Lindemann-Regner

TECHNICAL SOLUTION FOR AGRICULTURAL IRRIGATION SYSTEM

Photovoltaic-Energy-Storage DC Coupling Microgrid System

Version control

#	Date	Editor	Reviewer	Contents
Draft	09.10.2025	Bruce Wurilege	Erich L.F. Jiang	Draft version, outline
V1.2	12.10.2025	Bruce Wurilege	Erich L.F. Jiang	Add more pump varieties solutions
V1.3	16.10.2025	Bruce Wurilege	Erich L.F. Jiang	Add CoGS analysis analysis

Lindemann-Regner GmbH

October 2025

Contact

Erich L.F. Jiang

Lindemann-Regner GmbH

Liebigstr. 5, 85757 Karlsfeld, Germany

Telephone: +49 (0) 8131 61 49 236

Email:info@lindemann-regner.de

Contents

Table Lists

Figure List

1. ABBREVIATION

Table 1-1: Abbreviation Table

Abbreviation	Definition
AC	Alternating Current
ADC	Analog-to-digital Converter
ATS	Automatic Transition Switch
BEP	Best Efficiency Point
BESS	Battery Energy Storage System
BMS	Battery Management System
BMU	Battery Management Unit
CAPEX	Capital Expenditure
DC	Direct Current
DDP	Delivered Duty Paid
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
FFS	Fire Suppression System
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
LCOE	Levelized Cost of Energy
LFP	Lithium-ion Phosphate Battery, LiFePO4
MPPT	Maximum Power Point Tracking
OPEX	Operational Expenditure
PCS	Power Conversion System
PCU	Power Control Unit
PLC	Programmable Logic Controller
PPE	Personal Protective Equipment
PV	Photovoltaic
ROI	Return on Investment
SCADA	Supervisory Control and Data Acquisition
SKD	Semi Knock Down
SOC	State of Charge
SOH	State of Health
STS	Static Transition Switch
TBD	To Be Determined
VFD	Variable Frequency Drive

2. APPLICATION BACKGROUND

This project aligns with the global transition toward renewable and efficient rural energy, responding to strong policy momentum that promotes clean, resilient, and low-carbon development in agriculture. As international organizations such as the International Energy Agency (IEA) and International Renewable Energy Agency (IRENA) highlight rapid growth in solar and energy storage deployment, many countries are prioritizing decentralized renewable solutions for productive rural uses, including irrigation. National initiatives—such as China's green microgrid programs and India's PM-KUSUM scheme—further reinforce this direction, encouraging PV- and storage-based systems that reduce emissions, enhance energy access, and support agricultural modernization. Within this global policy framework, PV and BESS microgrids represent a mature, scalable pathway to achieve sustainable water–energy management.

In agricultural irrigation systems, electric water pumps are the dominant power consumers, and their operation directly affects crop productivity and energy costs. Conventional power supplies—grid-only, diesel-only, or grid–diesel combinations—often face high operating costs, unstable supply, and poor efficiency. By integrating PV generation, battery storage, and diesel backup under coordinated microgrid control, the proposed system delivers stable and economical power for irrigation, improving reliability, reducing fuel dependency, and aligning farm-level operations with broader carbon-reduction and energy-transition goals.

2.1 Analysis To Key Agricultural Irrigation Equipment

The following provides a detailed analysis of the principal equipment used in agricultural irrigation systems, covering their functions, power-consumption characteristics, and critical power-supply requirements. The discussion highlights pain points of current diesel-dominated and grid-assisted architectures and establishes the technical basis for adopting a PV–BESS–Diesel–Grid hybrid microgrid solution.

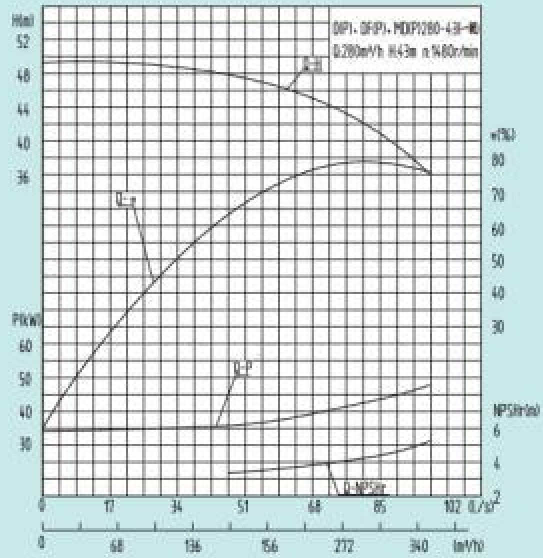
2.1.1 Deep-Well Water Pump (Submersible Type)

Function: The deep-well water pump is the primary device used to lift groundwater for irrigation. Installed below the static water level, it consists of a multi-stage centrifugal impeller set driven by a submersible electric motor. The pump raises water through long riser pipes to surface storage or directly into pressurized irrigation networks. It is indispensable in areas with deep aquifers or fluctuating groundwater levels, providing the flow and pressure needed for continuous field irrigation. In optimized irrigation systems, the deep-well pump can be operated primarily during daylight hours to lift and store water using solar energy, thereby reducing nighttime energy demand and enabling stable operation of smaller distribution pumps.

Power Consumption Characteristics: The deep-well water pump is the largest single energy consumer in agricultural irrigation, typically accounting for more than 80 percent of total electrical demand. Motor ratings generally range from several kilowatts to several hundred kilowatts, depending on pumping depth, discharge flow, and irrigation area. Operation is often continuous during irrigation cycles, with long duty hours and heavy mechanical loading.

Due to the large hydraulic head and the need for sustained discharge pressure, these motors require high starting torque. Under direct-on-line (DOL) starting, a submersible induction motor draws five to seven times its rated current, imposing substantial transient electrical and mechanical stress. Variable Frequency Drives (VFDs) or soft starters can reduce this surge to roughly 150–200 percent of rated current, allowing smoother acceleration and speed control. However, in most remote agricultural regions, VFDs are not commonly applied because of their higher cost, technical complexity, and sensitivity to unstable power quality from local diesel generators.

280–43型泵性能曲线和性能参数表
Performance curve and data table



级数 Number of stage	流量 Capacity Q		扬程 Head H	转速 Speed n	效率 Eff. η	功率Power kW		必需汽蚀余量 NPSHr	泵口径 Diameter of pump		泵重量 Pump weight
	m³/h	L/s	m	r/min	%	轴功率kW Shaft power	电机功率kW Motor power	m	进口mm Import	出口mm export	KG
	200	55.6	141		70	109.8					
3	280	77.8	129		78.5	125.4	160				1271
	335	93.1	114		77	135.2					
	200	55.6	188		70	146.4					
4	280	77.8	172		78.5	167.2	200				1397
	335	93.1	152		77	180.2					
	200	55.6	235		70	183.0					
5	280	77.8	215		78.5	209.0	250				1523
	335	93.1	190		77	225.3					
	200	55.6	282		70	219.6		3.0			
6	280	77.8	258		78.5	250.8	315				1649
	335	93.1	228		77	270.3					
	200	55.6	329	1480	70	256.2		4.5	200	200	
7	280	77.8	301		78.5	292.6	355				1775
	335	93.1	266		77	315.4		[illegible]			

Figure 2-1: Typical deep water pump performance curve, rated power 280kW

During steady-state operation, power consumption depends on the pumping head, discharge rate, and overall hydraulic efficiency. Variations in water level, pipe friction, or valve throttling lead to significant fluctuations in motor load and power factor. When the pump operates away from its best efficiency point (BEP), both electrical and hydraulic performance decline sharply. In addition, long submersible cable runs introduce further voltage drop and thermal losses, increasing total energy consumption.

2.1.2 Horizontal Water Pump (Surface Type)

Function: The horizontal water pump, also referred to as a surface or booster pump, is widely used in irrigation systems that draw water from surface sources such as rivers, canals, ponds, or storage reservoirs. It can also serve as a booster pump to maintain pressure in long-distance pipelines or elevated distribution networks. The pump is typically installed at ground level, driven by an electric motor, and connected to the irrigation mainline to deliver the pressure required for sprinklers, drip systems, or open-field flooding applications.

Power Consumption Characteristics: The horizontal water pump is a medium- to high-power load, depending on system scale, discharge pressure, and elevation differences. Motor ratings generally range from a few kilowatts to several tens of kilowatts. In large irrigation stations, multiple units may operate in parallel to serve different zones or maintain constant pressure under variable demand.

2.1.3 Diesel Generator Set

Function: The diesel generator set serves as the primary power source for irrigation systems in most remote or semi-off-grid agricultural areas. It provides electrical power to drive deep-well pumps, horizontal booster pumps, and auxiliary equipment when grid electricity is unavailable, unstable, or insufficient. Diesel generators are valued for their autonomy and flexibility, enabling continuous irrigation regardless of grid access or weather conditions.

Power Supply Characteristics: In irrigation applications, the generator must handle high starting currents from large induction motors. To avoid voltage collapse or frequency drop during pump startup, diesel generators are typically oversized to two or three times the nominal power of the main pump. While this ensures reliable starting performance, it results in inefficient operation during steady-state pumping, where the electrical load is often less than 50 % of generator capacity.

At partial load, diesel engines operate below their optimal combustion temperature, leading to increased specific fuel consumption, wet stacking, carbon buildup, and accelerated wear. Furthermore, rapid load variations from pump switching or valve actuation cause frequent torque fluctuations and fuel-governor instability, further reducing efficiency and reliability. Routine maintenance intervals are short, and overall operating costs are high due to fuel, lubricants, and spare parts.

2.1.4 Grid Power Supply

Function: The public utility grid provides supplementary or backup power to irrigation systems, particularly in large-scale agricultural schemes or regions with partial grid access. It supplies power directly to pump stations, or indirectly through local distribution transformers feeding deep-well and booster pumps. In some cases, the grid is used primarily for off-peak pumping or to recharge on-site batteries, complementing diesel or solar-based generation.

Power Supply Characteristics: Although grid electricity offers lower energy cost compared with diesel, power reliability and quality in rural areas are often inadequate. Long feeder distances, aging infrastructure, and seasonal voltage fluctuations lead to voltage sags, frequency deviations, and occasional blackouts. These disturbances can trip pump motors or damage electronic controls. When several large pumps start simultaneously, the resulting inrush current can cause severe voltage dips and flicker on weak feeders, affecting nearby consumers.

Another limitation arises from demand-based electricity tariffs. Irrigation loads are typically concentrated in specific time windows, creating high peak demand and incurring costly capacity or time-of-use charges. In addition, expanding grid connections to new irrigation areas often requires lengthy permitting and reinforcement of existing lines, increasing capital cost and project timelines.

A prevalent obstacle to deploying agricultural technology in developing regions is the absence of a reliable electrical grid or the presence of severe power quality issues. A standard mitigation strategy is to employ an isolation transformer, which eliminates adverse electrical interference caused by grid instability.

2.2 Analysis of Agricultural Irrigation System

Across the pilot agricultural irrigation sites in Saudi Arabia, Bangladesh, and Senegal, irrigation activities depend on deep-well and surface water pumps operating in remote areas with no stable grid connection. Existing diesel-powered systems commonly experience voltage and frequency fluctuations, high fuel costs, and maintenance challenges. A further critical issue lies in the high inrush power during pump startup, which can reach several times the rated load and often causes generator instability, voltage sags, or pump trips—making reliable operation difficult under conventional setups.

To overcome these challenges, each site is evaluated for integration with a hybrid renewable power system that provides stable, efficient, and low-carbon energy suitable for agricultural irrigation. The design focuses on achieving smooth motor starting, steady pressure control, and reliable day-long operation under varying solar and load conditions. Depending on scale and technical requirements, the configuration flexibly combines renewable generation, energy storage, and controlled power conversion to manage transient loads while minimizing diesel dependency.

A centralized Energy Management System (EMS) oversees system operation, coordinating energy flow, monitoring state-of-charge battery, and scheduling pump activities according to irrigation demand and resource availability. Real-time data are transmitted through 4G/5G communication to a unified monitoring platform for remote supervision, diagnostics, and predictive maintenance. This integrated and intelligent control framework ensures stable voltage and frequency, optimized renewable utilization, and high operational reliability, forming a replicable, sustainable model for modern agricultural irrigation across diverse regional contexts.

Table 2-1: Overview of information at pilot agricultural irrigation sites worldwide

N o#	Country	Power Supply Condition	Operational Requirement	Total Head (m)	Flow Rate (m3/h)	Cont. Load (kW)	Peak Load (kW)	Daily Conso (kWh)	Diesel Generator Cost	Surrounding Land Type	PV Land Availability	Remarks
1	Kingdom of Saudi Arabia	No grid access, remote site	3 × 350 kW deep-well pumps (225 m depth) for high debit demand irrigation; continuous seasonal operation;	200 to 250 m	Up to 300 m3/h during daytime	200 kW per pump depend on usage	350 kW per pump depend on usage	2,000 kWh	Own property, 1 new, 2 x 2nd hand aggregate	Agricultural farmland / pump station, no reservoir	~50,000 m²	VFDs are stand-alone (local ramps); EMS handles run/stop, SoC gating, DG dispatch; PV for kWh, BESS for surge & stability
2	Bangla-desh	No grid access, remote site	1 x 22 kW river side pump, banana field irrigation, year-over operation	Up to 5m	30 m3/h	22 kW	180 kW in start phase	250 kWh	Own property, 2nd hand aggregate	Near to banana field, 6m to river side	Heavy palm tree coverage, ~100 m2	VFD not available on-site due to cost reasons.
3	Senegal	No grid Access, remote site	1 x 50 kW Deep-well pump (50 m depth). Power supply for dehydration machine 20kW desired too. Seasonal operation	Up to 50 m	20 m3/h	30 kW	100 kW in start phase	Highly volatile, 100-300 kWh	Own property, 225 kW power	National agriculture demo farmland	> 10,000 m2	Turnkey solution needed. VFD shall be considered but as part of turn-key solution from supplier.

3. SYSTEM CONCEPT DESIGN

3.1 Design Target

This technical solution is designed to provide a reliable, efficient, and flexible power supply for the agricultural irrigation system. It ensures stable operation of deep-well pumps under varying solar conditions while minimizing diesel generator usage and maintaining high power quality.:

- **Supply Voltage**: Three-phase AC 0.4 kV ± 10%
- **Frequency**: 50 ± 0.5 Hz
- **Power**: Customized based on actual requirements
- **PV Capacity**: Customized based on actual requirements
- **Diesel Generator**: Customized based on actual requirements
- **System Backup Time**: On customer specifications
- **Output Power**: On load requirements
- **DC Coupling Voltage**: Designed with a DC bus voltage of 800 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.

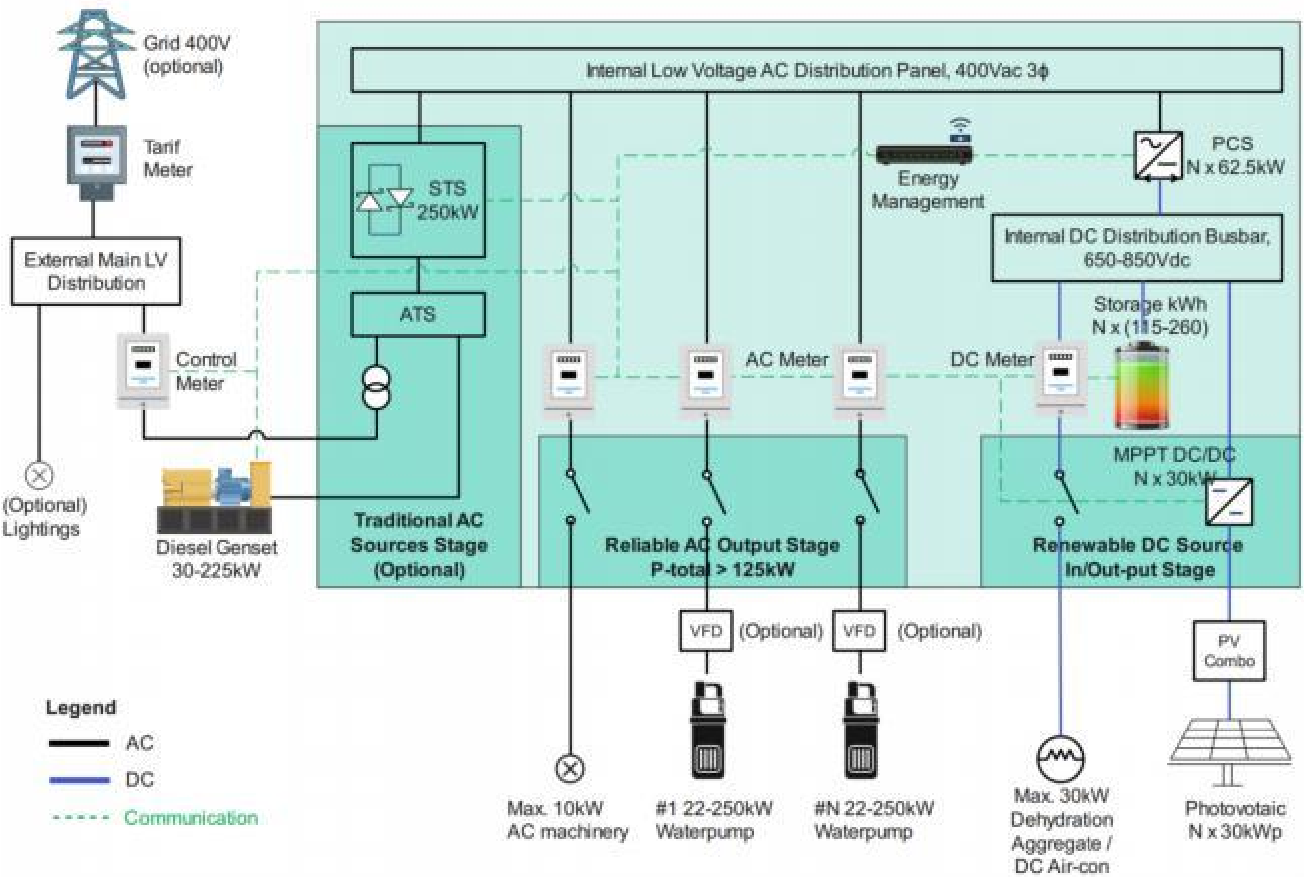


Figure 3-1: Typical microgrid architecture of in-/off-grid agricultural irrigation microgrid solution

This design adopts a centralized PV–BESS–Diesel hybrid microgrid architecture based on a common 650–850 V DC bus. Photovoltaic arrays and the battery energy storage system are connected through dedicated DC/DC converters, while one or more 62.5 kW grid-forming PCS units convert DC power to a stable 400 V, 50 Hz AC supply for all irrigation pumps and auxiliary loads. A diesel generator and optional grid connection are integrated on the AC side through ATS/STS for firm backup and black-start capability. The DC-coupled configuration reduces conversion losses, improves transient response during pump startup, and enables seamless coordination among PV, BESS, and DG under the energy management system (EMS). This architecture ensures reliable off-grid irrigation operation, stable voltage and frequency, and high renewable energy utilization with minimal diesel runtime.

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. **Pump Starting Mode (Transient, Any Time)**: When a deep-well pump starts, the BESS and PCS deliver the required surge power to maintain voltage and frequency stability, while the diesel generator (if online) provides additional inertia and reactive support. PV contributes proportionally based on instantaneous irradiance. After acceleration, the system returns to normal operating mode automatically.
2. **PV-Dominant Mode (Daytime, 20% < SOC < 90%)**: PV generation supplies the irrigation load; excess energy charges the BESS. Diesel remains on standby.
3. **PV + BESS Hybrid Mode (Daytime, 20% < SOC < 90%, PV insufficient)**: PV output partially supports the load; the BESS discharges to maintain balance and voltage stability.
4. **Battery-Only Mode (Nighttime or Low Irradiance, 20% < SOC < 90%)**: The BESS supplies all loads; diesel remains offline to save fuel.
5. **Battery Full Mode (SOC > 90%)**: PV supplies the load directly; excess PV generation is curtailed automatically to maintain DC bus stability.
6. **Diesel-Assisted Mode (SOC < 20% or Extended Low Solar Periods)**: The EMS starts the diesel generator. DG supplies load and recharges the battery simultaneously, operating near its optimal efficiency range.
7. **Generator Recovery Mode (SOC restored to threshold, e.g., 40-50%)**: When sufficient battery charge is restored, the generator stops, and the system returns to PV–BESS mode.
8. **Grid-Connected Mode (Optional)**: When the external grid is available, it can support load supply, battery charging, or startup events, depending on EMS scheduling.

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 deep-well pumps.
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 centralized DC-coupled hybrid microgrid offers a reliable and replicable model for sustainable, low-carbon agricultural irrigation. It is particularly suitable for remote areas with weak or no grid access, representing a forward-looking solution aligned with global renewable energy and rural electrification initiatives.

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 each deep-well pump, including motor voltage, operating current, rotational speed, and other key indicators.
- Automatic logging of irrigation data such as pumping duration, flow rate, and total water output for performance analysis and scheduling.
- 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

As a notably larger-scale microgrid compared to similar deployments, the KSA pilot project (Table 2-1) serves as a salient case study. The subsequent analysis is derived from this project.

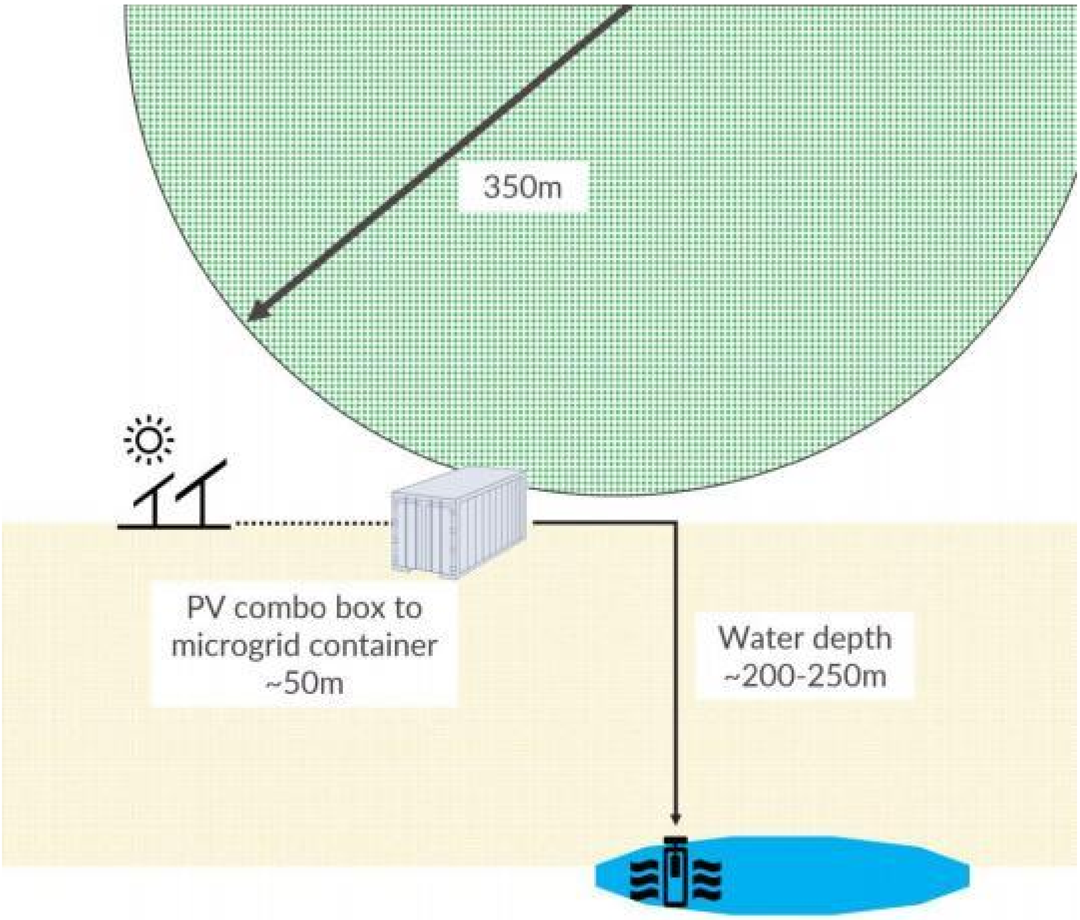


Figure 4-1: Representative diagram of KSA pilot project

4.1.1 Power Generation Capacity Metrics

As shown in the figure, the annual effective photovoltaic power generation hours at KSA installation site can reach 1,935 hours, averaging approximately 5.30 hours per day. The minimum monthly effective generation hours occur in June, with 138.7 hours, averaging about 4.62 hours per day.

Figure 4-2: Typical PV output for pilot project site KSA

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:

$$\mathbf{PV\_capacity = P\_req / (\eta \times t\_eff)}$$

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, 5 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 (5 hours)
- P_load = 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 × 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

Table 4-1: Overview of key metrics at pilot agricultural irrigation systems worldwide

N o#	Country	Power Supply Condition	Operational Requirement	Total Head (m)	Flow Rate (m3/h)	Cont. Load (kW)	Peak Load (kW)	Daily Conso (kWh)	PV Capacity (kWp)	Storage Capacity (kWh)	PCS Capacity (kW)	STS Capacity (kVA)
1	Kingdom of Saudi Arabia	No grid access, remote site	3 × 350 kW deep-well pumps (225 m depth) for high debit demand irrigation; continuous seasonal operation;	200 to 250 m	Up to 300 m3/h during daytime	200 kW per pump depend on usage	350 kW per pump depend on usage	2,000 kWh	450	2,080	500	Optional
2	Bangla-desh	No grid access, remote site	1 x 22 kW river side pump, banana field irrigation, year-over operation	Up to 5m	30 m3/h	22 kW	180 kW in start phase	250 kWh	60	115	180	Optional
3	Senegal	No grid Access, remote site	1 x 50 kW Deep-well pump (50 m depth). Power supply for dehydration machine 20kW desired too. Seasonal operation	Up to 50 m	20 m3/h	30 kW	100 kW in start phase	Highly volatile, 100-300 kWh	125	215	125	Optional

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.

Figure 4-3: Typical containerized microgrid product with reinforced thermal management for Middle East

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 ±1%, 50Hz ±1%, THD ≤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 agricultural irrigation 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	±3%
	Voltage Unbalance	<2% (<4%, 3s-1min)
	THD	≤3% (linear load)
	Rated Frequency	50 Hz
	Frequency Range	49.5-50.5 Hz
	Transient Response	≤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	≤1%
	Current Regulation	≤1%
	Voltage Ripple	≤2%
	Current Ripple	≤2%
	Charging (Lead-Acid)	3-stage
	Charging (Li-ion)	BMS-controlled
PV DC Stage	Rated Power	30 kW (Per String), multiple string possible
	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	20
	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 ℃ to +45 ℃
	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 the pilot project in Senegal 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.

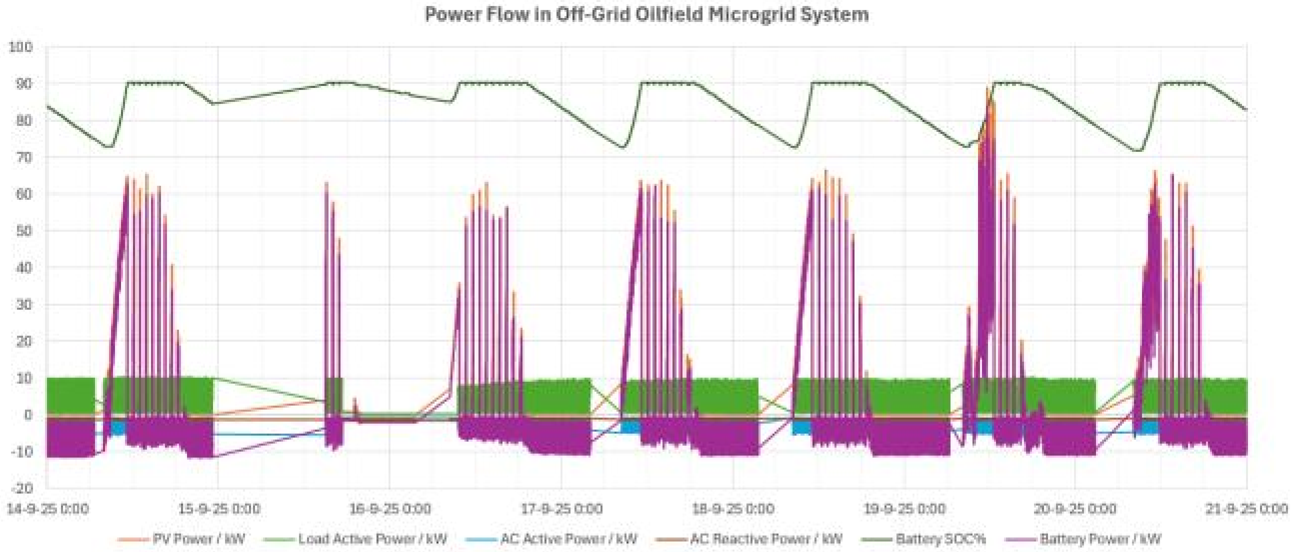


Figure 5-1: Usage profile of off-grid microgrid system in practice, 14-21 September 2025

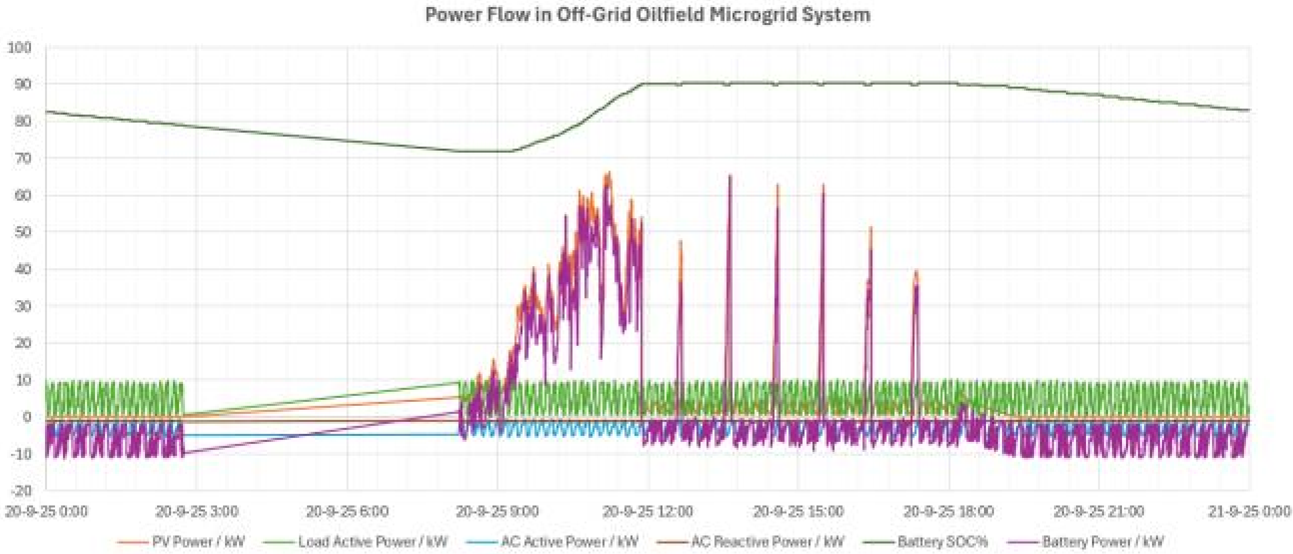


Figure 5-2: Usage profile of off-grid microgrid system, instable PV power, 20 Sept 2025

6. INVESTMENT AND FINANCE ANALYSIS

This analysis delineates the financial model and Return on Investment (ROI) assessment for an aggregated, in/off-grid agricultural power generation and supply system. The scope of this evaluation is explicitly confined to the capital expenditure (CAPEX) and operational expenditure (OPEX) attributable to the energy system itself.

The object under analysis is an aggregated, in/off-grid agricultural power generation and supply system comprising the following core components:

- **Power Generation & Storage Aggregate**: A seamlessly integrated unit combining photovoltaic (PV) panels, battery energy storage system (BESS), and requisite power electronics.
- **Power Conversion System**: Including inverters (DC/AC), rectifiers (AC/DC), and power switch components (ATS, STS) to handle power disruption and surge.
- **Thermal Management**: Active or passive cooling mechanisms essential for maintaining optimal operating temperatures for the battery storage and power electronics, thereby ensuring longevity and efficiency.
- **AC & DC Distribution**: The 400V low-voltage AC and/or 800V DC distribution board, incorporating protection devices such as circuit breakers, surge protection devices (SPDs), and isolation switches, also providing sufficient electrical connection ports for consumers.
- **Control & Monitoring Mechanisms**: A supervisory control and data acquisition EMS system for system orchestration, performance monitoring, and remote management.

It is critical to note that this financial model explicitly excludes end-use agricultural loads such as electrical pumps and motors, Variable Frequency Drive (VFD), as well as any backup diesel generators or costs associated with connection to the primary power grid. This delineation ensures a clear evaluation of the standalone power system's value proposition.

6.1 Hardware Capital Expenditure (CAPEX) and Sourcing Model

The foundation of the cost model is the Delivered Duty Paid (DDP) structure for the core hardware.

- **Manufacture and Assembly**: The aggregate is assembled in Mainland China, which location provides competitive procurement costs for components and access to a mature industrial ecosystem.
- **Total Delivered Cost Calculation**: The DDP quotation is a holistic figure that encapsulates all direct and indirect costs to deliver the system to the customer's specified site, including Ex-Works (EXW) Cost, International Logistics, Inland Logistics, Insurance, export duties, import tariffs, value-added tax (VAT), and any applicable customs brokerage fees.

6.2 Project Soft Costs and Turn-Key Solution Expenditure

Beyond the hardware CAPEX, a full turn-key project deployment incurs significant "soft costs" related to engineering, construction, and commissioning. These costs are highly variable and are heavily influenced by the project's geographical location and local regulatory environment. They are typically expressed as a percentage of the DDP hardware cost.

- **Project Development & Management**: Costs associated with initial site surveys, feasibility studies, system design engineering, permitting, and overall project management.
- **Civil Engineering & Construction**: This encompasses all site preparation work, including the construction of foundations for the PV array and system aggregate shelters, trenching for cable runs, and any necessary structural reinforcements.

- **Electrical Installation & Commissioning**: Costs for the physical installation of all components, cable laying and termination, grounding, and the comprehensive commissioning of the entire system to ensure operational readiness and safety.
- **Grid Interconnection Study & Application Fees**: In cases where the system is designed for potential grid interaction (e.g., net metering), even as a primary off-grid source, there are costs associated with access to the grid.

The aggregate of these soft costs is non-trivial and can range from 30% to 100% of the DDP hardware cost. This wide variance is attributable to regional disparities in labor rates, the complexity of local permitting regimes, the distance of the site from established infrastructure, and the specific requirements of the responsible grid operators.

6.3 Operational Expenditure (OPEX)

A critical differentiator of this renewable energy solution is its structurally lower OPEX compared to traditional diesel generator sets. It replaces continuous fuel expenditure with predictable, infrequent maintenance and a single major component replacement (the battery). This translates to a stable, known cost profile over the project's lifetime, insulating the operator from energy price volatility and leading to a significantly lower Levelized Cost of Energy (LCOE) in the long run.

6.3.1 OPEX of the Renewable Energy Solution

The OPEX for the described solar-battery in-/off-grid aggregate system is characterized by its predictability and minimal variable costs, which can be boiled down to:

- **Preventive & Corrective Maintenance:** Scheduled servicing of the system, primarily involving visual inspections, cleaning of PV panels, checking electrical connections, and verifying control system software. This is typically a fixed annual cost.
- **Component Replacement**: The most significant future OPEX is the planned replacement of the Battery Energy Storage System (BESS) after it reaches its end-of-life, typically defined as a 20-30% capacity degradation from its original rating, usually occurring between 5,000 and 10,000 cycles, equivalent to 8-10 years. Power electronics (inverters) have a longer lifespan, typically 15 years.
- **Operational Labor**: Minimal operational oversight is required due to extensive remote monitoring and control capabilities via the SCADA/PLC system.

6.3.2 OPEX ofa Traditional Diesel Generator Solution

In contrast, the OPEX for a diesel generator is dominated by high and volatile variable costs, making it financially unpredictable and operationally burdensome.

- **Fuel Cost**: This is the largest and most volatile OPEX component. Fuel consumption is continuous during operation and is subject to global oil price fluctuations and local fuel subsidies or taxes.
- **Engine Maintenance**: Diesel gensets require frequent and costly maintenance, including regular oil changes, air, oil, and fuel filter replacements, and periodic overhauls of injectors, pumps, and other high-wear components. Maintenance frequency intensifies with runtime.
- **Major Overhauls**: A complete engine rebuild or replacement is often necessary after a certain number of operational hours, e.g., 2,000 hours, especially when the second-hand diesel genset is popular in field due to low initial cost.
- **Operational Labor**: Requires significant on-site labor for refueling, daily checks, and manual start/stop operations.
- Environmental & Health Costs: While often externalized, costs associated with noise pollution, air quality impacts, and potential soil contamination from fuel spills contribute to the total cost of ownership.

6.4 Return on Investment Analysis and Volatility Factors

The ROI for the described aggregated power supply system is not a fixed value but is subject to significant variance due to a complex interplay of operational and regional factors. The primary financial benchmark for comparison is the LCOE produced by the system versus the prevailing local retail electricity price or the equivalent cost of diesel-generated power.

6.4.1 ROI Calculation Framework

We model the simplified ROI over a defined period, typically 8-10 years depending on use severity of the system.

- **Total Investment (I)**:
  DDP Hardware Cost + Turn-Key Soft Costs (Civil, Installation, etc.)
- **Annual Operational Savings (S)**:
  Annual Energy Output [kWh] x Local Grid Electricity Price, or
  Annual Energy Output [kWh] x Diesel Gen-set LCOE [$/kWh]
- **Annual Operational & Maintenance Cost (O&M)**: Low, predictable cost for aggregate microgrid power supply system.
- **Simplified Payback Period (Years)**:
  I / (S - O&M)

6.4.2 Key Factors Influencing ROI Volatility

- **Local Energy Tariffs**: The single most impactful variable. The annual savings (S) are maximized when offsetting high-cost grid power or diesel generation.
- **Solar Resource Availability**: The capacity factor of the PV system, determined by local solar irradiance, directly impacts annual energy output.
- **Operational Regime and Load Profile**: The consistency and magnitude of the agricultural load affect how efficiently the generated energy is utilized and the requisite sizing of the BESS. A higher operational utilization factor directly correlates with a reduced payback period, as the fixed capital investment is amortized over a greater energy output.
- **Regulatory and Subsidy Environment**: Government incentives for renewable energy can dramatically improve ROI by reducing the net initial investment (I).
- **System Degradation and Lifetime**: The performance degradation of PV panels and the finite cycle life of batteries are critical factors in long-term financial modeling. Follow EMS instruction for in-time maintenance in order to prolong the lifetime of system.

6.5 Field-Validated Performance Index

Given the inherent volatility in theoretical ROI calculations, we supplement our financial models with empirical data derived from our global pilot stations. This "field index" provides a realistic, ground-truthed benchmark for performance and economics.

Based on operational data from diverse agricultural pilot projects, the typical system described can achieve LCOE ranging between 0.08 ~ 0.20ε per kWh over a 8-year project lifespan. This range is highly competitive in numerous markets, particularly when compared to the LCOE of diesel-generated power, which typically falls between 0.30 ~ 0.60ε per kWh depending on local fuel prices and generator efficiency.

This stark contrast in LCOE, driven by the low OPEX of the renewable solution, solidifies the investment case for deploying the aggregate microgrid systems in the agricultural sector, especially in remote areas or regions with unreliable grids.

Table 6-1: Empirical ROI data (CAPEX focus) from pilot agricultural irrigation systems worldwide

N o#	Country	Cont. Load (kW)	Peak Load (kW)	Daily Conso (kWh)	PV Capacity (kWp)	Storage Capacity (kWh)	PCS Capacity (kW)	Hardware DDP Cost (ε)	Turn-key Project Cost (ε)	Yearly Energy (kWh)	E-Price 2025 (ε/kWh)	LCOE 8 years (ε/kWh)	Diesel Price (ε/L)	Diesel LCOE (ε/kWh)
1	Kingdom of Saudi Arabia	200 kW per pump depend on usage	350 kW per pump depend on usage	2,000 kWh	450	2,080	500	451,800	564,000	730,000	***0,06***	***0,097***	0,41	***0,117***
2	Bangla-desh	22 kW	180 kW in start phase	250 kWh	60	115	180	40,600	55,700	91,250	***0,12***	***0,076***	0,72	***0,206***
3	Senegal	30 kW	100 kW in start phase	Highly volatile, 100-300 kWh	125	215	125	81,560	97,745	76,650	***0,19***	***0,159***	1,14	***0,328***