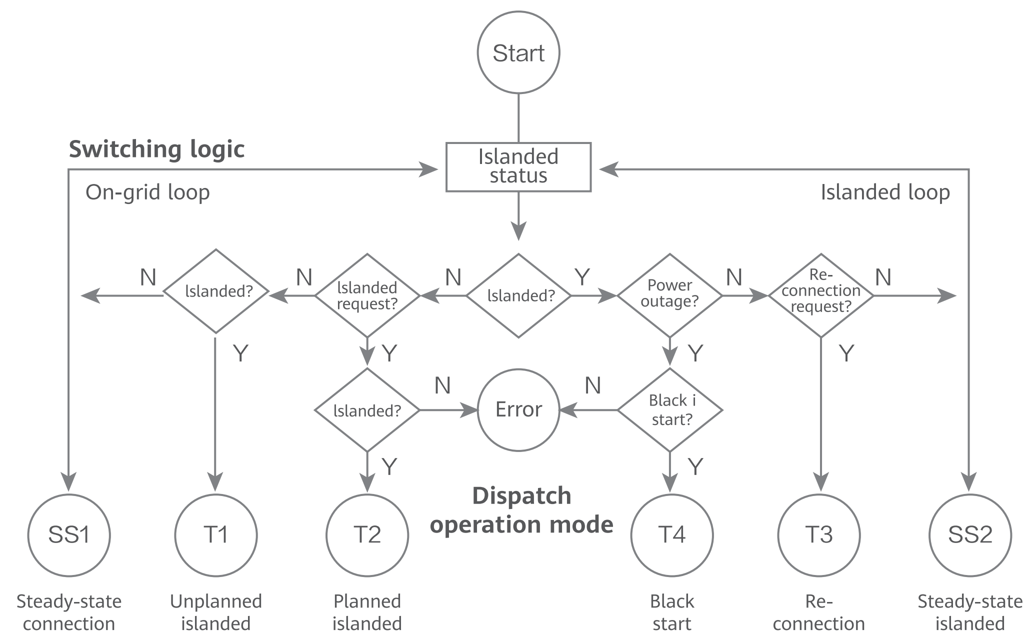


Figure 2-2: Typical operation modes and switching processes of a microgrid

3. Huawei Smart Microgrid Solution's Architecture Innovation and Key Technologies

3.1 Hierarchical Control Architecture

To tackle challenges faced by microgrids, Huawei provides a lightweight and standardized Smart Microgrid Solution. Hierarchical control is vital for a microgrid system to achieve the optimal balance between economy and stability. Huawei's microgrid control system carefully considers time-based control and function implementation and is divided into three layers: stable grid-forming control, efficient coordinated control, and intelligent optimized dispatching.

① Stable grid forming control: Using the frequency and voltage regulation capability of equipment, the grid forming power supply and topology are designed to ensure stable synchronous grid forming with 100% renewable energy and support continuous power supply to loads.

② Efficient coordinated control: The MGCC serves as the hub on this layer to execute rapid coordinated control of generation, grid, load, and storage in the system within 100 ms. When the power load is unbalanced, fluctuation smoothing is implemented to stabilize the microgrid frequency and voltage. The solution also features seamless on/off-grid switching and fast black start. In the future, the coordinated control layer will become highly integrated. A set of equipment will converge data collection, centralized control, and communication functions. The integrated design will significantly improve data collection and processing efficiency, ensure high performance, reduce equipment investment, and simplify subsequent commissioning and maintenance, laying a solid foundation for large-scale replication and system capacity expansion.

③ Intelligent optimized dispatching: The EMS works in the center of this layer to ensure balanced power in the microgrid with dispatching optimization in minutes and operational safety margin management. Microgrid optimized dispatching needs to predict the future power generation based on weather or historical power generation data, properly plan the charge and discharge power of the ESS based on forward-looking results, and estimate the consumption based on power generation. Bidirectional coordination between generation and consumption will help achieve energy independence.

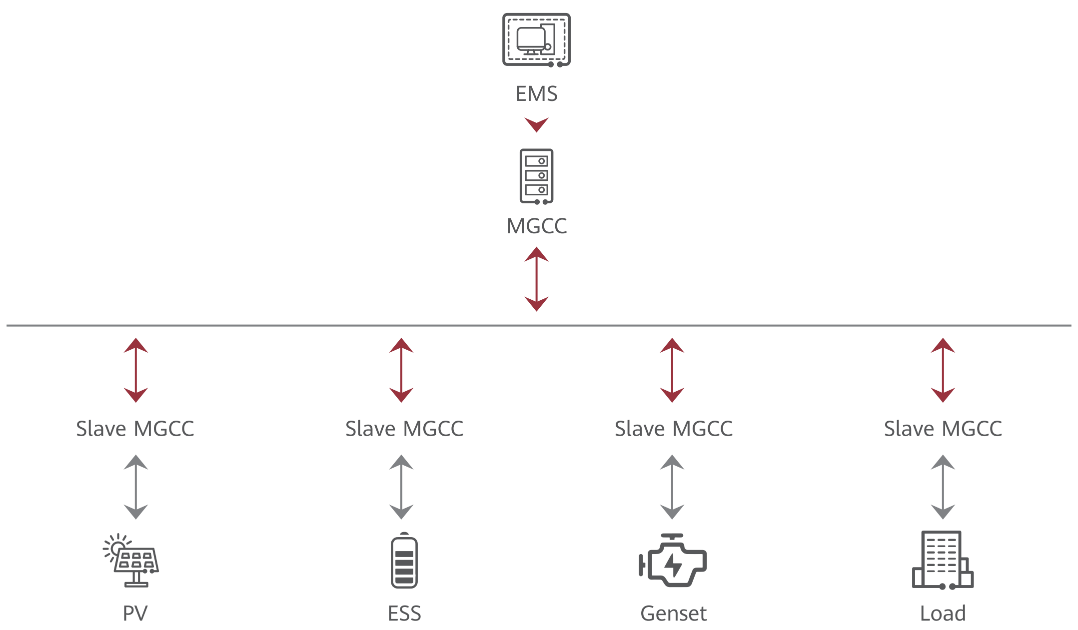


Figure 2-3: Hierarchical control architecture for microgrids

3.2 Six Key Technologies for Stable Operation

(1) Large-scale ESS grid forming

Challenges With breakthroughs in grid forming ESS technology and declining PV-ESS costs, GWh-level microgrids have become a reality. However, large-scale parallel operation of grid forming ESSs still faces critical challenges.

When hundreds to thousands of independent voltage sources operate in parallel, achieving stable and synchronized operation becomes a major technical hurdle. Key issues include: (1) circulating currents leading to uneven power distribution, (2) wideband oscillations caused by multi-device interactions, and (3) high-precision synchronization and coordination difficulties in control algorithms. Overcoming these challenges is essential for enabling power systems with a high proportion of renewable energy.

Solution To address grid stability issues arising from high-proportion renewable energy integration, Huawei's grid forming ESS adopts the VSG technology.

By emulating the operating characteristics of traditional synchronous generators, and leveraging power electronic converters for millisecond-level power regulation, the system ensures stable voltage and frequency within microgrids. Huawei Smart String PCSs feature a high switching frequency and control bandwidth, which can better suppress circulating currents.

① Active fast primary frequency regulation (PFR)
During microgrid operation, sudden load changes or power fluctuations of the distributed power source may cause power generation and consumption imbalance, leading to frequency deviations. Huawei's grid forming ESS uses a governor model to detect frequency changes in real time, calculate active power adjustment commands, and complete dynamic response within 5 ms. This enables active power–frequency droop control and rapidly restores system frequency stability.
Active fast primary voltage regulation (PVR)

② Voltage fluctuations also threaten the safe operation of microgrids. Huawei's grid forming ESS dynamically adjusts the internal potential and reactive power output based on the exciter model. The system voltage is adjusted within 5 ms when the system voltage changes abruptly, effectively suppressing voltage deviations and improving grid voltage stability.
The technology simulates the inertia, damping, and frequency and voltage regulation characteristics of synchronous generators, so that the ESS can function as a stable voltage source during off-grid operation. The ESS independently supports the voltage and frequency of the microgrid, ensuring stable power supply without relying on the main power grid. This effectively improves the autonomy and reliability of the off-grid power system.

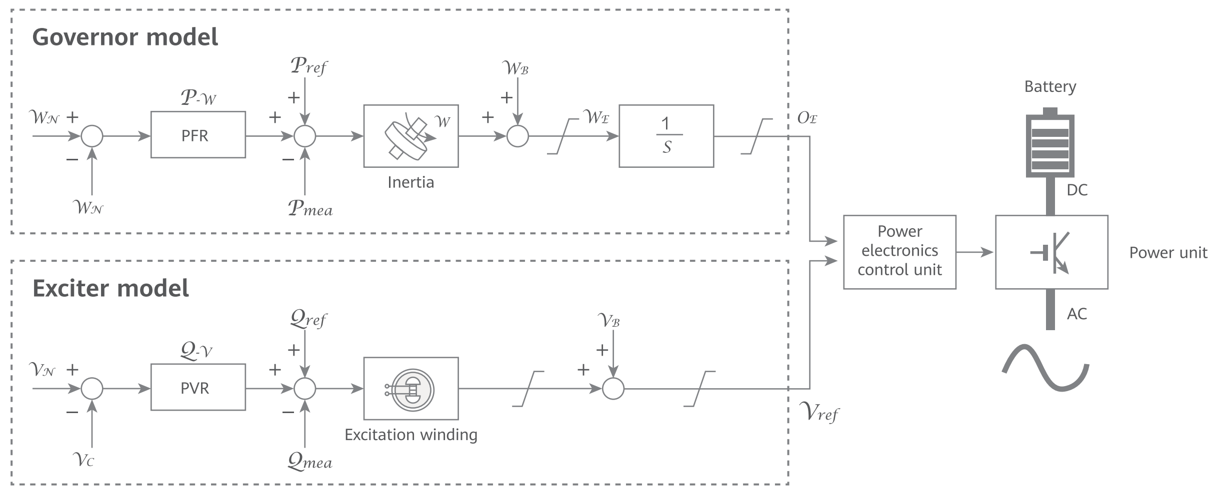


Figure 2-4: Working principle of the grid forming ESS VSG

(2) Large-scale black start ESS

Necessity

In the event of a complete blackout of the power system, black start is the process of gradually restoring power supply by relying on the internal power source (such as the ESS or genset) that has the automatic startup capability.

For a 10 MW off-grid mine, a power outage can result in economic losses ranging from hundreds of thousands to over a million yuan per hour. Therefore, fast and reliable black start is critically important. Since the main power grid cannot be relied upon, the mine must restore power independently through distributed power sources. Currently, China has explicitly mandated that mining microgrids possess black start capability and is developing a national standard—Technical Specification for Microgrid Black Start (applicable to systems of 35kV and below). Meanwhile, regions such as the EU and Australia have also imposed strict regulatory requirements on emergency power supply and black start for mining operations.

Challenges

A single traditional genset has a large capacity and can easily drive a wide scope of loads during black start, featuring simple operation.

In contrast, the power of a single electrochemical energy storage array is limited. In high-load scenarios such as mines, direct startup is likely to cause device overload and even secondary system breakdown. Therefore, a 100 MW-level mining microgrid must rely on multiple ESS arrays to work together to complete black start, providing sufficient capacity to support the gradual load startup. When multiple PCSs are running in parallel in voltage source mode, slight voltage or phase differences may cause circulating current, triggering overcurrent protection and causing black start failure.

Solution

To address this challenge, a non-synchronous parallel line voltage synchronization technology can be adopted.

The system ensures precise and synchronized dispatch of EMS commands in the following ways: enabling automatic voltage synchronization and sampling calibration among multiple PCSs, supporting synchronous voltage boost in soft start of multiple parallel PCSs in an array (multi-PCS synchronous paralleling technology and multi-PCS automatic phase lock re-synchronization technology) and synchronous voltage boost in soft start of multiple parallel arrays (multi-array GOOSE broadcast communication synchronization technology), and integrating a high-precision hardware communication protocol. This setup can smoothly build full system voltage from zero within one minute, effectively suppressing circulating currents between PCSs and keeping the current RMS deviation within 5%. Once the transmission and distribution network is synchronously soft-started, simply activating the corresponding distribution lines enables rapid restoration of power across the entire grid, significantly enhancing system self-recovery capability and power supply reliability.

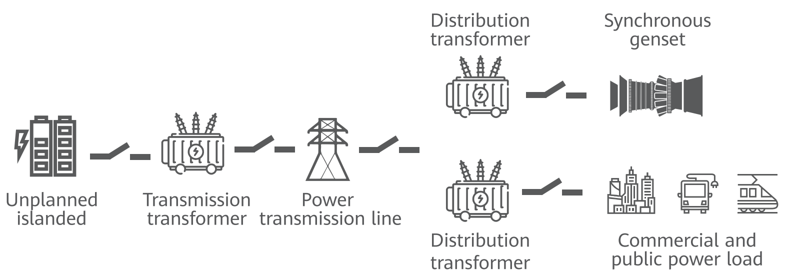


Figure 2-5: Simplified black start topology

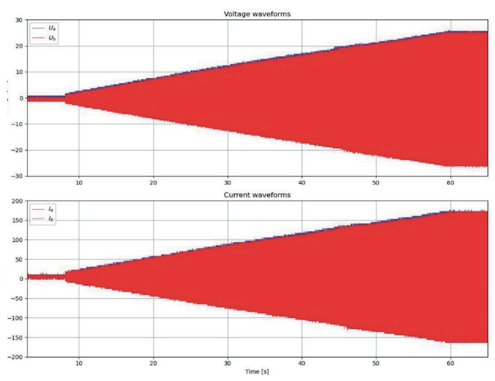


Figure 2-6: Loaded ESS black start waveform

(3) Off-grid fault ride-through

Necessity

The operating environment of a mining microgrid is special and complex. Large mining equipment on the load side frequently starts and stops, causing abrupt power changes.

The genset on the power supply side responds slowly, and the PV+ESS output is highly random. In addition, the impedance of long-distance power supply lines is high, and harsh environmental factors such as severe dust and strong electromagnetic interference make the system prone to voltage fluctuations, causing devices to be disconnected from the grid or even the entire grid to collapse. Therefore, improving the high and low voltage ride-through (HVRT/LVRT) capabilities of the system is the key to ensuring continuous and stable operation of the mining power supply.

Challenges

As the core voltage source of the microgrid, the grid forming ESS must have complete fault ride-through capabilities, including LVRT, HVRT, and continuous fault ride-through, to ensure that the mining microgrid remains stable in various disturbances.

Compared with an on-grid system that only needs to implement simple current limiting protection, an islanded microgrid composed of 100% renewable energy faces greater challenges in fault ride-through. The system must not only provide sufficient short-circuit current to support the correct operation of protection devices, but also maintain phase angle stability and quickly rebuild the voltage and restore power supply after the fault is cleared.

Solution

Off-grid fault ride-through is the most challenging issue in large islanded grids. Currently, there is no mature mechanism or standard available worldwide.

By integrating multidisciplinary technologies, we have achieved comprehensive dynamic response coverage ranging from microseconds to seconds during faults. Practical implementations have confirmed that even in high-voltage generation and transmission systems with multiple power sources and 100% power electronics, safe and reliable fault ride-through is achievable. These capabilities significantly enhance system robustness and power supply continuity, effectively reducing unplanned shutdown and equipment damage caused by voltage issues. They support continuous mining operations under harsh conditions, lowering operational risks and economic losses.

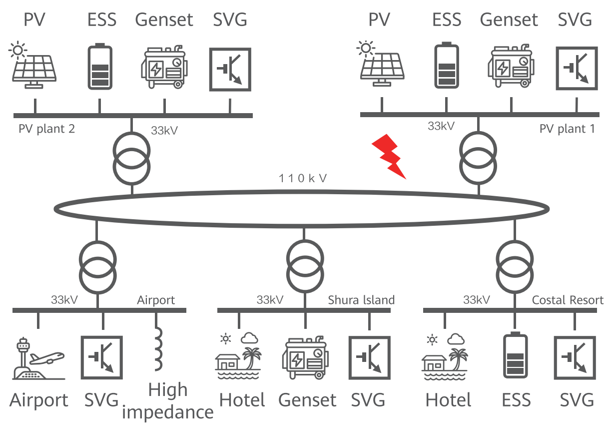


Figure 2-7: Fault ride-through

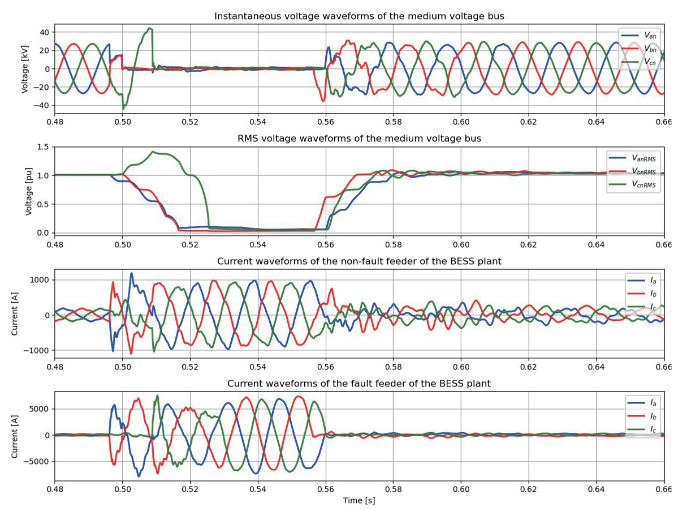


Figure 2-8: System-level re-synchronization algorithm after a fault

(4) Transformer inrush current tolerance

Necessity

Mining microgrids face unique challenges of frequent transformer energization/de-energization, with annual operations reaching 100–200 times. This is primarily due to:

① Load impact characteristics: Large-scale mining equipment such as crushers and ball mills (with power of single equipment reaching the MW level) frequently are started and stopped, causing severe grid fluctuations. In the following figure, a 3000 kW ball mill can generate a transient impact 6–8 times its rated current during startup, with peak apparent power reaching 9–13 times the rated value and lasting several seconds. To stabilize voltage, the system must frequently adjust transformer tap positions or switch on/off standby transformers, which exacerbates the transient process instability.

② Complex operation modes: Mining microgrids often switch between on-grid and islanded modes. Long-distance cables are prone to lightning strikes and other disturbances, resulting in high fault rates. During faults, transformers must be switched on/off rapidly, and the resulting excitation inrush current can reach 6–12 times the rated current.

Solution

To address these challenges, the advanced anti-excitation inrush current technology integrates sophisticated control algorithms into the power converters and enhances system overload capacity.

By combining fast current limiting, active current balancing, and anti-phase jump technologies, the system implements the excitation control function when transformers are directly energized. This effectively suppresses inrush current and extends excitation time without triggering system overload protection. Project validations show that PCSs can withstand transformer inrush currents up to 150% of their rated capacity, handling the impact of large-scale transformer energization/de-energization without requiring an additional ESS configuration. Experimental data confirms that even when transformer energization causes brief voltage dips or overshoots on the MV bus, the system remains stable, ensuring continuous and reliable power supply for customers.

Core value

- Reduced investment costs: Eliminate the need to expand the ESS capacity to handle transformer impact, saving upfront equipment investment.
- Improved system stability and reliability: Effectively suppress excitation inrush current and transient voltage fluctuations, ensuring continuous operation of critical loads and reducing the risk of production interruption.
- Enhanced operational adaptability: Support frequent and complex switching between operation modes and transformer operations, adapting to harsh mining conditions and high-failure-rate environments.
- Extended equipment lifespan: Reduce electrical equipment stress and maintenance requirements by suppressing current impact and abrupt voltage changes.

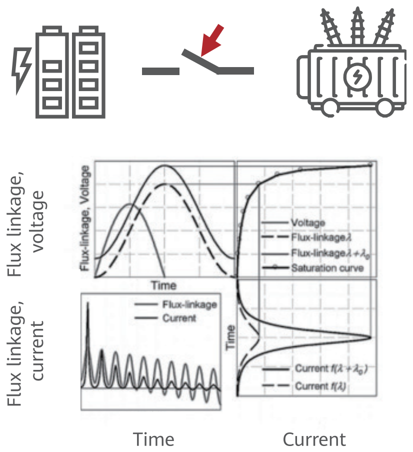


Figure 2-9: Transformer energization/de-energization

Inrush current of transformer energization caused by saturation characteristics of ferromagnetic materials, remanence, and switching angle

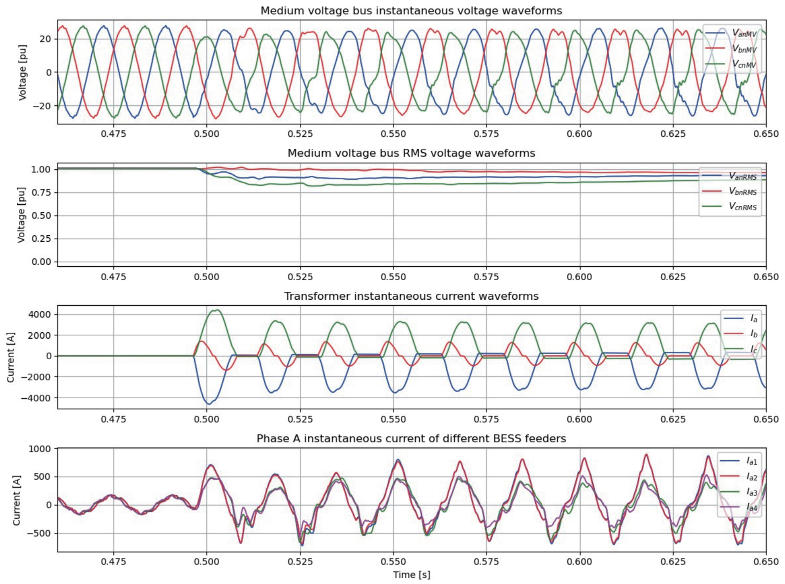


Figure 2-10: Measured excitation impact waveforms of large transformers in the microgrid ESS

(a) Microgrid transient voltage (b) Microgrid RMS voltage (c) Transformer inrush current (d) ESS feeder current

(5) On/off-grid uninterrupted power supply upon power outage

Necessity

The power supply system of mining microgrids faces stringent requirements for high continuity and stability, especially when serving large-scale equipment: (1) Safety-critical loads: Prolonged power outages can directly endanger human safety and lead to major accidents.

(2) Process-critical loads: Interruptions to loads requiring continuous production can cause operational downtime, reducing annual effective production time. For example, a copper mine with an annual output of 100,000 tons may incur losses of approximately CNY850,000 for every hour of outage. (3) Large motor-driven equipment: The startup current can reach 6–8 times the rated value and last several seconds, causing a sharp drop in bus voltage and leading to microgrid system collapse. Table 2-1 lists critical mining equipment and corresponding power supply requirements.

Table 2-1: Examples of load levels and power supply requirements for typical mining equipment

Load Requirement	Load Classification	Equipment Type	Allowed Downtime	Power Outage Consequence	Design Requirement
Level-1 load	Power loads that may lead to casualties, major equipment damage, significant economic losses, or serious impact on public safety in case of power supply interruption	Emergency lighting and communication	≤ 500 ms	Personnel safety accidents	Dual-loop power supply + fast switching + intelligent monitoring
		Long-distance belt with energy recovery	≤ 2s	Belt deviation, mechanical damage	
		Main fan	≤ 10 min	Gas explosion risk	
Level-2 load	Power load that may cause considerable economic losses, production suspension, or impact on the operation of important public facilities, but does not directly endanger personal safety or cause major disasters in case of power supply interruption	Ball mill	≤ 10 min	Consolidation of grinding medium, time-consuming cleaning	Dual-loop power supply, allowing short switching delay
		Mine slurry pump	≤ 10 min	Pipe blockage and chemical deposition	
		Copper electrolytic cell	≤ 20 min	Copper re-dissolution, requiring rework	

Solution

The core to ensure uninterrupted power supply upon power outage is the collaboration of power generation equipment, protective relays, and loads.

① Fault identification and ride-through of the microgrid: Quickly and accurately identify various short-circuit and open-circuit faults inside and outside the microgrid, and accurately control the switch-on and switch-off operations of the POI switch. The unique off-grid fault ride-through technology can maintain sufficient short-circuit current during on/off-grid switching and ensure that the power angles of a large number of PCSs are synchronized. After the POI switch is disconnected, all PCSs in the system can quickly rebuild the microgrid voltage synchronously to ensure continuous power supply to loads.

② Voltage dip tolerance optimization for critical loads: The motor startup mode is improved to reduce the system impact, optimize load running parameters, and reduce equipment startup/shutdown frequency. In addition, the voltage dip tolerance capability of critical sensitive loads is improved (from ≤ 20 ms to ≥ 300 ms) to ensure continuous running of critical equipment during microgrid switching.

The following figure shows the seamless switching test results of the microgrid when the external power grid is faulty.

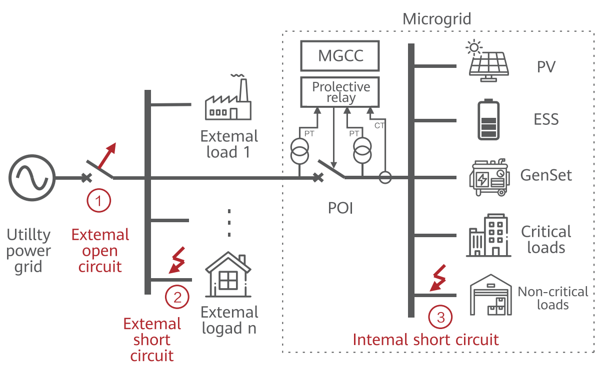


Figure 2-11: On/Off-grid switching

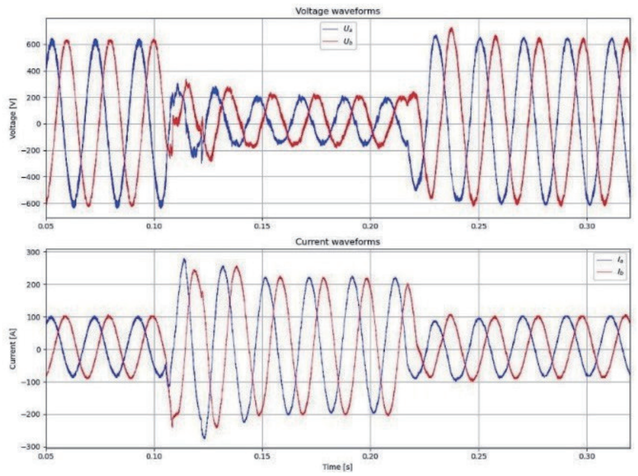


Figure 2-12: Lab test results of unplanned on/off-grid switching

Customer benefits

This solution implements seamless switching of the microgrid when the external power grid is faulty through coordinated control of power generation and load sides, minimizing safety accidents and production interruption caused by power outages, effectively improving the continuous runtime of the system, and building a reliable and resilient power supply system for customers.

(6) PV+ESS+genset synergy

Challenges

In a traditional microgrid system that uses the genset and PV system as main power sources, as the frequency regulation capability of the genset is limited, the PV system needs to run at reduced load to ensure system stability. This not only reduces the PV power generation efficiency, but also causes energy waste. In addition, frequent power outages significantly affect the availability of the microgrid. To improve the system stability, this has become a key topic in microgrid transient stability research: The genset and ESS function as the voltage sources and back up each other, and the PV system, ESS, and genset operate in synergy to achieve millisecond-level dispatching response. However, the following challenges still linger:

① Multi-device parallel coordination: When multiple grid forming PCSs operate in parallel, issues such as circulating currents or loss of synchronization can easily occur.

② Mode switching: During on/off-grid switching, differences in control policies between the genset and PCSs (such as VSG grid forming mode and PQ grid following mode) may lead to voltage and frequency fluctuations or brief power interruptions.

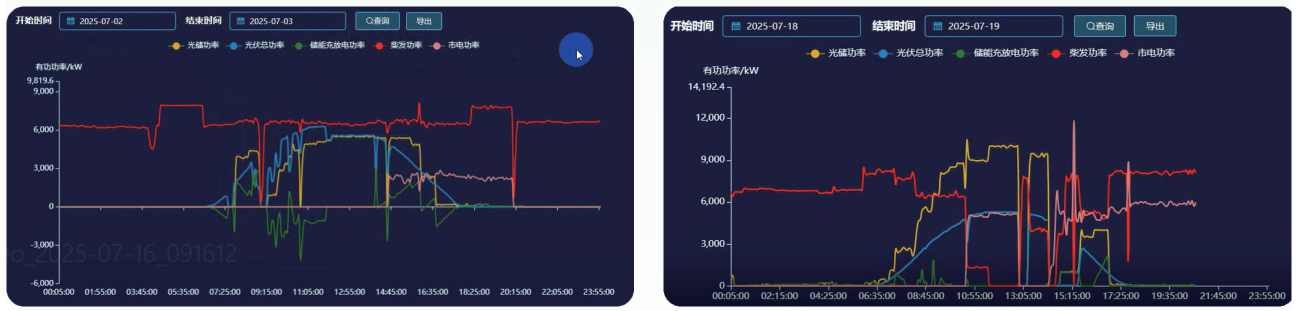
③ Voltage and frequency stability: When dual voltage sources operate in parallel, the excitation and speed regulation characteristics of the genset may cause voltage and frequency fluctuations.

④ System economic efficiency: Traditional single-voltage-source microgrids require large capacity margins to handle sudden load changes, resulting in low resource utilization efficiency.

Solution

Huawei Smart Microgrid Solution innovatively uses the grid forming ESS technology to effectively solve the circulating current among multiple devices connected in parallel. In addition, the advanced PV+ESS microgrid adaptive control algorithm is used to enable the system to intelligently perceive environmental conditions, load requirements, and grid status, and implement independent optimization of operation policies. In this solution, the ESS and genset function as dual voltage sources and work together to form a grid, greatly improving the stability and reliability of the microgrid system. This solution has three core advantages:

Automatic maximum PV output: PV modules always work in maximum power point tracking (MPPT) mode to automatically maximize the power output. The system monitors PV power generation and load requirements in real time, and dynamically adjusts the charge and discharge status of the ESS to ensure stable and efficient operation of the microgrid, effectively reducing PV curtailment and improving the overall energy yield.



Without PV+ESS+genset synergy algorithm

With PV+ESS+genset synergy algorithm

Figure 2-13: PV+ESS+genset operation curves of the Mabende mining microgrid project in Congo-Kinshasa

Millisecond-level response of dual voltage sources: When the PV power drops sharply (for example, due to cloud cover or sunset), the grid forming ESS technology is effectively used to quickly detect and respond within 10 ms, effectively avoiding out-of-step oscillation of the PV+ESS+genset system. In contrast, the traditional genset system takes 2 to 3 seconds to complete frequency regulation, during which the frequency deviation can reach ±0.5 Hz or higher.

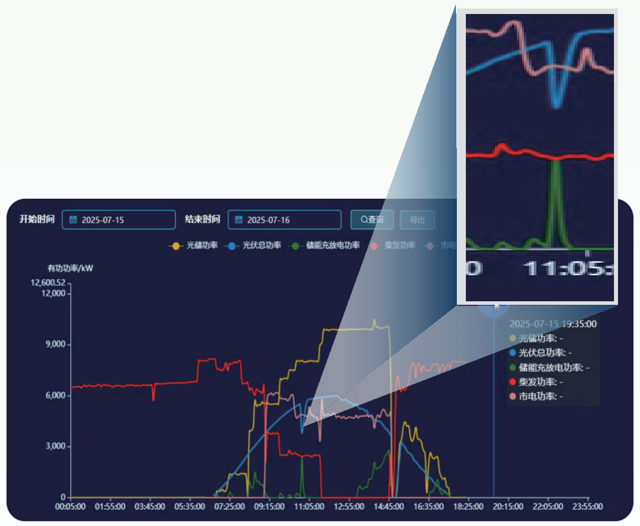


Figure 2-14: Active power fast response of the Mabende mining microgrid project in Congo-Kinshasa

Enhanced impact resistance: The grid forming ESS and genset work together to form a grid and effectively cope with the impact of frequent startup and shutdown of high-power equipment. The system uses intelligent power distribution to quickly suppress sudden current changes and ensure voltage stability. It is especially suitable for mining areas with unstable power supply.

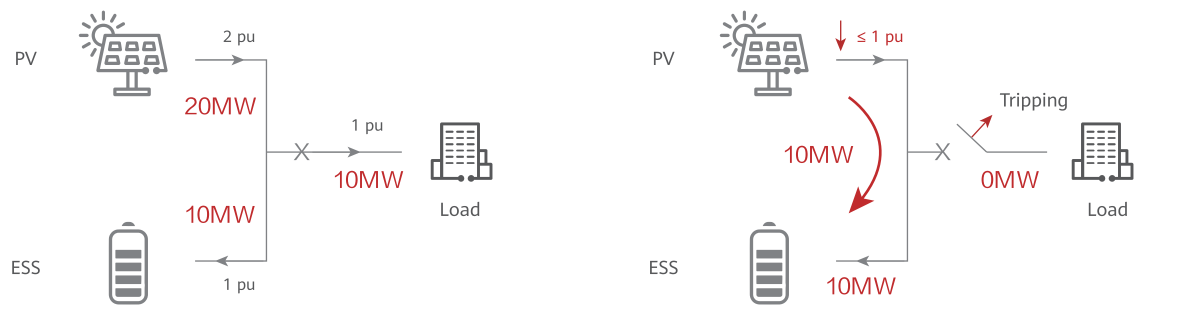
Figure 3-15: Energization/De-energization curves of the 300 kW ball mill in the Mabende mining microgrid project in Congo-Kinshasa

3.3 Key Technologies for Economical Operation

(1) High PV-to-ESS ratio of 2:1

To tackle challenges faced by microgrids, Huawei provides a lightweight and standardized Smart Microgrid Solution. Hierarchical control is vital for a microgrid system to achieve the optimal balance between economy and stability. Huawei's microgrid control system carefully considers time-based control and function implementation and is divided into three layers: stable grid-forming control, efficient coordinated control, and intelligent optimized dispatching.

Through intelligent PV-ESS collaboration, Huawei Smart Microgrid Solution successfully implements stable operation at a PV-to-ESS ratio of 2:1 in off-grid mode. This breakthrough reduces the system LCOE by 30%, significantly improving the economic efficiency. When the PV-to-ESS ratio is 2:1 and the load decreases abruptly, the PV system charges the ESS at a rate twice the rated power of the ESS. Huawei Smart PV inverters can adapt to weak grids and detect real-time fluctuations in bus voltage and frequency. In critical moments, they can autonomously trigger power-reduction commands without EMS dispatch, cutting PV output to levels the PCS can safely handle within milliseconds. This enables rapid and precise restoration of voltage and frequency, ensuring stable microgrid operation.



(a)Steady-state operation at 2:1 PV-to-ESS ratio (b) Rapid PV power limiting in case of sudden load shedding

Figure 2-16: Off-grid operation with a high PV-to-ESS ratio

(2) Wide state of charge (SOC) range for grid forming

The grid forming ESS must be able to withstand load disturbances during operation to maintain the power balance of the microgrid. When the PV power is high and the load decreases abruptly, the ESS needs to quickly switch from discharging to charging. When the load is high and the PV power decreases abruptly, the ESS needs to quickly switch from charging to discharging. To ensure the grid forming capability, the ESS must reserve sufficient charge and discharge margins at any time to avoid full charge or discharge. If the capacity margin is insufficient, system protection may be triggered or loads may be cut off, causing a microgrid power failure. Therefore, necessary buffers must be reserved at the end of charge and end of discharge to ensure stable system operation.

Based on the accurate SOC calculation, fast power allocation, and unified dispatching of multiple resources, Huawei Smart String Grid Forming ESS can implement grid forming at 5%–98% SOC in the off-grid scenario, while the industry average is at 10%–90% SOC. This saves the initial configuration by more than 13%.

Solution

Four-level SOC management

Plant level

MGCC: plant-level SOC management
The MGCC configures charge and discharge control parameters, enabling refined control down to each array.
The MGCC quickly dispatches PV+ESS+genset+load resources on the entire grid based on the charge and discharge capabilities reported by arrays, implementing power re-allocation.

Array level

SACU: array-level SOC management
The SACU configures charge and discharge control parameters, enabling refined control down to each rack.
The SACU collects the SOC values and charge/discharge capabilities in the array and reports the data to the MGCC.

Rack level

Smart String Grid Forming ESS: rack-level SOC management
The SOC differences of battery packs are proactively identified, and power allocation is dynamically adjusted to improve the SOC accuracy of the entire rack.
Huawei-developed high-accuracy calibration algorithm is automatically triggered.

Pack level

Pack-level active balancing module: pack-level SOC management
Huawei-developed chip realizes a high SOC accuracy of ±3%.
The active and passive balancing technologies help avoid the bucket effect of cells for battery packs and achieve full charge/discharge.

(3) Deep generation-load interaction for improved benefits

The core of achieving optimal economic efficiency of mining microgrids is to solve the dynamic balancing issue between renewable power generation fluctuations and power consumption requirements. As shown in the following figure, the PV and wind power outputs have significant randomness and fluctuations. In an ideal situation, the load demand curve perfectly aligns with the PV and wind output curves, eliminating the need for additional energy storage or power curtailment. That is, the flexible adjustment capability of loads can be used to offset renewable energy fluctuations in real time, forming a self-balancing system.

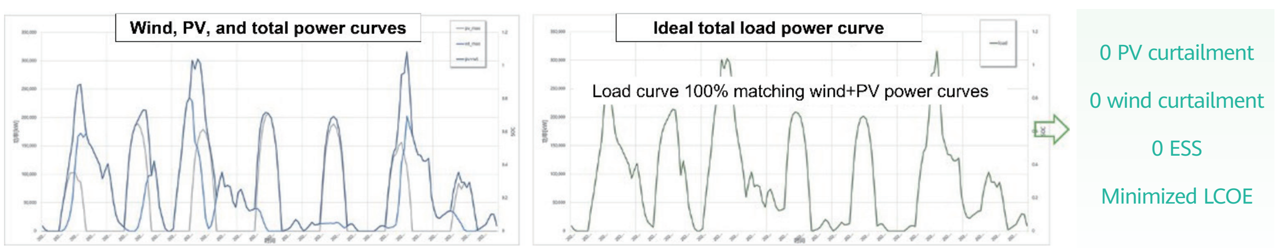


Figure 2-17: Power generation curve and load demand curve in ideal scenarios

Hierarchical load management
In the construction of a new power system, the ideal "generation-load interaction" mode is often limited by real-world conditions, such as insufficient load adjustment capability, limited prediction accuracy, and device response delay. To ensure power supply reliability and maximize renewable energy integration, hierarchical load management can be used.

By applying differentiated control methods, near-optimal performance can be achieved for certain adjustable loads under quasi-ideal conditions.

- Critical loads require continuous and stable power supply. The traditional load-based power generation mode is used to ensure power consumption safety.
- Adjustable loads follow the output fluctuations of renewable energy within a limited range, implementing power generation-based load adjustment and improving system flexibility.
- Flexible loads interact with power generation sources through dynamic electricity prices or demand response incentives, maximizing the matching with the wind and PV power generation curves and reducing wind and PV power curtailment.

Balance between power generation and consumption curves and continuous dispatching optimization

- Day-ahead economical dispatching: Based on high-accuracy wind and PV power prediction curves, the system dynamically optimizes the ESS charge and discharge power, SOC status, and genset output plan, with the objective of minimizing overall system operating costs, subject to hard constraints of real-time power balance and energy conservation across time periods.
- Real-time correction policy: Based on ultra-short-term deviations in wind and PV forecasts and load fluctuations, the system dynamically adjusts ESS power allocation online to maintain real-time power balance while closely aligning with day-ahead economical targets.

3.4 Mining Microgrid Solution Design Process

(1) Solution engineering design

To tackle challenges faced by microgrids, Huawei provides a lightweight and standardized Smart Microgrid Solution. Hierarchical control is vital for a microgrid system to achieve the optimal balance between economy and stability. Huawei's microgrid control system carefully considers time-based control and function implementation and is divided into three layers: stable grid-forming control, efficient coordinated control, and intelligent optimized dispatching.

Drawing on key insights from past projects, and in response to the high complexity and unique scenarios of microgrid systems, Huawei and industry experts have jointly developed a methodology for Smart Microgrid Solution engineering design. This framework—structured around a four-phase solution and a fourteen-step process—provides end-to-end guidance for customers and design institutes. At its core, this engineering mindset transforms "invisible system risks" such as voltage collapse and oscillations caused by abrupt load changes into standardized parameters that are researchable, configurable, and verifiable. This enables the system to maintain 99.99% power supply reliability while reducing delivery duration by over 50%. This breakthrough marks the evolution of microgrids from customized projects to replicable solutions. Currently, the power-on commissioning of a 100 MWh-level microgrid can be completed within one month.

Requirement survey

- Collect customer requirements (power consumption scenarios and pain points).
- Conduct preliminary project review (feasibility analysis).

Requirement and policy analysis

- Process analysis: Clarify production process (such as hydrometallurgical copper refining and lithium extraction from salt lakes).
- Load analysis: Collect statistics on electrical equipment, draw load curves, and distinguish between critical loads and adjustable loads.
- Pain point analysis: The grid is weak or there is no utility power, and the genset cost is high.
- Operation policy: Check whether on/off-grid switching and black start capabilities are required.

Resource analysis and capacity design

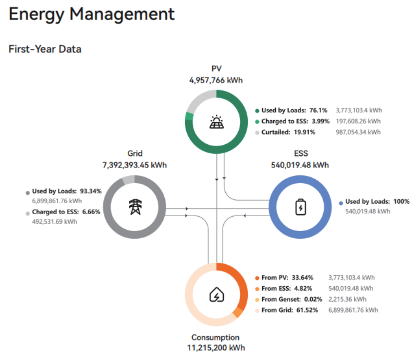
- PV resource evaluation: PVsyst simulates the energy yield, considering shading and policies (subsidies/electricity prices).
- Intelligent capacity design: Match PV, ESS, and genset resources with load characteristics to deliver optimal performance.

Design phase

- PCS verification: Verify the impact of large motor startup (such as ball mill).
- Device selection: Select models of PV, ESS and genset devices and protection devices.
- Access design: Connect the microgrid to the power distribution system in the mining area.
- Simulation verification: Perform digital simulations, hardware-in-the-loop (HIL) simulations, and physical tests.
- Detailed design: Design the primary/secondary system, UPS, and protection configuration.
- Output list: Output the complete equipment list and construction solution.

Figure 2-18: Four-phase and fourteen-step solution design

(2) Three weapons for solution design and verification



Intelligent capacity design

Microgrid planning and capacity design is the core of microgrid design. It aims to optimize the capacity configuration of distributed energy sources (such as the PV system, ESS, and genset) to meet load requirements and achieve efficient and economical operation. The core is to optimize loads based on production technologies in complex scenarios such as mines, and under the constraints of power and energy balance, obtain the optimal PV+ESS configuration solution based on financial indicators such as the best LCOE or internal rate of return (IRR). Huawei SmartDesign matches the operating logic of Huawei-developed PV-ESS devices and supports the import of load data of N years x 8760 hours. It can accurately complete planning, capacity design, and economic viability analysis, optimizing the PV-ESS configuration by 10% in the design phase.

Global Power Grid Simulation Center

Through dynamic analysis of system operation, control, and stability, mining microgrid simulation optimizes the energy configuration and ensures power supply reliability, facilitating green and low-carbon transformation. Considering the characteristics of mines, such as large load fluctuation and long power supply distance, simulation can expose problems such as voltage collapse and ESS overcharge in advance, verify the PV-ESS-genset synergy, and test the system redundancy and black start capabilities in extreme scenarios. Huawei's Global Grid Simulation Center has more than 10 simulation tool platforms and over 2000 simulation nodes. The center currently provides high-precision electromechanical simulation, electromagnetic transient simulation, and HIL simulation capabilities to comprehensively verify various complex steady/transient-state working conditions, ensuring safe and efficient operation of mining microgrids.

Grid Forming ESS Platform Application and Test Center

Huawei's Grid Forming ESS Platform Application and Test Center is the largest grid-level test and experiment campus in the world, covering an area of about 20,000 m2. The total investment is USD43 million, and the overall testing capacity is 40 MW/100 MWh. The center focuses on the verification of grid forming PV, grid forming ESS, on/off-grid PV-ESS, and microgrid plant solutions. The physical test platform can verify the actual performance of products during solution design to ensure delivery quality. In addition, the platform can quickly reproduce onsite problems during project O&M, greatly shortening the commissioning period and improving O&M efficiency.

Chapter III

Huawei Smart Microgrid Solution Application Cases

Case 1—Democratic Republic of the Congo: First Copper Mining Microgrid Project

Democratic Republic of the Congo has a severe shortage of power supply. Only 9% of the country's population has access to power supply, and the total energy yield is 2.67 GW. The power infrastructure is weak, with an average of 10 hours of power outage per day. As a result, 1.4 TWh of high-cost electricity (USD0.18–20/kWh) is imported from Zambia every year. This compels mining enterprises to depend on diesel power generation—costing as much as USD 0.40–0.50/liter—while subjecting them to mounting carbon tax pressures. The power supply issue reduces mining enterprises' annual output by over 20%. Taking the M mine as an example, the following power supply challenges exist:

① Loads require high stability, and the LCOE is high. The peak load of the original power system is 16 MW, with an average load of 15 MW in daytime and 8 MW in nighttime, fluctuating within 10%.
② Frequent startup and shutdown of impact loads can easily trigger power outages. In the mining area, high-power inductive equipment such as ball mills and semi-autogenous mills rely on direct-on-line (DOL) startup. The resulting inrush current during startup is excessively high, which may force gensets into protective shutdown, leading to a plant-wide outage and posing severe challenges for the continuous and stable operation of the microgrid system.

Solution implementation

To address these challenges, Huawei provided the M mine with a comprehensive Smart Microgrid Solution. The system configuration includes a 18 MWp PV system, a 10 MWh ESS, and six 1.8 MW gensets to form a microgrid at the mining site. Intelligent control is achieved through Huawei MGCC and SPMS. From equipment arrival to plant-wide power-on and commissioning, the entire process was completed in just 10 days. The solution adopts the grid forming ESS technology, enabling PV-ESS-genset synergy:

① During the daytime, the PV+ESS system reliably supplies the majority of power, substantially cutting reliance on diesel and costly imported electricity. This significantly lowers the LCOE.
② The grid forming ESS effectively mitigates the intermittency and fluctuations of PV power generation, greatly reducing power outages and production losses caused by insufficient system stability.
③ The grid forming ESS instantly absorbs and offsets the inrush current during he startup of ball mills and semi-autogenous mills, reducing the inrush current from seven times to three to four times and shortening its duration from six seconds to about three seconds. This greatly eases the adjustment burden on the gensets, maintains system-wide frequency and voltage stability, and further minimizes power outages and production losses caused by instability stability.
④ In on/off-grid scenarios, automatic adjustment enables gensets to operate within their economic range and the PV system to deliver maximum output. This reduces curtailment, boosts power generation efficiency by 30%, and lowers monitoring workload by 70% through intelligent automation.
⑤ The Smart Microgrid Solution supports fast deployment and wizard-based commissioning, accelerating the commissioning by 50%.

Project achievements and benefits

To address these challenges, Huawei provided a complete Smart Microgrid Solution based on the grid forming ESS technology for the M mine, enabling PV +ESS+ genset synergy in on-grid and off-grid scenarios.

On the power generation side, the solution achieves multiple performance breakthroughs. The PV power curve perfectly aligns with the irradiance curve, automatically maximizing the output, reducing the PV curtailment rate, and eliminating the need for onsite manual adjustment. The grid forming ESS can quickly respond to PV power drop in milliseconds, effectively avoiding system oscillations caused by PV-ESS-genset asynchronization, significantly improving the overall system stability and minimizing the use of gensets. PV+ESS supply capacity increased from 35 MWh to over 75 MWh per day in July, and daily copper output increased by 12.3 tons, or about USD120,000.

On the user side, the solution also brings significant improvements. The grid forming ESS and gensets work together to form a grid, significantly mitigating the risk of inrush currents triggered by the switching of high-power inductive loads. When the ball mill is started, the genset inrush current decreases from seven times the rated value to three to four times the rated value, and the inrush duration shortens from six seconds to about three seconds. In addition, when loads are switched on or off, operators no longer need to manually reduce the PV power to zero, greatly simplifying operations. The project has been operating stably for one year. The integrated PV +ESS +genset system is now fully managed through automated control by Huawei MGCC. Its performance has received high recognition from both the plant operator and mining site users.

With full takeover by the intelligent control system, the solution not only ensures stable and economical energy supply but also significantly reduces the need for manual intervention, effectively freeing up operational personnel.

Industry impact and demonstration significance

The PV-ESS microgrid project at M Mine presents an innovative approach for the mining industry in the Democratic Republic of the Congo. With grid forming ESS and multi-energy collaborative control technologies, the project significantly reduces diesel dependency and power generation costs, improves production efficiency, and reduces carbon emissions, providing a replicable success example for energy transformation in African mining areas.

Figure 3-1: M mine 18 MW PV + 10 MWh ESS copper mining microgrid project

Case 2—MAK, Mongolia: World's Largest Operational Mining Microgrid Program

As one of Mongolia's leading mining giants, MAK Group is facing a strategic window of opportunities over the next five years as precious metal prices continue to rise, driving an urgent need for business expansion. However, in southern Mongolia, weak grid infrastructure and severely insufficient power supply capacity—combined with a sharp 64% increase in electricity prices in recent years—have become the core bottlenecks restricting production capacity release and profit growth. To tackle this, the Group has formulated a phased solution. The primary goal is to rapidly deploy a PV+ESS microgrid system by the end of 2025, enabling the mining and residential areas to achieve energy self-sufficiency. This move is not only a pragmatic response to the power crisis but also deeply aligns with the Group's new ESG strategy, "30 Years of Green Future." The PV+ESS microgrid is designed as a long-term core asset. Even once grid constraints are resolved, it will continue powering the majority of onsite loads, ensuring a stable and low-carbon hybrid energy mix. In doing so, it not only safeguards profitability but also strengthens MAK's position as a leading green industrial brand.

Solution implementation

The project is planned with a total capacity of 53.7 MW PV and 139.5 MWh ESS, to be implemented in two phases. Phase I has a total installed capacity of 36.5 MW PV and 90 MWh ESS, covering three core sites that serve the cement plant, coal mine, and industrial park loads. Planning began in early 2024, and thanks to Huawei's efficient engineering execution and large-scale, multi-site collaboration capabilities, construction was completed in just half a year. The facilities have now been built and are being gradually put into operation. Phase II is planned with a capacity of 17.2 MW PV and 49.5 MWh ESS, and is expected to be delivered and put in operation in 2025. Once fully completed, the project will reach a scale of over 100 MWh, becoming the largest operational mining microgrid program in the world, and setting a benchmark for green energy transition in the mining industry.

Solution benefits

Huawei Smart Microgrid Solution successfully enabled the project to overcome world-class challenges of stable power supply for mines in weak-grid regions, even under extreme cold and off-grid conditions. In terms of stability, the ESS uses VSG technology to support planned and unplanned millisecond-level on/off-grid switching, preventing frequent disconnections and restarts caused by external grid fluctuations and significantly enhancing supply continuity. In off-grid mode, it autonomously establishes stable system voltage and frequency to ensure uninterrupted operation of mining loads. Moreover, the ESS delivers continuous HVRT/LVRT capability and withstands transformer inrush currents, ensuring the system remains connected even under the impact of mining motors. In terms of reliability, the ESS operates stably at extreme temperatures down to –40 °C, fully adapting to the harsh conditions of mining environments. In terms of economic performance, the solution achieves a PV-to-ESS power ratio of up to 2:1 in islanded mode, enabling greater PV integration with the same ESS capacity and significantly lowering the LCOE.

Once operational, the project will supply 92% of the mining area's annual electricity demand. The adoption of renewable energy significantly reduces carbon emissions while improving energy efficiency and lowering overall electricity expenses.In terms of environmental and social impact, the project will generate 64 million kWh of green electricity annually, cutting carbon emissions by 76,571 tons—equivalent to planting 70,000 trees—and providing strong momentum for the green transition of mining operations.

Figure 3-2: Mongolia MAK 53.7 MW PV + 139.5 MWh ESS coal mining microgrid project

Case 3—Manono, Congo-Kinshasa: Lithium Mining Microgrid Project

Against the backdrop of global energy transition and surging demand for critical mineral resources, the operational resilience and growth potential of mining enterprises increasingly depend on the stability of their energy supply and their ability to control costs. The Manono lithium project in Congo-Kinshasa, the first collaboration between Longking and Huawei in the country, serves as a benchmark for how renewable energy investment can directly strengthen core competitiveness. At the outset, the project faced severe challenges: Local grid infrastructure was underdeveloped, and future hydropower capacity could not meet the mine's full load demand. Relying on diesel power generation posed another dilemma—how to balance electricity costs as high as USD0.60/kWh while still ensuring the project could achieve its expected economic returns.

Solution implementation

To address this challenge, the project built the PV-ESS-genset microgrid as a long-term core asset. Designed with 5.1 MWp of PV, 2.5 MW/5 MWh of ESS, and backup gensets—tailored to local irradiance and rainy-season conditions—it precisely meets the mine's load demand of 1700 kW by day and 300 kW by night. By adopting Huawei Smart Microgrid Solution, the project delivers high reliability and efficient O&M even under harsh conditions, while enabling flexible expansion. In the long term, additional PV and ESS capacity will be integrated with hydropower to create a hydro-PV-ESS-genset microgrid system.

Project investment value

This strategic investment has transformed into substantial operational and financial gains, delivering both economic returns and environmental benefits.

① Significant cost reduction and efficiency improvement: With a PV-ESS penetration rate of 75%, the system supplies over 6.18 million kWh of green electricity annually. Compared with diesel power generation, this translates into direct annual savings of up to USD3.71 million in electricity costs, while reducing diesel consumption by about 1485 tons, along with associated transportation expenses.

② Significant improvement in production continuity: Self-sufficient power supply completely eliminates the risks of external grid instability and electricity price fluctuations, providing continuous and reliable energy for both project construction and future operations. This ensures steady development progress and is expected to cover the annual energy demand for exploiting approximately 22,500 tons of lithium concentrate, valued at around USD27 million.

③ Shaping green asset attributes: This solution not only resolves immediate power supply challenges but also embeds a "green gene" into the mine, establishing a solid foundation for long-term value growth amid the global energy transition.

Figure 3-3: Manono 5.1 MWp PV + 2.5 MW/5 MWh ESS lithium mining microgrid project

Case 4—The Red Sea Destination, Saudi Arabia

The microgrid for The Red Sea destination, the world's largest PV-ESS microgrid, is a flagship infrastructure initiative under Saudi Vision 2030 and marks the country's first public utility project developed through a public-private partnership (PPP) model. It is expected to supply 100% renewable energy to one million people annually. As the world's first GWh-level microgrid project, it consists of a 400 MW PV system and a 1.3 GWh ESS. A small number of gas gensets are deployed as backup. This system has high requirements on grid forming and grid stability. Huawei provides a complete Smart Microgrid Solution. All the project was delivered in the middle of 2023.

The microgrid has been operating stably for two years, achieving 99.9% main grid reliability. To date, it has delivered over 2 billion kWh of green electricity to Saudi Arabia, strengthening the nation's global reputation for sustainability. The microgrid for The Red Sea destination is essentially a 110 kV power grid composed of PV and ESS systems. Key challenges include project delivery timeliness, grid forming capability, and power supply stability for end users.

Huawei provides a modular and pre-integrated Smart Microgrid Solution, and supports customers through preparation, implementation, and field experiment design, enabling rapid and reliable microgrid delivery. As a grid featuring PV+ESS synergy, the overall operational logic and performance indicators must be carefully designed and thoroughly simulated. Leveraging its strengths in design, simulation, and microgrid test platforms, Huawei has supported customers in completing comprehensive microgrid logic design and simulation.

Figure 3-4: Saudi Arabia Red Sea destination 400 MW PV + 1.3 GWh ESS microgrid project

This includes PV-ESS grid forming, power grid SCR design, energy distribution logic design, and power grid control steady state design, transient state design, primary and secondary voltage and frequency regulation, PV/ESS/SVG dynamic voltage regulation, grid frequency and voltage control after load shedding, synchronous black start of over 1000 PCSs, multi-switch collaboration in the microgrid, and synchronous and asynchronous design. All have been validated in real-world environments, ensuring stable and reliable operation. This microgrid supplies clean electricity to hotels, desalination plants, sewage treatment plants, airports, hospitals, and more. Various power supply devices and operation types of different users pose challenges to the stable operation of the microgrid. In the real-world environment, multiple types of devices and operations have been verified to ensure stable running.

Huawei, together with industrial partners, provides an alternative energy supply to mines and other remote or weak-grid regions.

As a distributed energy system, microgrids can greatly enhance the reliability of energy supply, flexibly meet electricity demand under diverse conditions, and promote both renewable energy adoption and diversification of energy sources. Huawei remains committed to integrating digital technology with power electronics, PV with ESS, and energy flow with information flow to advance its Smart Microgrid Solution. By leveraging cutting-edge digital and intelligent systems, the solution delivers highly efficient energy management. Through continuous innovation in grid forming technologies, such as GWh-level PV-ESS black start, higher PV-to-ESS ratio, stronger system resilience, improved power quality, and PV-ESS-genset synergy, Huawei, together with industrial partners, provides an alternative energy supply to mines and other remote or weak-grid regions.

Huawei, together with industrial partners, provides an alternative energy supply to mines and other remote or weak-grid regions.

Reference

1	International Energy Agency. (2024). World energy outlook 2024. IEA. https://www.iea.org/reports/world-energy-outlook-2024
2	African Development Bank. (2024). Sustainable Energy Fund for Africa: Annual Report 2024. African Development Bank Group. https://www.afdb.org/en/documents/sustainable-energy-fund-africa-annual-report-2024
3	BHP. (2020). Climate change report 2020. https://www.bhp.com/-/media/documents/media/reports-and-presentations/2020/200915_climatechangereport.pdf
4	Rio Tinto. (2021). Rio Tinto climate transition strategy 2021. https://www.riotinto.com/en/sustainability/climate-change
5	Zijin Mining Group. (2023). Climate change action plan. https://www.zjky.cn/uploadfile/2024/0329/20240329105507813.pdf
6	Glencore. (2021). Climate Report 2021. https://www.glencore.com/.rest/api/v1/documents/5d9e6452-8e7e-4c26-95f1-8a9516e3a48c/Glencore-Climate-Report-2021
7	Vale. (2021). Decarbonization strategy and management. https://vale.com/sites/default/files/2021-10/decarbonization-strategy-management.pdf
8	Anglo American. (2018). Sustainable Mining Plan. https://www.angloamerican.com/sustainability/sustainable-mining-plan
9	Fortescue Metals Group. (2022, September). Decarbonisation Strategy and Plan. https://fmgl.com.au/media/kywnj0ix/fortescue-decarbonisation-strategy-plan.pdf
10	oGoldman Sachs. (n.d.). Sustainable finance framework. Retrieved October 20, 2024, from https://www.goldmansachs.com/citizenship/sustainable-finance-framework/index.html
11	JPMorgan Chase & Co. (2023). Climate Action Report. https://www.jpmorganchase.com/impact/our-structure/climate-action-report
12	BloombergNEF. (2025). Global energy cost report 2025. Retrieved from https://about.bnef.com/energy-transition/