

Lindemann-Regner

TECHNICAL SOLUTION FOR ZERO-CARBON OILFIELD WELLSITE

Photovoltaic-Energy-Storage DC Coupling Microgrid System



Version control

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1. ABBREVIATION

Table 1-1: Abbreviation Table

Abbreviation	Definition
AC	Alternating Current
ADC	Analog-to-digital Converter
BCU	Battery Charge Unit
BMS	Battery Management System
BMU	Battery Management Unit
CSC	Cell Supervisor Circuit
DC	Direct Current
DCIR	Direct Current Internal Resistance
DoD	Depth of Discharge
EMS	Energy Management System
EMU	Energy Management Unit
EoL	End of Life / End of Line, depending on context
ESS	Energy Storage System
EV	Electrical Vehicle
EVCS	Electrical Vehicle Charge Station
FAT	Factory Acceptance Test
FFS	Fire Suppression System
GCU	Grid Control Unit
HIL	Hardware-in-the-Loop
HMI	Human machine interface
HPC	High Power Charge
HVAC	Heating, Ventilation & Air-conditioning System
IoT	Internet of Thing
IP	Ingress protection
IPC	Industrial Personal Computer
LFP	Lithium-ion Phosphate Battery, LiFePO4
MPPT	Maximum Power Point Tracking
PCS	Power Conversion System
PCU	Power Control Unit
PLC	Programmable Logic Controller
PPE	Personal Protective Equipment
PV	Photovoltaic
SAT	Site Acceptance Test
SCADA	Supervisory Control and Data Acquisition
SKD	Semi Knock Down
SOC	State of Charge
SOH	State of Health
TBD	To Be Determined

2. APPLICATION BACKGROUND

This project aligns with the development needs of the energy industry and actively promotes low-carbon environmental principles, driving the transition toward green energy and the adoption of clean energy alternatives. It is dedicated to optimizing the industrial structure, advancing energy conservation and emissions reduction, and expanding new energy businesses to accelerate the application of green and clean energy.

Key equipment in oilfield sites, such as nodding donkeys, water injection pumps, oil transfer pumps, and submersible oil pumps, are core components of the production process, accounting for over 80% of the total electricity consumption in oil and gas fields. To comprehensively enhance energy efficiency and promote the effective use of new energy in the oilfield sector, seven pilot oil wells (Phase II) have been selected for this initiative to explore the development of zero-carbon oil wells, providing feasible green electricity solutions for the industry's carbon peak goals.

2.1 Analysis To Key Oilfield Equipment

The following is a detailed analysis of the functions and power consumption characteristics of these key pieces of equipment.

2.1.1 Nodding Donkey (Beam Pumping Unit)

Function: The nodding donkey is a traditional oil extraction device. It uses an electric motor to drive a walking beam structure, which moves the sucker rod and pump barrel up and down to lift crude oil from underground to the surface.

Power Consumption Characteristics: Its power consumption exhibits cyclical fluctuations with high electricity demand during startup due to significant torque load. Throughout the pumping cycle, the motor load varies considerably, often leading to inefficiencies such as light or no-load operation, commonly described as "an over-sized motor driving a smaller load." This makes it one of the major energy-consuming devices in oilfields.

2.1.2 Water Injection Pump

Function: Used to inject water into oil reservoirs to maintain or increase formation pressure, thereby driving crude oil toward production wells and enhancing recovery rates. It is essential for secondary oil recovery.

Power Consumption Characteristics: These pumps must continuously maintain high outlet pressure, operate at high power levels, and typically run 24/7, resulting in substantial electricity usage. Power consumption is directly related to injection pressure and flow rate, making operational efficiency critical for overall energy savings.

2.1.3 Oil Transfer Pump

Function: Installed in gathering pipelines, these pumps provide the necessary pressure to transport extracted crude oil through pipelines to processing stations or storage tanks.

Power Consumption Characteristics: Power usage depends on transportation distance, pipeline pressure, crude oil viscosity, and flow rate. Long-distance transport often requires multiple pumping stations, leading to significant cumulative electricity consumption. Inefficiencies arise when flow control relies on throttling instead of variable frequency drives, resulting in considerable energy waste.

2.1.4 Submersible Oil Pump

Function: A multi-stage centrifugal pump submerged below the fluid level in oil wells, directly lifting crude oil to the surface. It is commonly used in high-production wells.

Power Consumption Characteristics: As a high-power lifting device, it consumes a large amount of electricity. Operating in harsh downhole conditions with high temperature and pressure, even minor improvements in motor and pump efficiency can lead to notable energy savings. Additionally, power transmission through lengthy downhole cables involves certain line losses.

2.2 Analysis To Oilfield Pilot Sites

In remote oil fields located in desert and Gobi regions, oil extraction sites currently rely on diesel generators for power supply. Due to their isolated locations and long power transmission distances, significant energy losses occur, resulting in low economic efficiency. Additionally, the initial costs of grid infrastructure development are high, posing considerable technical and economic challenges. Therefore, building a clean and reliable microgrid system has become a crucial approach to meeting the electricity demands of such areas. For well sites 1, 2, 3, and 4, a complementary power supply model combining photovoltaic green electricity and energy storage will be implemented to construct an off-grid microgrid system, aiming to achieve zero-carbon well sites.

For well sites 5, 6, and 7, which are already connected to the main grid, distributed photovoltaic facilities will be constructed near the sites to gradually advance carbon reduction efforts. In later stages, depending on actual operational needs, a complementary photovoltaic and energy storage power supply structure can be further developed to establish a microgrid system capable of seamless switching between grid-connected and off-grid modes, ultimately achieving low-carbon or even zero-carbon operations.

A supporting microgrid monitoring and energy management system, along with video surveillance facilities, will be established. Data will be transmitted via an operator's 4G/5G network to the existing smart grid management platform and integrated into a unified smart grid management system for remote centralized monitoring and management.

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Table 2-1: Overview of energy consumption and available space for PV at pilot oil wells

No.	Power Supply Condition	Operational Requirement	Cont. Load (kW)	Intermittent Load (kW)	Total Load (kW)	Power Plan	Daily Conso (kWh)	Diesel Generator Rental Cost	Surrounding Land Type	Land Availability (Est. 215 m ² /kWp PV)	Utilized Acquired Land?	Remarks
1	No grid access	Continuous production	200	0	200	Remote, no grid access	4,800	788 USD/day	Forest, Grassland	17,720 m ²	Yes	
2	No grid access	Intermittent production	20	80	100	7 hours/d	1,040	788 USD/day	Farmland	15,013 m ²	Yes	
3	No grid access	Intermittent production	68	132	200	8 hours/d	2,688	788s USD/day	Forest	16,353 m ²	Yes	
4	No Grid Power. Well #1 & #2 each equipped with a pumping unit (18.5kW motor), powered by a 75-kW skid-mounted generator for intermittent production.	Must meet the intermittent production schedule (Well #2: 9h on/15h off; Well #1: 11h on/13h off), 24/7 signal transmission, oil heater power, and 4kW electric trace heating for freeze protection in winter.	50	20	70	Install 150kW PV, 300kWh storage with inverters, control systems, and lines.	1,400	Own generator	Unused land	3,000 m ²	No	No structures around site. Existing remote monitoring system. Land type for both wells is state-owned unused land.
5	Local grid access	Continuous production	200	0	200	Agricultural dedicated grid. Deficit in summer	4,800	-	Grassland	17,113 m ²	Yes	
6	Local grid access	Intermittent operation possible, 9:00-18:00 (9h)	10	22	32	Yes	438	Not leased	Bare Land	Yes	Yes	
7	Local Grid	Intermittent operation possible	20	45	65	Yes	885	Not leased	Bare Land	3,382 m ²	Yes	

3. SYSTEM CONCEPT DESIGN

3.1 Design Target

This technical solution is designed to achieve the following goals:

- **Supply Voltage:** Three-phase AC 0.4 kV $\pm$ 10%
- **Frequency:** 50 $\pm$ 0.5 Hz
- **Power:** Customized based on actual requirements
- **PV Capacity:** Configurable based on site conditions
- **System Backup Time:** On customer specifications
- **Output Power:** On load requirements
- **DC Coupling Voltage:** Designed with a DC bus voltage of 750 V
- **Backup Power Sources:** Diesel generator (optional), grid power (configurable as needed)

3.2 Microgrid Architecture

A microgrid is an integrated small-to-medium scale power generation and distribution system comprising distributed energy resources, energy storage units, power conversion devices, associated loads, energy management systems, and protection mechanisms. It is capable of operating in both in-grid and off-grid modes.

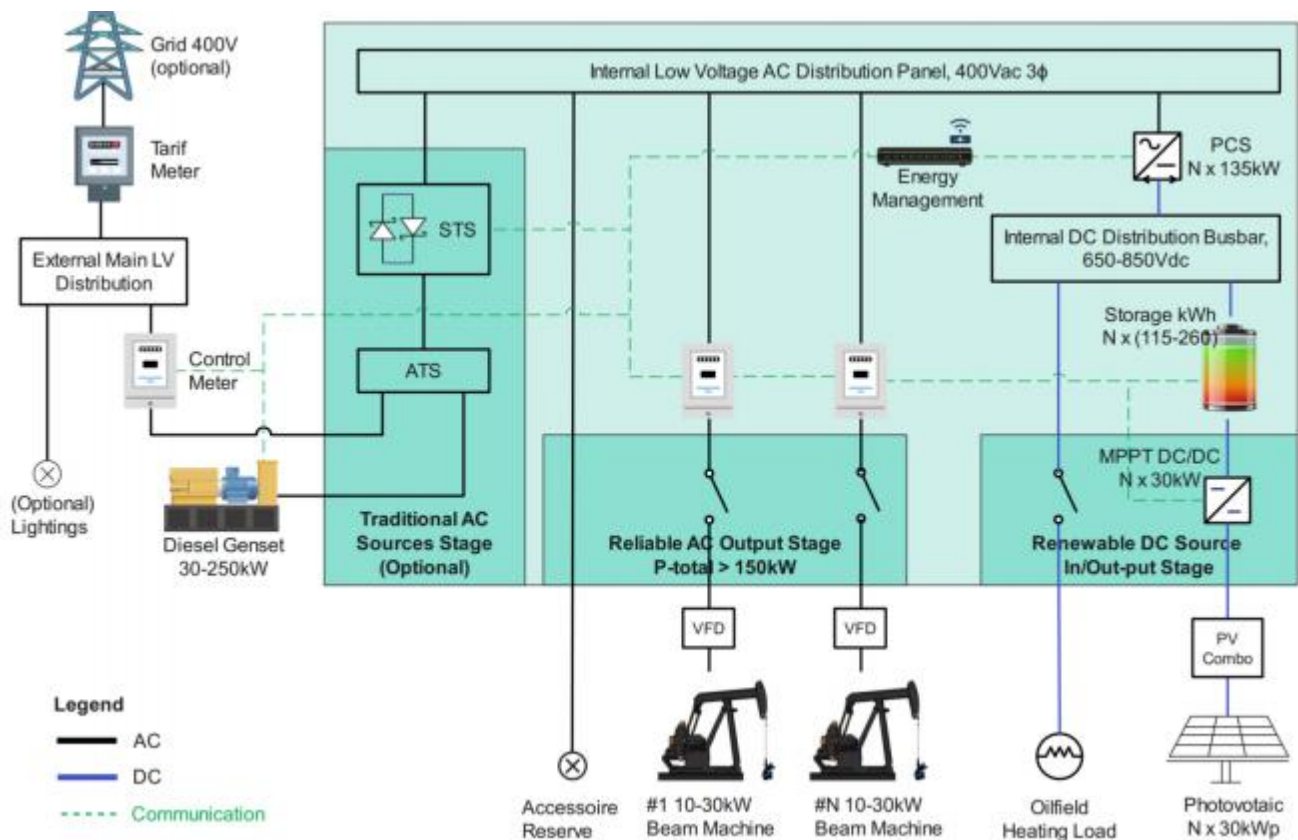


Figure 3-1: Typical Microgrid Architecture of In-/Off-Grid Oilfield Microgrid Solution

This design employs a PV and energy storage co-coupled DC bus microgrid architecture. Distributed resources (PV) and energy storage systems are connected to a common DC bus, with power uniformly supplied to loads via a bidirectional power conversion system (PCS), ensuring reliable off-grid operation. Key advantages include high system stability with minimized risk of disconnection, reduced AC-DC conversion losses through DC coupling, and improved overall efficiency.

3.2.1 System Operating Scenarios

Based on the state of charge (SOC) in the storage battery, the system operation can be divided into the following scenarios:

1. **Battery 10%<SOC<90%, Daytime:** PV power sufficient for load demand; excess energy charges the battery.
2. **Battery 10%<SOC<90%, Daytime:** PV power insufficient; PV and battery supply load together.
3. **Battery 10%<SOC<90%, Nighttime:** Battery supplies the load.
4. **Battery SOC>90%, Daytime:** PV supplies the load within available limits; any shortfall supplemented by battery.
5. **Battery SOC<10%:** System automatically starts the diesel generator with optimal working point to power the load; PCS uses excess generator energy to recharge the battery for optimal fuel efficiency.
6. **Generator Operation with Battery Recovery:** Once battery SOC reaches a specified level, the generator stops, and the battery resumes supplying the load.

3.2.2 Key Features

1. Powered by photovoltaic and storage systems, offering a green and sustainable solution.
2. Capable of operating independently or in hybrid mode.
3. Enables 24-hour power supply for oilfield pumping equipment.
4. All components are designed for outdoor operation, containerized with suitable thermal isolation if necessary, suitable for harsh environmental conditions.
5. Integrated system design simplifies installation and commissioning.
6. Optional diesel generator backup ensures operational safety and reliability.

This DC-coupled microgrid system represents an innovative model for achieving 100% renewable power supply in well sites. It is highly suitable for power retrofits or new installations in remote areas without grid access and stands as a significant example of microgrid applications aligned with global low-carbon energy trends.

3.3 Remote Control and Management

The microgrid system incorporates automated monitoring technology and is equipped with data acquisition modules and IoT communication units (supporting 4G/LTE networks) to collect real-time operational status and environmental data. Users can access system information in real-time through web or mobile interfaces, enabling remote monitoring, operational maintenance, and energy efficiency management.

Main functions include:

- Real-time acquisition of electrical parameters (voltage, current, power, etc.) from PV arrays, power electronics, energy storage batteries, and system control cabinets.
- Monitoring of operational status of oil extraction equipment, including motor voltage, operating current, rotational speed, and other key indicators.
- Collection of production data such as crude oil flow rate, pressure, daily production volume, and monthly cumulative output from oil transportation pipelines.
- Real-time system diagnostics and alerts for abnormalities including overvoltage, overcurrent, overload, short circuit, and motor stall faults.
- Support for remote start/stop control of electrical equipment and online system software upgrades.

- Integrated video monitoring interface for real-time onsite video surveillance and security monitoring.

This integrated monitoring and management system significantly enhances operational reliability, greatly reduces the need for onsite maintenance, and effectively lowers lifecycle operational costs.

4. SYSTEM DETAILED DESIGN

4.1 System Key Metrics Parameters

4.1.1 Power Generation Capacity Metrics

As shown in the figure, the annual effective photovoltaic power generation hours at this installation site can reach 1,461 hours, averaging approximately 4 hours per day. The minimum monthly effective generation hours occur in December, with 84.6 hours, averaging about 2.82 hours per day.



Figure 4-1: Typical PV output for Pilot Project Site

The system chooses purely photovoltaic generation as main supply power, with the PV and storage system providing electricity to the loads. Accounting for system efficiency, the required PV and energy storage capacities are calculated as follows:

$$PV_capacity = P_req / (\eta \times t_eff)$$

Where:

- P_req = daily electricity consumption at the installation point (kWh)
- η = overall efficiency of the PV and storage system (typically 0.88, or 88%)
- t_eff = average effective generation hours per day (here, 4 hours)

4.1.2 Energy Storage Metrics

This project uses lithium iron phosphate (LFP) batteries, which support a depth of discharge (DoD) of up to 90% and offer a high cycle life of up to 6,000 cycles. The energy storage capacity is calculated as follows:

$$P_B = (P_req / \eta) - (t_eff \times P_load)$$

Where:

- P_req = daily electricity consumption (kWh)
- η = system efficiency (e.g., 0.88)
- t_eff = average effective generation hours per day (4 hours)

- $P_{load} = \text{load power (kW)}$

4.1.3 Power Electronics Metrics

This design employs a common DC bus architecture, where both the PV arrays and energy storage system are connected to the same DC bus. The PV MPPT converters are designed as 30 kW single-string units, supporting multiple strings.

The capacity of the Power Conversion System (PCS) is sized to match the maximum load capacity. To accommodate reactive and impact loads,

$$PCS_capacity = k \times P_max$$

Where:

- k = sizing factor for reactive and impact loads (typically between 1.2 and 1.5)
- P_max = maximum load (kW).
- STS Capacity (if used) = $2 \times P_load$

4.2 Key Hardware Selection

4.2.1 Photovoltaic System Supply

- **PV Panel:** abbreviation
- **PV Frame and Mounting System:** abbreviation
- **Cabling:** abbreviation

4.2.2 Energy Storage System Supply

- **Battery Cells:** abbreviation
- **Battery Packs:** abbreviation
- **Battery Management System:** abbreviation

4.2.3 Power Electronics System Supply

- **PV DCDC Module:** abbreviation
- **Power Conversion System:** abbreviation
- **Power Control Unit:** abbreviation
- **Static Transition Switch:** abbreviation

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Table 4-1: Overview to system key metrics at pilot oil wells

No.	Power Condition	Cont. Load (kW)	Intermittent Load (kW)	Total Load (kW)	Power Plan	Daily Consumption (kWh)	PV Capacity (kWp)	Storage Capacity (kWh)	PCS Capacity (kW)	STS Capacity (kVA)
1	No grid access	200	0	200	Remote location, no grid power	4,800	1363	5,171	250	400
2	No grid access	20	80	100	7 hours/d	1,040	295	868	125	200
3	No grid access	68	132	200	8 hours/d	2,688	763	2,505	250	400
4	No Grid Power. Well #1 & #2 each equipped with a pumping unit (18.5kW motor), powered by a 75-kW skid-mounted generator for intermittent production.	50	20	70	Install 150kW PV, 300kWh storage with inverters, control systems, and lines.	1,400	397	1,456	100	150
5	Local grid access	200	0	200	Summer grid capacity insufficient	4,800	1363	5,171	250	400
6	Local grid access	10	22	32	Intermittent operation: 9:00-18:00 (9h) & 24/7 signaling.	438	124	410	60	100
7	Local Grid	20	45	65		885	251	828	100	150

4.3 Integral Microgrid Aggregate

The integral microgrid system aggregate, as the core power unit of the plant, performs power conversion and equipment control, executes commands from the energy management system, and coordinates the operation of all units within the microgrid.

This system is designed as a modular, plug-and-play energy router with integrated primary and secondary control, supporting both grid-connected and islanded operation. It allows flexible application across various scenarios and enables active, precise energy flow management.

Key Features:

- Dual-mode operation (grid-tied/off-grid) with seamless switching (<10 ms) for continuous power supply.
- High-precision MPPT algorithm for optimized PV harvesting and battery charging.
- EMS-interfaced dispatch control for generation optimization.
- Generation coordination based on electricity price, irradiance, and load demand.
- Configurable HMI interface for real-time monitoring, fault diagnosis, and energy statistics.
- High-efficiency (>97%) three-level PCS architecture.
- Interleaved parallel DC/DC design for reduced current ripple.
- Three-phase AC output: 380V $\pm 1\%$, 50Hz $\pm 1\%$, THD $\leq 3\%$; supports 110% load for 10 min, 120% for 1 min.
- Comprehensive protection: earth leakage, short-circuit, over-temperature, AC/DC overcurrent.
- Unbalanced load capability (<30% imbalance).
- Multi-protocol communication ports (CAN, RS485, etc.).

Table 4-2: General technical parameters of microgrid aggregate for oilfield application

Category	Parameter	Specification
AC Stage (Off-Grid)	Rated Power	* kVA
	Output Type	3-phase, 4-wire
	Rated Voltage	380 V AC
	Voltage Range	360–420 VAC
	Voltage Regulation	$\pm 3\%$
	Voltage Unbalance	<2% (<4%, 3s–1min)
	THD	$\leq 3\%$ (linear load)
	Rated Frequency	50 Hz
	Frequency Range	49.5–50.5 Hz
	Transient Response	$\leq 10\%$ (0–100% load)
	Switching Time	≤ 20 ms
Battery DC Stage	DC Voltage Range	540–850 V DC
	Max Charge/Discharge Current	150 A
	Voltage Regulation	$\leq 1\%$
	Current Regulation	$\leq 1\%$
	Voltage Ripple	$\leq 2\%$
	Current Ripple	$\leq 2\%$

	Charging (Lead-Acid)	3-stage
	Charging (Li-ion)	BMS-controlled
PV DC Stage	Rated Power	30 kW (Per String)
	Max Input Current	75 A
	Max Open-Circuit Voltage	1000 V DC
	MPPT Voltage Range	250-625 V DC
	Startup Voltage	250 V DC
	Max Input Strings	4
	Protections	Reverse polarity, OV, OC, OT
General	Dimensions	TBD
	Noise	<75 dB (@1m)
	Cooling	Forced air
	Insulation Resistance	≥100 MΩ
	Dielectric Strength	2500 V AC / 3500 V DC, 1 min
	Protection Rating	IP20
Environment	Operating Temperature	-10 °C to +45 °C
	Humidity	≤95% (non-condensing)
	Altitude	≤1000 m (derate above)
Communication	HMI	Touch screen
	Interfaces	2× LAN, 2× CAN/RS485
	Protocols	IEC104, Modbus TCP, CAN 2.0B, MODBUS

4.4 Aggregate Thermal Management

The microgrid aggregate utilizes an intelligent industrial air conditioning system to maintain appropriate operating temperatures for the internal equipment. The container is divided into two separate compartments: an electrical cabin and a battery cabin. Based on the heat dissipation requirements of the batteries and power electronics, industrial air conditioners with 5 kW cooling capacity have been selected for each compartment. Air ducts are designed inside the battery compartment to ensure uniform temperature distribution.

The thermal management system is designed to perform effectively under extreme ambient conditions. When outside temperatures range from -40°C to +65°C, the internal temperature can be maintained between 25°C and 35°C. The station's design accounts for various harsh environmental conditions, including high-altitude, extreme cold, and coastal applications. Under extreme climate conditions, the system may operate at derated capacity to ensure safety and reliability.

To enhance thermal performance in extreme temperatures, the container incorporates specialized insulation design. This includes high-performance thermal insulation materials, enhanced sealing to minimize air leakage, and auxiliary heating systems to maintain operating temperature during extremely cold conditions. The design ensures thermal stability and protects critical components from temperature-related degradation or failure.

4.5 System Performance and Energy Management

4.5.1 Self-Recovery and Operational Control

The unit is equipped with a watchdog self-reset circuit that automatically detects and recovers from program abnormalities. If normal operation cannot be restored after reset, a fault signal is automatically reported. The system startup time does not exceed 5 seconds (from command issuance to rated power operation), and the shutdown time does not exceed 200 milliseconds (from command reception to AC-side circuit breaker disconnection).

4.5.2 Control Modes

The system supports two control modes: local and remote. In local mode, the unit receives BMS data and only responds to onsite commands, suitable for debugging and maintenance. In remote mode, it accepts commands from a remote upper computer and BMS data, ignoring local control inputs. Local control is performed via the cabinet HMI, while remote control is implemented through the monitoring system using communication protocols.

4.5.3 Operating Modes & States

The system supports both grid-connected and off-grid operating modes. Each mode includes five operational states:

- Charging mode: Charges the battery via PV or grid power, supporting either single-source or hybrid charging.
- Charge/Discharge mode: PV power simultaneously charges the battery and supplies the load/grid through the PCS; this is the primary operational state.
- Standby mode: The system is on standby, awaiting operational commands.
- Fault mode: Operation is halted due to a detected anomaly, requiring maintenance.
- Emergency shutdown mode: The system enters an immediate stop condition and requires manual intervention to resume.

4.5.4 Power Quality

The system includes control functions to ensure AC output power quality complies with the technical specifications outlined in previous section.

The system can continuously and rapidly regulate active (P) and reactive (Q) power output within capacity limits upon receiving commands from the monitoring system, enabling decoupled P and Q control. The maximum power ramp rate complies with grid code and dispatch requirements.

5. SYSTEM PERFORMANCE EVALUATION

The usage profile for Pilot Station #6 demonstrates the system's successful design for complete grid independence. Analysis confirms that the local energy generation from solar panels, coupled with the integrated battery storage, fully meets the site's load requirements without grid supplementation.

To ensure this seamless operation year-round, the system was deliberately over-dimensioned. This design strategy involves sizing the photovoltaic (PV) array to generate sufficient power even on short, cloudy winter days, and specifying a battery bank with enough capacity to cover energy consumption throughout extended periods of low sunlight (e.g., several overcast days). This capacity buffer is critical for mitigating the risk of power shortages during seasons of low solar resource availability.

As illustrated, the beam pumping unit (also known as a "nodding donkey") is a highly cyclical, reciprocating mechanical system. Its electrical load profile is exceptionally demanding and presents two core challenges to the power supply system:

- **Severe Cyclical Power Fluctuations:** During the **upstroke**, the motor must lift the entire load (the weight of the rod string and the fluid column), resulting in peak power demand (up to 10kW). Conversely, during the **downstroke**, the load decreases significantly, and the motor may even enter a regenerative state, causing the net power demand to plummet to near zero or become negative. This drastic, second-scale fluctuation between 0 and 10kW represents a massive impulsive load on the local grid or generator, highly likely to cause **voltage fluctuations and flicker** on the bus.
- **Significant Harmonic Current Pollution:** To drive this heavy inertial load, pumping units typically use high-starting-torque induction motors or Variable Frequency Drive (VFD) systems. Particularly when VFDs are used, their rectification stage injects rich characteristic harmonics (such as the 5th, 7th, 11th, 13th, etc.) into the grid. These harmonic currents cause voltage waveform distortion, degrading power quality. s

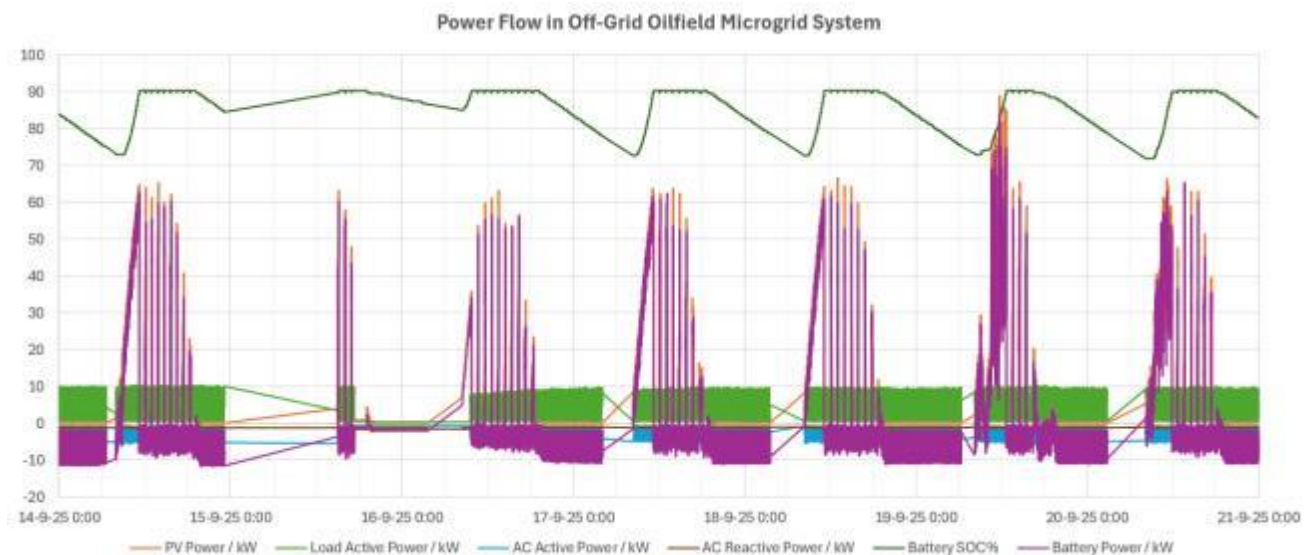


Figure 5-1: Usage profile of off-grid oilfield #6 microgrid system in practice, 14-21 September 2025

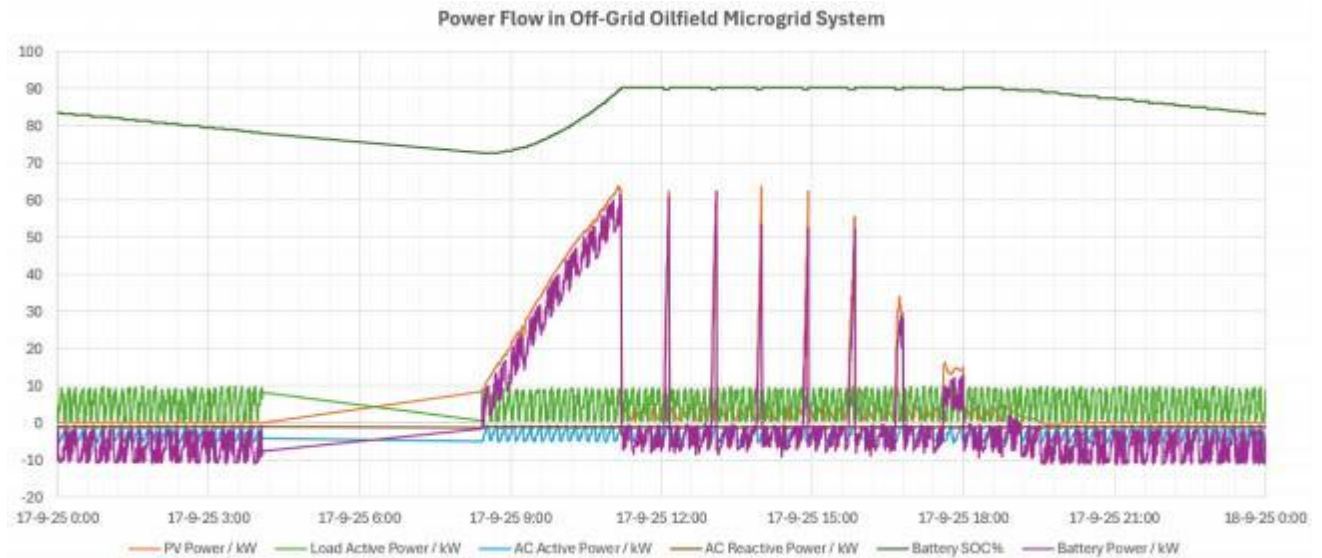


Figure 5-2: Usage profile of off-grid oilfield #6 microgrid system in practice, stable PV power, 17 Sept 2025

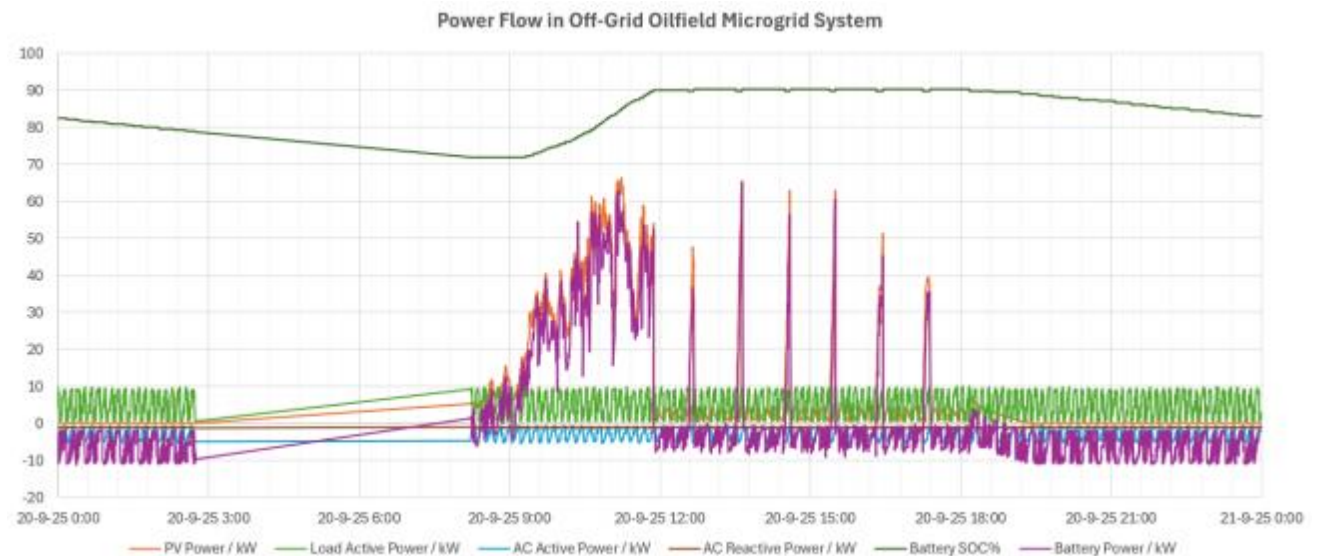


Figure 5-3: Usage profile of off-grid oilfield #6 microgrid system, instable PV power, 20 Sept 2025

The core algorithms of our solution aggregates extend beyond basic grid-tie/off-grid functionality to incorporate advanced Active/Reactive Power (PQ) Control and Active Power Filtering (APF), enabling localized, real-time mitigation of power quality issues.

- **Real-Time Monitoring & Control:** Employing high-speed DSP monitoring, the PCS analyzes load and grid-side waveforms at kHz frequencies. Using advanced algorithms, it decomposes the load current into its fundamental and harmonic components within milliseconds.
- **Dynamic Power Compensation:** The PCS acts as a high-speed "power buffer" to smooth cyclical load swings. This "peak shaving and valley filling" isolates the grid from impulsive loads, stabilizing bus voltage.
- **Active Harmonic Filtering:** Functioning as an APF, the PCS generates compensating currents equal in magnitude but opposite in phase to the load harmonics. Injecting these currents in real-time cancels the harmonics, resulting in a clean grid-side sinusoidal current and ensuring THD compliance with standards like IEEE 519.

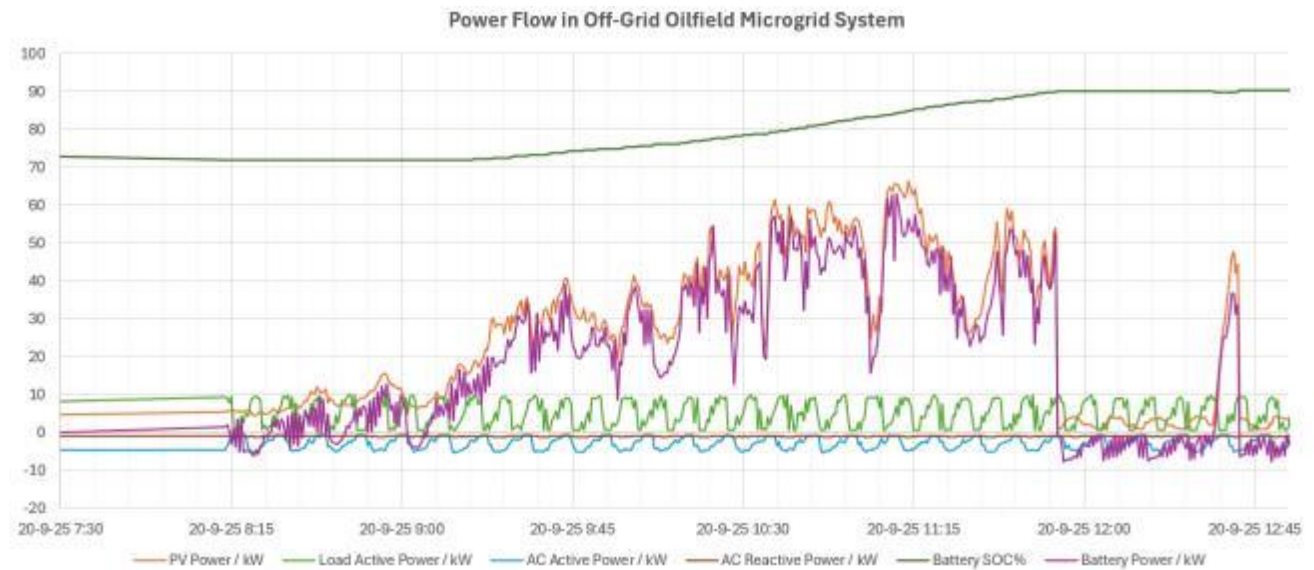


Figure 5-4: Usage profile of off-grid oilfield #6 microgrid system, power quality control in operation

6. INVESTMENT AND FINANCE (ROI)

To be provided based on real situation in target market.