



A Constraint-Based Hierarchical Energy Management Strategy for Peak Shaving in PV–Wind–Battery Hybrid Systems

Syahrul Ramadhan^{1,*}

¹ Master' Study Program in Renewable Energy Engineering, Graduate School, Universitas Darma Persada, Jakarta, Indonesia

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ABSTRACT

Purpose of the study: Peak load fluctuations can increase diesel generator loading and trigger standby-generator operation. This study develops and evaluates a constraint-based hierarchical Energy Management System (EMS) for peak shaving in a PV–wind–battery hybrid system while maintaining the existing Power Management System (PMS) as the primary controller.

Methodology: An analytical case study and numerical simulation were conducted using operational load data and the designed hybrid configuration. The system comprises 57.6 kWp PV, 15 kW vertical-axis wind turbines, a 141.12 kWh VRLA battery bank, and three 20 kW hybrid inverters. A rule-based EMS was formulated considering PMS loading thresholds, renewable power availability, inverter capacity, battery State of Charge (SoC), voltage, and current constraints. The PMS threshold was maintained at 824.4 kW, with an EMS dispatch trigger of 764.4 kW.

Main Findings: The hybrid system provides up to 60 kW of peak support under favorable conditions. Battery-only output is limited to approximately 43.1 kW at 43.2 V and a combined discharge current of 1,050 A. The theoretical load boundary without exceeding the PMS threshold is 884.4 kW. For a 916.1 kW load spike, 60 kW support reduces residual generator load to 856.1 kW, resulting in partial peak shaving.

Novelty/Originality of this study: The proposed framework integrates constraint-based EMS dispatch with PMS authority without modifying the existing PMS philosophy, enabling early peak support, battery-aware dispatch, and fail-safe operation. This provides a practical framework for hybrid power systems with constrained generation capacity.

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Corresponding Author:

Syahrul Ramadhan,

Master's Study Program in Renewable Energy Engineering, Graduate School, Universitas Darma Persada,
Jl. Radin Inten II (Terusan Casablanca), Pondok Kelapa, Duren Sawit, Jakarta, Indonesia.

Email: Syahrulsetara@gmail.com

1. INTRODUCTION

The increasing integration of renewable energy sources (RES) and energy storage into isolated power systems has created new opportunities to reduce dependence on conventional diesel generation while maintaining power-system reliability. In isolated offshore and floating production facilities, however, the integration of renewable sources cannot be treated solely as an energy-efficiency problem because the power system must continuously respond to fluctuating loads, renewable intermittency, and strict operational constraints [1], [2]. Diesel generators therefore remain essential as the primary controllable power source, while

renewable energy and battery energy storage systems (BESS) can be utilized as supplementary resources for reducing generator loading and managing short-duration power fluctuations [3], [4]. Previous studies have demonstrated that hybrid PV–wind–battery–diesel configurations can improve renewable-energy utilization, reduce diesel consumption, and enhance the reliability of isolated power systems [5], [6].

The FSO Gagak Rimang power system in the Banyu Urip Project [7] operates as an isolated electrical system with a 440 VAC, three-phase, three-wire, 60 Hz, ungrounded configuration. The diesel generator (DG) has a rated active power of 916 kW per unit and operates in Single DG Mode under the supervision of the Power Management System (PMS) [3], [8]. In this configuration, the PMS performs the primary power-system functions, including generator start/stop, synchronization, load sharing, and load-dependent generator operation. The existing PMS applies a load-dependent start threshold of 90% of the DG rated capacity, corresponding to 824.4 kW. Consequently, rapid load increases approaching or exceeding this threshold can result in the initiation of standby-generator operation even when the load excursion is relatively short. Such operating conditions create an opportunity for a supplementary energy source to provide short-duration peak support without replacing the primary role of the DG or modifying the established PMS philosophy [9].

The proposed hybrid system consists of 57.6 kWp photovoltaic (PV) generation, 25 vertical-axis wind turbines (VAWTs) with a combined rated capacity of 15 kW, a 141.12 kWh VRLA OPzV battery bank, and three 20 kW hybrid inverters with a total rated output of 60 kW. The hybrid capacity therefore represents only a limited fraction of the 916 kW DG capacity. This configuration indicates that the hybrid system is not intended to replace the DG as the principal power source or to supply the complete load during islanded operation [10], [11]. Instead, its operational value is associated with short-duration supplementary power, particularly during transient load increases. Preliminary operational data recorded on August 13, 2025, indicate an average hotel-mode load of approximately 703 kW, equivalent to about 77% of the DG rated capacity, with higher short-duration load excursions occurring during operation. This condition creates a technically relevant operating region between normal loading and the PMS generator-start threshold where limited hybrid power support may be useful [12], [13].

The technical challenge is that the available hybrid power cannot simply be assumed to equal the nominal inverter capacity [14], [15]. The actual support capability depends on renewable generation availability, inverter limits, battery State of Charge (SoC), battery terminal voltage, allowable discharge current, and system protection constraints. In the proposed configuration, the three inverters provide a maximum nominal active-power capability of 60 kW. However, under the conservative battery operating condition, with a minimum operating voltage of 43.2 V, a combined allowable discharge current of 1,050 A, and an assumed conversion efficiency of 95%, the battery-only output is approximately 43.1 kW. Thus, the nominal 60 kW hybrid capacity and the actual battery-supported capacity represent different operational constraints that must be explicitly incorporated into the EMS.

From a control perspective, the existing PMS must remain the highest operational authority because it is responsible for maintaining generator availability and system security [16]–[18]. Therefore, an EMS that simply overrides or modifies the PMS load-dependent start threshold would introduce an undesirable change to the established protection and generation philosophy. Instead, the problem-solving approach adopted in this study is to place the EMS as a supervisory/permissive control layer below the PMS authority. The PMS threshold remains fixed at 824.4 kW, while the EMS initiates supplementary power support before the load reaches this threshold. Based on the maximum 60 kW hybrid output, the proposed EMS dispatch trigger is established at 764.4 kW. Accordingly, the EMS can provide up to 60 kW of support within the operating region between 764.4 and 824.4 kW and can continue providing supplementary power above the PMS threshold when sufficient hybrid capacity is available [19], [20]. The residual DG load is then continuously evaluated against the PMS threshold.

Previous international studies have established several approaches for energy management in hybrid renewable–diesel systems. Hong & Alano [21] states that developed a three-level hierarchical EMS for a PV–wind–diesel–energy-storage microgrid, with the control architecture designed to coordinate power sharing among distributed energy resources under variable operating conditions. Other studies which is conducted by Dosa et al., [22] have proposed hierarchical EMS strategies for stand-alone diesel-based microgrids by incorporating load and renewable-resource uncertainty into scheduling and real-time control, with objectives including reliability improvement and fuel-cost reduction. Optimization-based approaches have also been developed for PV–wind–battery–diesel systems, primarily emphasizing economic operation, fuel consumption, renewable-energy penetration, and optimal power dispatch [23], [24]. These studies confirm the effectiveness of EMS-based coordination but generally formulate the EMS as the principal mechanism for determining source dispatch or optimizing system-level operation.

More recent research has further expanded EMS functionality toward centralized coordination, SoC equalization, active-power curtailment, load shedding, and diesel-generator backup. For example, a study proposed a centralized management architecture for PV–wind–battery systems with diesel support, incorporating SoC management and load-shedding functions to maintain power balance and protect the battery from excessive discharge [8], [25], [26]. Other recent work has investigated adaptive or optimization-based EMS strategies for

autonomous PV–wind–diesel–BESS microgrids, with emphasis on minimizing operational cost and improving reliability under varying renewable and load conditions [27], [28]. These developments demonstrate that the research field has increasingly moved toward intelligent and optimization-oriented energy management.

Nevertheless, a specific research gap remains in the application of EMS for constrained peak shaving in an existing isolated industrial/offshore power system where the PMS already possesses primary generator-control authority. The literature reviewed largely emphasizes optimal energy dispatch, fuel-cost minimization, renewable-energy penetration, reliability, or autonomous microgrid operation [29], [30]. In contrast, the present problem requires the EMS to operate within a predetermined PMS threshold without bypassing or modifying that threshold. More specifically, the EMS must determine when supplementary power should be dispatched based on the relationship between load demand and the PMS threshold while simultaneously considering the maximum inverter output, actual renewable availability, battery SoC, minimum battery voltage, allowable discharge current, and fail-safe conditions. This combination of PMS-preserving hierarchical control and constraint-based peak shaving represents the principal gap addressed by this study.

The urgency of this research arises from the limited power margin between the normal operating load and the PMS generator-start threshold. A 60 kW hybrid system represents only approximately 6.55% of the 916 kW DG rating, yet this relatively small capacity can be operationally significant when applied during short-duration load excursions. Under ideal 60 kW support, the highest load that can theoretically be maintained at or below the 824.4 kW PMS threshold is 884.4 kW. However, an extreme load spike of 916.1 kW would still result in a residual DG load of 856.1 kW after full hybrid support, which remains above the PMS threshold. Therefore, the hybrid system should not be interpreted as a complete generator-start prevention mechanism [31], [32]. Rather, its operational role must be differentiated between early support, standby-generator-start avoidance within the available power margin, and partial peak shaving when the load exceeds the maximum support boundary. This distinction is important for realistic system planning and prevents overestimation of the hybrid system's capability.

Based on this gap and the identified operating constraints, this study develops a rule-based, constraint-based hierarchical EMS that coordinates PV, wind, and battery power as supplementary resources while preserving the PMS as the primary controller. The proposed EMS defines operating regions according to load demand, determines the required hybrid support, limits dispatch according to available renewable power and inverter capacity, and applies battery constraints related to SoC, voltage, and discharge current [4], [28]. The strategy also incorporates fail-safe permissives, including grid-health conditions, emergency shutdown status, reverse-power protection, battery operating limits, temperature constraints, and communication status. The approach is intended to provide a practical control framework that can be evaluated using actual operational load characteristics rather than assuming continuous availability of the nominal hybrid capacity.

Accordingly, the objectives of this study are: (1) to characterize load-spike behavior and its relationship with the PMS load-dependent generator-start threshold; (2) to determine the hybrid power support required to maintain the residual DG load within the PMS threshold; (3) to evaluate the practical power capability of the PV–wind–battery system considering inverter capacity, renewable availability, battery SoC, voltage, and current constraints; (4) to identify the load range in which hybrid support can prevent or reduce the need for standby-generator operation and the range in which only partial peak shaving is achievable; and (5) to formulate a constraint-based hierarchical EMS that provides supplementary peak support without modifying the primary PMS control philosophy. Based on these objectives, the research questions are formulated as follows:

RQ1: What are the characteristics of load spikes and how do they relate to the PMS load-dependent generator-start threshold?

RQ2: How much hybrid power support is required to maintain the residual DG load below the PMS threshold?

RQ3: What is the practical peak-support capability of the PV–wind–battery system when inverter, renewable-generation, SoC, voltage, and discharge-current constraints are considered?

RQ4: Within what load range can the hybrid system provide sufficient support to avoid or reduce standby-generator operation, and at what load level does the system transition to partial peak shaving?

RQ5: How can a constraint-based hierarchical EMS be formulated to coordinate hybrid power support while preserving PMS authority and maintaining fail-safe operation?

The novelty of this research therefore lies not merely in integrating PV, wind, and battery resources, but in developing a PMS-preserving, constraint-based hierarchical EMS for peak shaving in which the supplementary power dispatch is explicitly bounded by the actual hybrid-system capability and operational safety constraints. The resulting framework provides an engineering-oriented approach for utilizing limited renewable and battery capacity to manage short-duration load peaks without changing the established primary generation-control philosophy.

2. RESEARCH METHOD

2.1 Experiment and Treatment Design

This study employs an analytical case study method combined with numerical simulations based on real operational data from the FSO Gagak Rimang offshore facility, operated by ExxonMobil Cepu Limited. A key characteristic of the FSO Gagak Rimang electrical system is its isolated operation (isolated microgrid) at a low voltage of 440 VAC (3-phase, 3-wire, 60 Hz) utilizing an ungrounded distribution system. The system's primary power source consists of conventional Heavy Fuel Oil (HFO) diesel generators, each with a continuous rated power capacity of 916 kW during single-generator operation (Single DG Mode).

The treatment evaluated in this study involves the integration of a hybrid renewable energy system—comprising Solar Photovoltaic (PV) units, a Vertical Axis Wind Turbine (VAWT), and a battery energy storage system (battery bank) acting as an energy buffer—to perform partial peak shaving. The fundamental design philosophy positions this hybrid system as a secondary (supplementary) energy source [33], [34]. The existing electrical network continues to rely on an HFO diesel generator as the primary grid-forming source, responsible for controlling bus voltage and frequency parameters. To ensure operational safety and the reliability of the offshore refinery's electrical system, this study establishes clear and definitive control hierarchy boundaries between the vessel's existing Power Management System (PMS) and the hybrid system's local Energy Management System (EMS). Coordination workflows and operational limits are governed by the technical specifications shown in Figure 1.

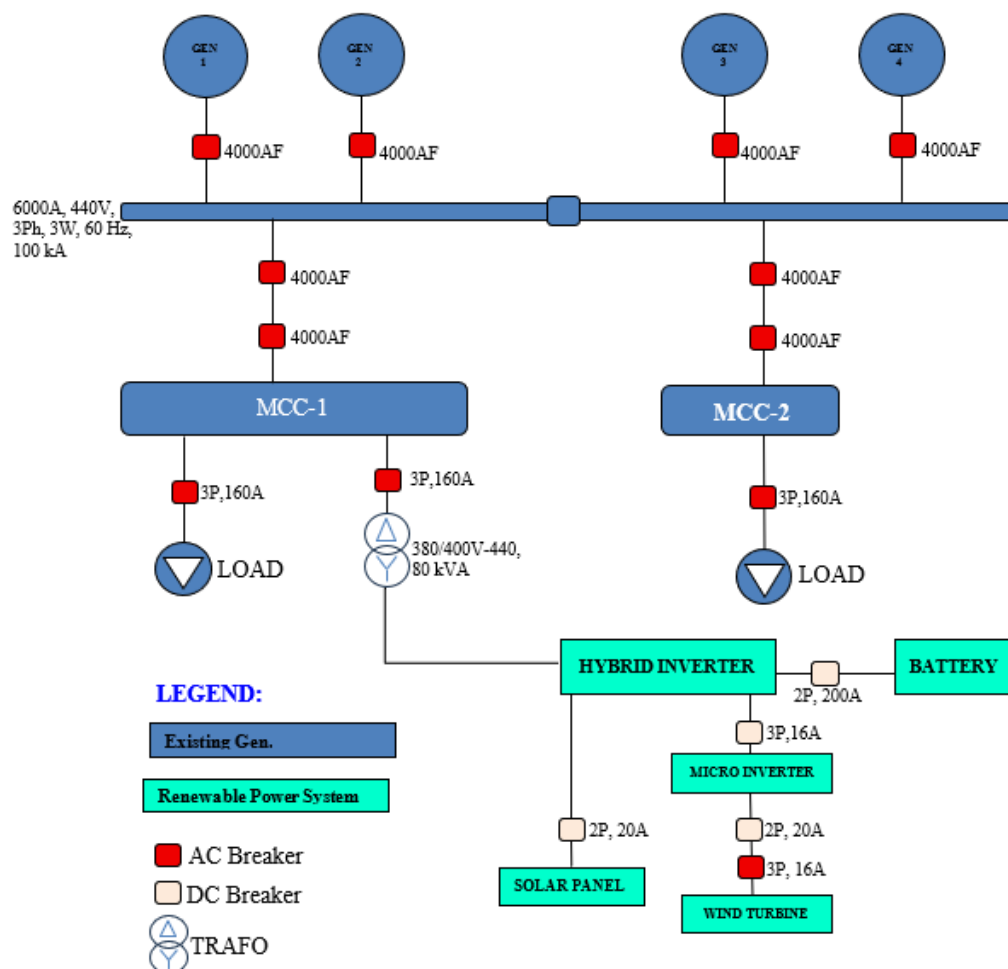


Figure 1. Single-line diagram

2.1.1 Standby Generator Automation Threshold (PMS Master Authority)

The electrical automation system of the FSO Gagak Rimang is fully controlled by the existing Power Management System (PMS). The PMS continuously monitors grid parameters and executes the Load-Dependent Start function. The auto-start threshold for triggering the standby diesel generator (DG) is fixed at 90% of a single DG's rated power, equivalent to 824.4 kW [35], [36]. This PMS safety threshold is permanent; it is neither altered, modified, nor bypassed by the hybrid system or the EMS controller in this study.

2.1.2 Hybrid Power Dispatch Set Point Limit (Local Authority EMS)

The hybrid Energy Management System (EMS) is designed to operate permissively under the control of the PMS. To optimize the utilization of renewable energy before the PMS issues a command to start the backup generator, a hybrid support set point (EMS peak-support trigger) is established at a load of 764 kW (equivalent to 83.45% of a single Diesel Generator's rated power). This 764 kW figure defines the threshold at which the three hybrid inverter units begin dispatching active power from the battery and renewable sources to the MCC-1 AC bus. This 764 kW set point serves purely as a control parameter for activating the hybrid inverters and in no way alters the operational capacity limits or physical capabilities of the existing Diesel Generator.

2.1.3 Residual Load Handling Logic

Based on the PMS threshold of 824.4 kW, the EMS early trigger of 764.4 kW, and the maximum hybrid support of 60 kW, the operating range is divided into four conditions:

$$P_{\text{load,max,avoid}} = P_{\text{PMS,threshold}} + P_{\text{hybrid,max}} \quad \dots(1)$$

$$P_{\text{load,max,avoid}} = 824,4 + 60 = 884,4 \text{ kW}$$

1. Normal Load Region ($P_{\text{Load}} \leq 764,4 \text{ kW}$). The system does not require peak-support discharge because the load remains below the EMS early trigger.
2. Early Support Region ($764,4 \text{ kW} < P_{\text{Load}} \leq 824,4 \text{ kW}$). The EMS begins providing incremental support to establish a margin before the PMS threshold is reached. In this region, the PMS does not yet require a standby DG based on the load criterion; therefore, the hybrid system's primary function is to maintain the margin and reduce the load on the DG.
3. Standby-Call Avoidance Region ($824,4 \text{ kW} < P_{\text{Load}} < 884,4 \text{ kW}$). Without hybrid support, the load has exceeded the PMS Load Dependent Start threshold. However, if sufficient hybrid power is available, the residual DG load can be reduced to below 824.4 kW, thereby avoiding a standby-DG call based on the load criterion.
4. Partial Peak-Shaving Region ($P_{\text{Load}} \geq 884,4 \text{ kW}$ or when available hybrid power is insufficient). Under these conditions, even with the maximum nominal support of 60 kW, the residual DG load may remain at or above the PMS threshold. The PMS retains final authority to operate the standby DG in accordance with the existing operating philosophy.

2.2 Research Procedures and Observation Parameters

The research implementation procedure is structured to evaluate the techno-ecological performance of the hybrid microgrid system without compromising the safety parameters of the offshore installation. The stages of the research procedure are outlined as follows:

1. Load Analysis and Existing Data Audit Phase: Extraction of historical daily electrical load profile data for FSO Gagak Rimang, obtained from the refinery's PMS data records dated August 13, 2025. The evaluated transient data includes an average hotel mode load fluctuation of 703 kW (77% DG loading) and the duration characteristics of instantaneous load spikes.

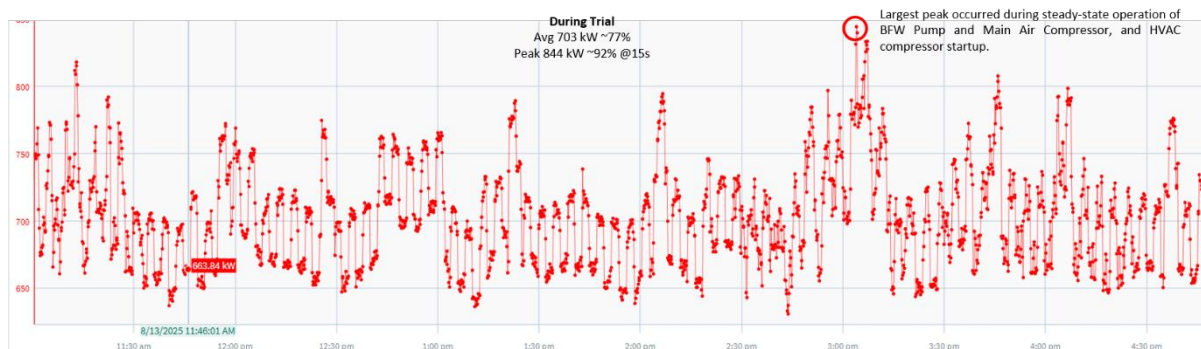


Figure 2. FSO Load: Single DG Test Run

2. Numerical Simulation Phase for New and Renewable Energy (NRE) Production: PVsyst V8.0.21 software is used to model a 57.6 kWp Solar PV array based on solar irradiation data from offshore Tuban to project the system's Performance Ratio (PR). Simultaneously, wind mechanical potential is evaluated using HOMER Pro software based on the annual average wind speed distribution at the FSO mooring site (2.15 m/s to 7.80 m/s) to estimate daily energy production from 25 VAWT system units.
3. EMS Rule-Based Control Logic Design Phase: Developing a rule-based control algorithm embedded in the hybrid inverter controller. This algorithm maps six power flow scenarios based on the dynamic interaction between the FSO's total load level and the battery's State of Charge (SoC).

4. AC Network Protection Adequacy Test and Validation Phase: Conducting mathematical verification of short-circuit interrupting capacity, protection coordination for Molded Case Circuit Breakers (MCCBs), and isolation transformer apparent power ratings, as well as developing a hybrid fail-safe interlock matrix for the vessel's Safety Instrumented System (SIS).

To maintain the integrity and reliability of the operating system, a battery discharge command to support the peak support function is permitted to execute only if the entire matrix of safety permissive conditions listed below is fully met at the system level (fail-safe response) in Table 1:

Table 1. Operational Safety Protection Limit Matrix (Permissive Requirements)

Operation Verification Parameters	Set Point / Safety Limit	Sensor Method / Data Source	Failure Action/Response (Fail-Safe)
Grid Healthy Status	440 VAC ($\pm 5\%$), 60 Hz ($\pm 2\%$)	PO PCC-1 Bus Voltage and Frequency	The inverter triggers a restart inhibit and isolates itself from the AC grid.
ESD Safety Link	Status: Normal / Contact Closed	Hardwired Interlock of Safety Instrumented System (SIS)	The Normally-Open contact opens automatically, disconnecting the hybrid main contactor in less than 100 ms.
Reverse Power Status	Return Power to DG: 0 kW (Zero Export)	POI Metering and Reverse Power Protection Relay (ANSI 32) at the DG	The EMS controller instantly reduces power injection (anti-motoring protection).
Battery State of Charge	Routine Operating Range: 50% to 95% SoC	Battery Monitoring/Balancer Module via inverter communication data	If SoC $\leq 50\%$, the system triggers the discharge inhibit function.
Battery Voltage Limit	Critical Voltage Limit: > 43.2 VDC	Hybrid Inverter Main DC Bus Voltage Sensor	If the bus voltage is ≤ 43.2 VDC (cell ≤ 1.8 V), a hardware hard cutoff occurs.
Equipment Temperature	Battery Room AC Temperature: 20°C - 25°C	Battery Storage Room RTD Sensor / Thermocouple	The hybrid inverter activates the output power reduction function (thermal derating).
Communication Link	Heartbeat Signal: Active	Modbus TCP/IP Master Inverter to Kongsberg PMS	The hybrid inverter enters Standby Safe Mode due to a communication failure.

2.3 Materials and Tools

This research on energy management analysis and optimization utilizes key equipment materials for an offshore hybrid microgrid system designed to withstand the corrosion and salinity of the marine service environment. Detailed technical specifications regarding the research materials and equipment are presented systematically in Table 2.

Table 2. Detailed Specifications of Research Hardware and Software

Category	Equipment Component Name	Manufacturer Brand / Model	Key Technical Specification Parameters	Specific Functions within the Network
Renewable Energy Power Plant	Solar Panels (Solar PV)	Canadian Solar CS7L-640TB-AG	Capacity: 640 Wp, Monocrystalline Bifacial type, Efficiency: 22.6%, Voc: 43.7 V, Imp: 17.54 A	Converting solar photon radiant energy into DC power on the deck area.
	Vertical Axis Wind Turbine (VAWT)	REXCO RC-600SV Helical	Capacity: 25 units $\times$ 600 W (Total 15 kW), 3-phase AC Voltage, Cut-in: 3.5 m/s, Rated Wind: 12 m/s	Converts the kinetic energy of offshore wind into multi-directional AC/DC electrical power.
Power Conversion	Paralleled Hybrid Inverter	Deye SUN-20K-SG05LP3-EU-SM2	Capacity: 3 units $\times$ 20 kW (Total 60 kW / 66 kVA), Efficiency 97.6%, Mode: Grid-Following	Bidirectional power conversion (AC/DC), energy management, and bus synchronization unit.
	Wind Micro-Inverter	Hoymiles MIT-4000-8T	Capacity: 4 units $\times$ 4 kVA (Total 16 kVA), Output 230/400 VAC, 3-Phase, 60	Converting the DC power resulting from the rectification of wind

Category	Equipment Component Name	Manufacturer Brand / Model	Key Technical Specification Parameters	Specific Functions within the Network
Storage	Rectifier Bridge	MDS Series Three-Phase Module	Hz, IP67 Protection Maximum Current: 60 A, Maximum Working Voltage (V _{rrm}): 1,600 V, Metal Casing Type: VRLA OPzV, 2 V / 420 Ah, 168 cells, Configuration: 24S7P (Voltage: 48 VDC nominal, Energy: 141.12 kWh)	turbine clusters into hybrid 400 V AC. Rectifying the inductive AC output of the VAWT generator into direct current (DC) voltage.
	Battery	Ritar	Capacity: 80 kVA, 60 Hz, Voltage: 400 VAC / 440 VAC, Vector Group: Dyn5, Winding: Copper	Primary energy buffer for absorbing peak load surge transients.
	Isolation Transformer	B&D Dry-Type Transformer	Windows 11-based computer system, equipped with the Meteornorm 8.2 meteorological database.	Provides galvanic isolation and voltage matching with the 440V FSO bus.
Distribution & Analysis	Simulation Software	PVsyst V8.0.21 & HOMER Pro		Simulating PR performance, shading losses, and daily power flow modeling.

2.3.1 Important Notes on Low-Voltage Battery Configuration Structure (Low-Voltage BESS Configuration)

Based on the hardware design specifications required by the hybrid inverter vendor (the Deye SUN-20K-SG05LP3, which has a low battery input operating voltage range of 40 V to 60 VDC), an array of 168 VRLA OPzV battery cells—each rated at 2 V / 420 Ah—must not be connected in a single series string to form a high-voltage 24S7P system (48 VDC, 2,940 Ah, 141.12 kWh). The physical configuration implemented in the field utilizes a Low-Voltage 24S7P architecture, with the mathematical calculations detailed as follows:

1. Series Configuration per String (24S): Each battery string is formed by a combination of twenty-four 2V battery cells connected in series. This configuration results in a nominal voltage of: String Nominal Voltage: 24 cells in series × 2 VDC = 48 VDC. Under full-charge conditions (float target with a voltage of 2.25 V per cell), the maximum DC bus voltage is: Maximum Bus Voltage = 24 cells × 2.25 V = 54.0 VDC. This value proves to be safe and falls within the inverter's input operating range (40–60 VDC).
2. Parallel String Configuration (7P): To achieve the target total energy storage capacity, seven of these series-connected circuit strings are connected in parallel within a Battery Combiner Box. This configuration yields a total rated current capacity of: Total Current Capacity = 7 parallel strings × 420 Ah = 2,940 Ah.
3. Calculation of System Energy Accumulation (E_{total}): The total accumulated nominal DC electrical energy storage capacity within the air-conditioned battery room is:

$$E_{\text{Total}} = \text{System Nominal Voltage} \times \text{Total Current Capacity} \quad \dots(2)$$

$$E_{\text{Total}} = 48 \text{ VDC} \times 2,940 \text{ Ah} = 141.120 \text{ Wh} = 141.12 \text{ kWh.}$$

2.3.2 Limitation of Battery Storage Device Functions

Within the scope of this study, the 141.12 kWh battery bank storage system functions strictly as a buffer for renewable energy intermittency, a stabilizer for load-side power transients (energy buffer), and a provider of limited short-term peak load support. This battery storage unit operates purely as a supportive instrument and is neither designed nor configured—nor does it possess the technical capability—to replace or assume the functions of: a) Existing HFO diesel generator main power generation unit; b) Emergency Diesel Generator (EDG) system for the vessel's emergency power supply; c) Uninterruptible Power Supply (UPS) system for critical navigation instruments; d) Full automation control via the Power Management System (PMS); and e) Automated load shedding procedure for electrical protection. The battery lacks the independent emergency supply capability to energize the grid when the FSO main bus is in a total shutdown condition (blackout/dead bus).

2.4 Data Analysis

The stages of data processing and technical evaluation for energy management engineering are carried out through three primary quantitative computational analysis approaches:

2.4.1 Calculation Formula for Diesel Generator Residual Load

The performance effectiveness of the partial peak-shaving function is evaluated using the residual load power balance formulation for the secondary circuit, as follows:

$$P_{\text{residual DG}}(t) = P_{\text{Load Spike FSO}}(t) - P_{\text{Hybrid Support}}(t) \quad \dots(3)$$

The magnitude of hybrid support is not assumed to be a constant 60 kW. The EMS first calculates the peak support requirement based on the difference between the total load and the early trigger. Subsequently, the dispatchable power is constrained by the maximum inverter output and the actual available power from PV, wind, and battery sources. With this approach, a battery-only output of approximately 43.1 kW does not directly limit the total hybrid support when PV or wind power is available.

$$P_{\text{EMS,req}}(t) = \max[0, P_{\text{Load}}(t) - P_{\text{EMS,trig}}] \quad \dots(4)$$

$$P_{\text{available}}(t) = P_{\text{PV}}(t) + P_{\text{Wind}}(t) + P_{\text{Batt,available}}(t) \quad \dots(5)$$

$$P_{\text{Hybrid,support}}(t) = \min[P_{\text{EMS,req}}(t), P_{\text{INV,max}}, P_{\text{available}}(t)] \quad \dots(6)$$

$$P_{\text{DG,residual}}(t) = P_{\text{Load}}(t) - P_{\text{Hybrid,support}}(t) \quad \dots(7)$$

The calculated residual load power value ($P_{\text{residual DG}}$) is then directly compared digitally against the PMS auto-start threshold value (824.4 kW). The result of this comparison is used to map the probability of reducing HFO generator start-stop cycles.

2.4.2 Analysis of Battery Charging Cycle Efficiency and C-Rate Limits

To preserve the service life of the OPzV lead-acid battery components in accordance with IEEE 485 standards, the hybrid controller limits the charging power supplied by the diesel generator to a maximum value (charging clamp limit) of 25 kW during low-load phases. Data analysis evaluates the nominal charging current (I_{charge}) and the battery charging C-rate using the following technical equations:

$$I_{\text{charge}} = P_{\text{charge}} / \text{DC System Voltage} \quad \dots(8)$$

$$I_{\text{charge}} = 25.000 \text{ W} / 48 \text{ VDC} = 520,8 \text{ A}$$

In a 24S7P configuration, the battery bank consists of seven parallel strings, each with a capacity of 420 Ah. Assuming even current distribution, a total charging current of 520.8 A equates to approximately 74.4 A per string. The C-rate is then calculated based on the 420 Ah capacity per string, yielding approximately 0.177 C (or 0.18 C). The final allowable charging current value must be compared against the battery vendor's recommendations rather than being determined solely by general standards.

$$I_{\text{charge,total}} = 25.000 / 48 = 520,8 \text{ A}$$

$$I_{\text{string}} = 520,8 / 7 = 74,4 \text{ A/string}$$

$$\text{C-rate} = 74,4 / 420 = 0,177 \text{ C} \approx 0,18 \text{ C}$$

The resulting C-rate of approximately 0.18 C is subsequently compared against the allowable charging current and charging recommendations provided by the battery vendor. If the IEEE 485 standard is cited, its application is limited to serving as a reference for the battery sizing/capacity methodology—consistent with the standard's scope rather than as a direct source for the charging C-rate range, unless a specific clause explicitly supports that value.

2.4.3 Modeling of Transformer Impedance Vector Integration

The harmonic characteristics resulting from current injection by three hybrid inverter units operating in grid-following mode were analyzed at the MCC-1 AC bus interconnection. The configuration of an 80 kVA isolation transformer with a Dyn5 vector group (Delta on the 400 V inverter primary side; Star with accessible neutral on the 440 V MCC-1 secondary side) was mathematically analyzed to verify its capability to provide an isolation circulation path for zero-sequence (triplen) harmonic components. This ensures that the integration of the hybrid system does not introduce voltage harmonic distortion (Total Harmonic Distortion – THD) fluctuations that could interfere with the synchronization sensitivity of the existing protection relays at FSO Gagak Rimang.

3. RESULTS AND DISCUSSION

3.1. Research Result

3.1.1 FSO Load Characteristics and DG Operating Limits

An evaluation of the FSO Gagak Rimang electrical system indicates that the main distribution network operates at 440 VAC (3-phase, 3-wire, 60 Hz) using an ungrounded interconnection system. Primary power generation is provided by a conventional diesel generator (DG) with a rated power capacity of 916 kW. Visual documentation of the floating facility where the load profile data was collected is presented in Figure 3.



Figure 3. FSO Gagak Rimang

Based on historical operational data, the electrical load profile of this floating facility is highly dynamic and frequently experiences momentary surges (load spikes) due to the operation of large motors. To mitigate this, the existing Power Management System (PMS) controls the operation of the backup generator using Load Dependent Start logic. The auto-start threshold for the backup generator within the PMS is permanently fixed at 90% of a single diesel generator's (DG) rated power—specifically, 824.4 kW. The settings and internal parameters of this PMS protection circuit are absolute and remained unmodified throughout this study.

To maximize active power penetration from the renewable hybrid system, the Energy Management System (EMS) algorithm is configured to request peak power support precisely when the DG load reaches a reference point of 764 kW (equivalent to 83.45% of the generator's rated capacity). This 764 kW parameter serves solely as a trigger for the local inverter controller to inject additional energy from the battery storage system. Consequently, the Diesel Generator and PMS retain primary control authority over electrical busbar stability, while the three hybrid inverter units act as sources of limited support. The process for determining the hybrid system component capacities was structured according to the steps outlined in Figure 4.

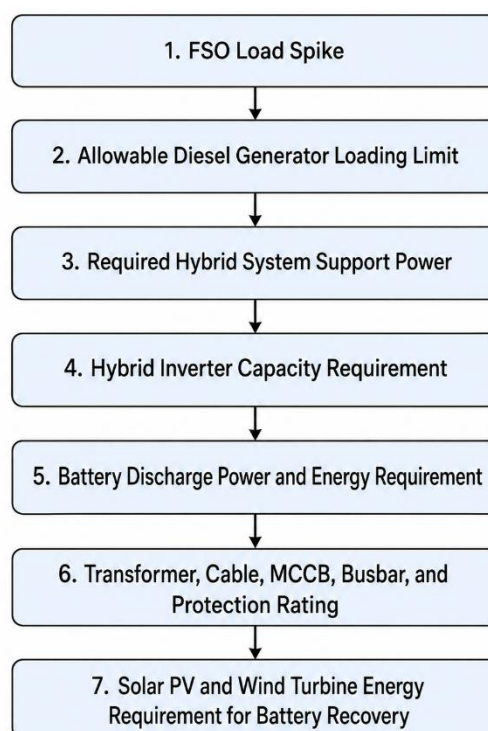


Figure 4. Hybrid System Sizing Flow

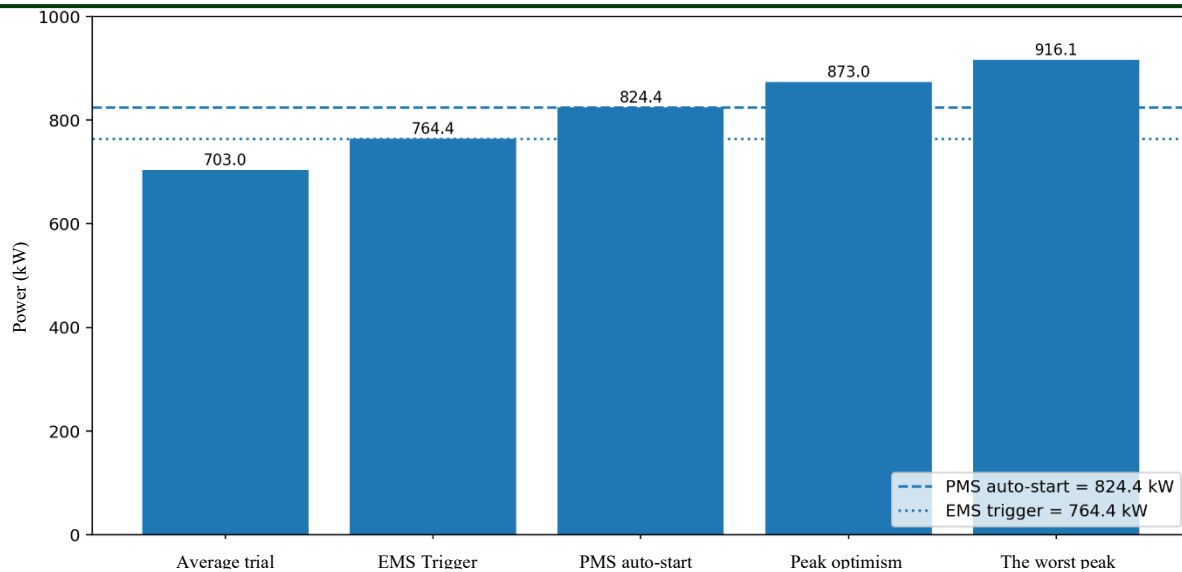


Figure 5. Relationship between EMS set point, PMS threshold, and peak load.

Figure 5 shows that 764.4 kW serves as an early trigger to secure a 60 kW nominal margin before the PMS threshold of 824.4 kW is reached. When actual available power drops to 43.1 kW during battery-only operation, the equivalent trigger rises according to the calculation: $P_{\text{trigger}} = P_{\text{threshold PMS}} - P_{\text{battery-only}} = 824.4 - 43.1 = 781.3$ kW. In implementation, the control system must utilize an available-power estimator to avoid assuming 60 kW of support when PV/wind resources are unavailable or battery current limits have been reached.

Based on the PMS threshold of 824.4 kW and a maximum hybrid support of 60 kW, the theoretical maximum total load that can be reduced to exactly the PMS threshold is 884.4 kW. Therefore, the critical range for the standby-DG avoidance function is when the total load exceeds 824.4 kW but remains below 884.4 kW, provided sufficient hybrid power is available. For instance, at a total load of 850 kW with full hybrid support of 60 kW, the residual DG load becomes 790 kW, placing it below the PMS threshold. At a total load of 880 kW, the residual DG load becomes 820 kW, which is still below the threshold. Conversely, during an extreme spike of 916.1 kW, the residual DG load becomes 856.1 kW, remaining above the PMS threshold. These results demonstrate that the effectiveness of peak support should be evaluated in terms of an operating envelope rather than based solely on a single extreme spike scenario.

Table 3. Operating Envelope of Hybrid Support for Standby-DG Avoidance Based on PMS Threshold

Total Load (kW)	Hybrid Support (kW)	Residual DG (kW)	Interpretation
760	0	760	Normal; peak support OFF
800	35,6	764,4	Early support; residual below PMS threshold
824,4	60 max	764,4	The threshold has not been exceeded following the support level.
850	60	790	Standby DG activation can be avoided based on load criteria.
880	60	820	Still below the PMS threshold.
884,4	60	824,4	Theoretical boundary
916,1	60	856,1	Partial peak shaving; the PMS can trigger the standby diesel generator.

3.1.2 Renewable Energy Production

a. Solar Panel (PV) System

Simulation results using PVsyst V8.0.21 software indicate significant energy production potential at the Tuban offshore refinery site. The 57.6 kWp PV system generates DC electrical energy, which is subsequently converted to AC by an inverter to supply essential loads while simultaneously recharging the batteries. Details regarding monthly performance and the system's average Performance Ratio (PR) of 73.54% are presented in Figure 6.

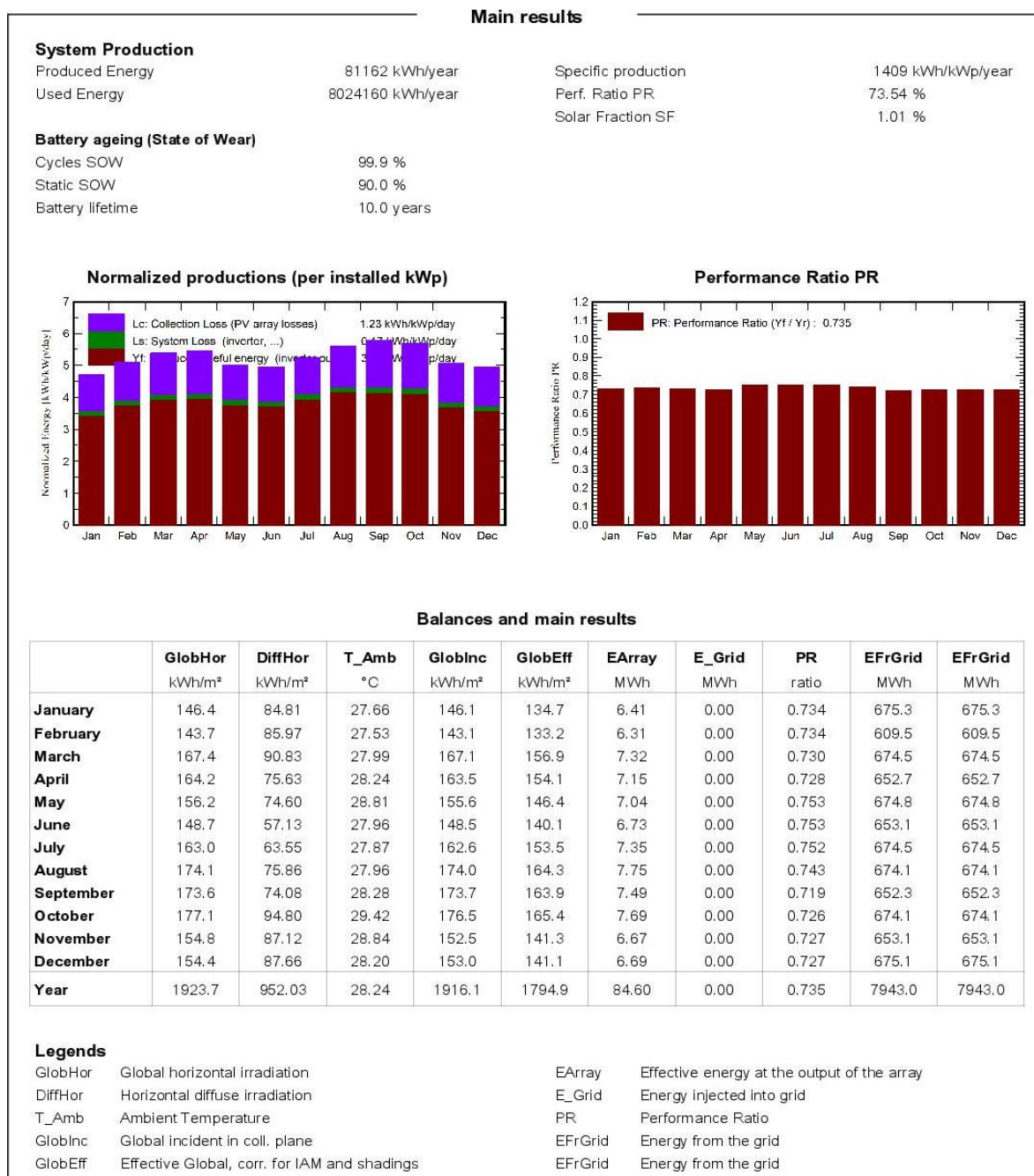


Figure 6. PVsyst Simulation Report

The PVsyst results used as the final basis differ from some of the initial inputs in the HOMER model. Consequently, the annual PV production output is determined based on the latest report, while the HOMER fuel-saving result is treated as a comparative estimate until the model is re-run using the final PV time-series data.

Table 4. Summary of Latest PVsyst Results

Parameter	Grade	Interpretation
Installed PV capacity	57,6 kWp (90 × 640 Wp)	Limited by the deck area and inverter configuration.
AC inverter capacity	60 kW	DC/AC ratio = 0,96
Annual energy	81.162 kWh/year	The latest basis for energy evaluation
Specific yield	1.409 kWh/kWp/year	Location-specific/model-specific production
Performance Ratio	73,54%	Includes losses due to temperature, shading, cabling, and conversion.
String configuration	6 string; 90 modules in total	The final allocation per MPPT follows the approved PVsyst/SLD.

The specific yield and Performance Ratio values in Table 4 are derived from the ratio of the system's annual energy output to the installed capacity and the ideal energy under Standard Test Conditions (STC), as formulated below:

$$\text{Specific Yield} = \text{Annual Energy} \div \text{Installed Capacity} = 81.162 \text{ kWh} \div 57,6 \text{ kWp} \approx 1.409 \text{ kWh/kWp/year}$$

$$\text{PR} = \text{Actual Energy (AC)} \div \text{Ideal Energy (STC)} \times 100\% \approx 73,54\%$$

b. Vertical Axis Wind Turbine (VAWT) System

Estimated energy production from the Vertical Axis Wind Turbine (VAWT) indicates a potential power contribution that complements the PV system, particularly during periods of low solar radiation. The actual power output of the VAWT depends on actual wind speed, the turbine power curve, generator/converter efficiency, and operating limits. Therefore, the 15 kW installed capacity is treated as the nameplate capacity and is not assumed to represent the continuous output modeled in Figure 7.

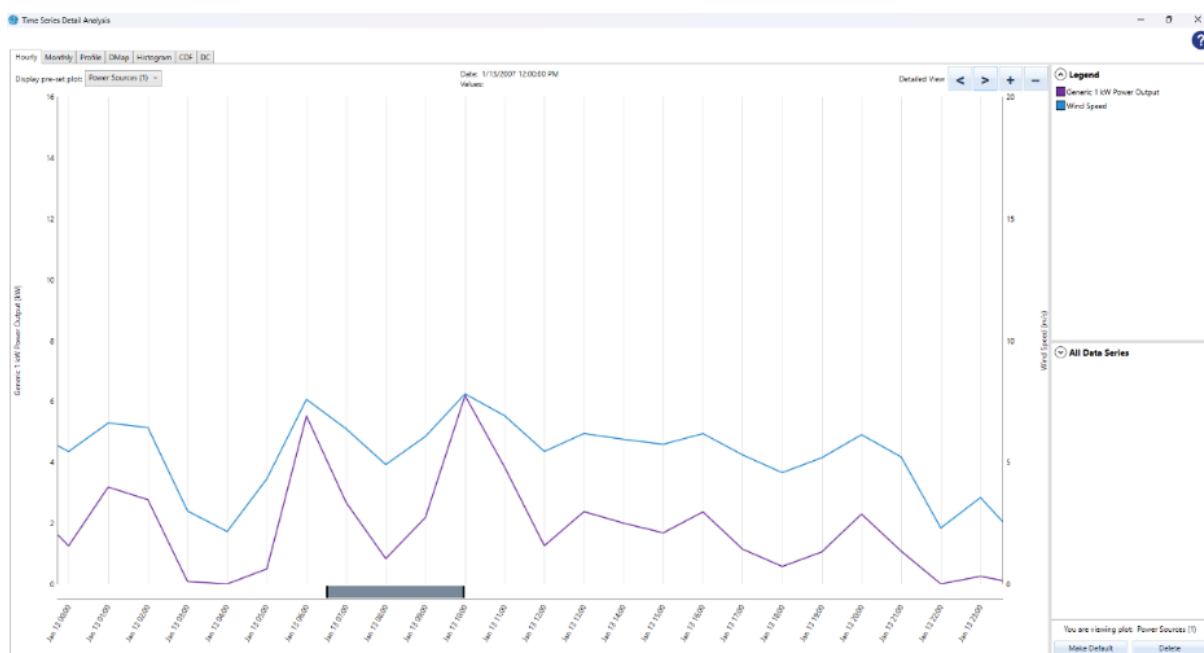


Figure 7. Wind Speed and Wind Turbine Power Output

The entire 600 W wind turbine unit is integrated into the local hybrid bus via a three-phase bridge rectifier circuit and an AC micro-inverter, with the electrical interconnection flowchart presented in Figure 8.

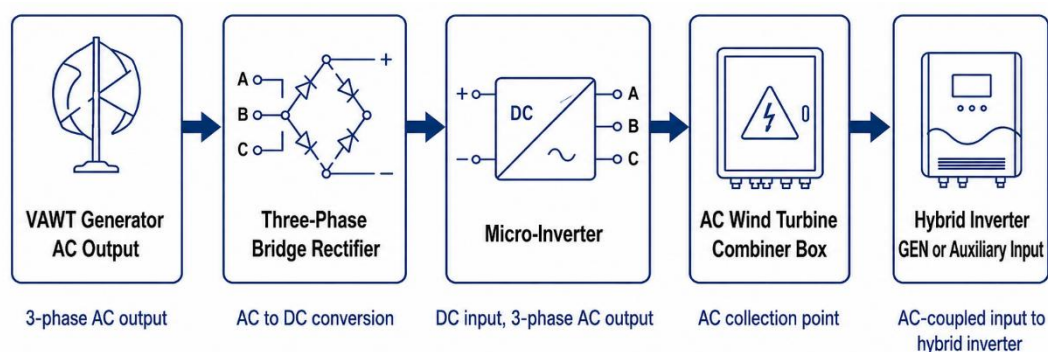


Figure 8. Wind Turbine Integration Flowchart

3.1.3 Comparison of HOMER Pro Scenarios

The HOMER model compares four scenarios to isolate the effects of renewable energy and batteries on fuel consumption. All scenarios are reported with zero unmet load and zero capacity shortage. Case 1 yields the best results in the initial model, whereas Case 2 demonstrates that overly conservative battery dispatch or inappropriate charging strategies can increase fuel consumption.

Table 5. Comparison of HOMER Pro Simulation Results

Scenario	Fuel (L/year)	Difference vs Baseline	Percentage	Conclusion
Case 0 - DG only	2.015.573	-	-	Baseline
Case 1 - DG+PV+WT+ Battery	1.982.484	Save 33,089 L	1,64%	Initial recommendation
Case 2 - Conservative Battery	2.040.951	Add 25,378 L	-1,26%	Not recommended
Case 3 - DG+PV+WT Battery not included	1.991.796	Save 23.777 L	1,18%	Benefits of renewables without storage

The fuel savings percentage in Table 5 is calculated relative to the baseline Case 0 (DG only) using the formula: % Savings = [(Fuel Baseline – Fuel Case) ÷ Fuel Baseline] × 100%. For example, for Case 1: % Savings = [(2.015.573 – 1.982.484) ÷ 2.015.573] × 100% = (33.089 ÷ 2.015.573) × 100% ≈ 1,64%.

Note: the figures above are the results of comparative models from simulation documents. For final research figures, HOMER needs to be re-run using PVsyst output of 81,162 kWh/year, validated DG fuel curve, final dispatch strategy, and load profile with adequate time resolution.

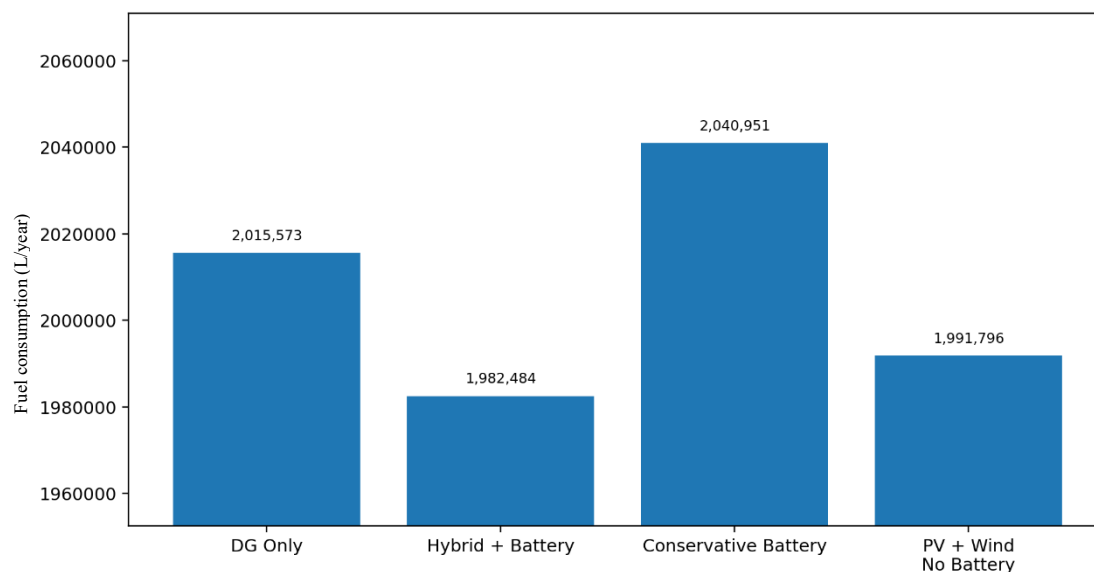


Figure 9. Comparison of fuel consumption across HOMER scenarios

3.1.4 Peak Shaving Performance and Equipment Adequacy

Component capacity verification indicates that three Deye hybrid inverter units, with a combined capacity of 60 kW, are sufficient to support partial peak shaving functionality. To ensure the reliability of the devices and interconnection circuits, an acceptance criteria verification matrix for key components was developed, referencing Table 6.

Table 6. Equipment Adequacy Matrix

Key Components	Verification Parameters	Status	Notes
Hybrid Inverter	Total Capacity 60 kW	Adequate	Supports peak shaving up to 60 kW.
Battery Bank	Discharge Current and Capacity	Adequate	Capable of handling short-duration load spikes.
Solar Panels (PV)	String Voltage & DC Current	Adequate	Compatible with inverter input
Wind Turbine	AC/DC Integration	Adequate	Decoupling the hybrid system from the main FSO network.
Isolation Transformer	Power and Insulation Ratings	Adequate	Decoupling the hybrid system from the main FSO network.
Protection Device	Breaking Capacity	Adequate	Coordination with the existing system is maintained.

3.1.5 Analysis of Battery Adequacy and Inverter Current Limits

The nominal energy of the battery bank is calculated based on a 24S7P configuration. An operating window of 50%–95% yields an operational energy of 63.50 kWh. Although this energy is sufficient for several

short-duration spikes, instantaneous power capability is limited by the maximum DC current of the three inverters.

$$E_{\text{nom}} = 48 \text{ V} \times 2.940 \text{ Ah} = 141,12 \text{ kWh}$$

$$E_{\text{operational}} = (0,95 - 0,50) \times 141,12 = 63,50 \text{ kWh}$$

$$I_{\text{required}, 60\text{kW}} = 60.000 / (43,2 \times 0,95) = 1.462 \text{ A}$$

$$P_{\text{batt,max}} = 1.050 \times 43,2 \times 0,95 \approx 43,1 \text{ kW}$$

$$E_{\text{spike}} = 60 \text{ kW} \times 0,25 \text{ h} = 15 \text{ kWh}; \Delta\text{SoC} \approx 15/141,12 = 10,6\%$$

$$\text{SoC}_{\text{min,start}} = 50\% + 10,6\% \approx 61\%$$

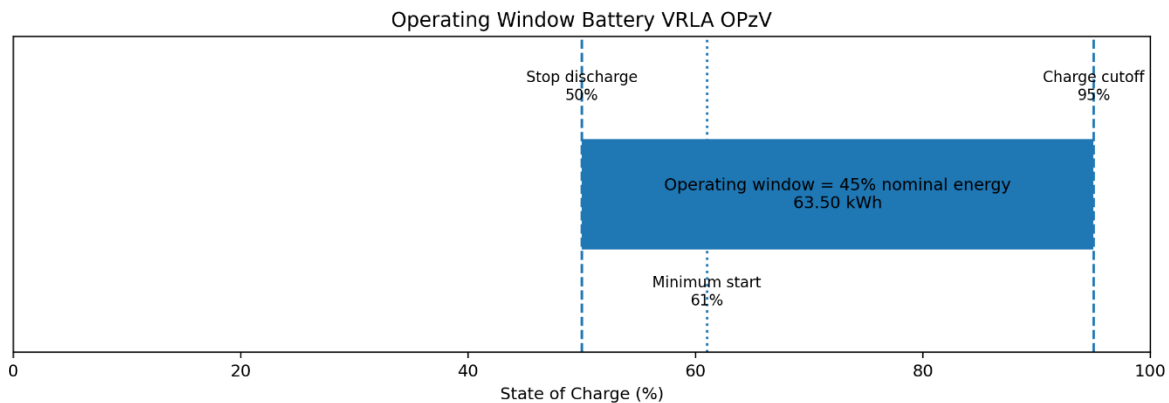


Figure 10. SoC Operating Window and Minimum SoC to Initiate Peak Support

These results alter the interpretation of adequacy: the battery has sufficient energy for short-term support, but it cannot be assumed capable of continuously supplying 60 kW under minimum conditions without exceeding the inverter's current limit. Delivering 60 kW is only feasible when PV or wind contributions reduce the power load required from the battery, or if the vendor approves a higher current rating. At the beginning of life, the theoretical operational energy is equivalent to approximately four 15 kWh discharge events; at the end of life—or when applying a conservative margin—the safe capacity is lower.

3.1.6 Analysis of Isolation Transformer Adequacy

The 80 kVA isolation transformer accommodates the inverter's nominal apparent power rating of 66 kVA at a loading of approximately 82.5%. However, if vendor recommendations limit reverse power to 80% of the transformer's rating, the permissible capacity becomes 64 kVA. For an active power transfer of 60 kW, the minimum required power factor is $60/64 = 0.9375$. Therefore, the EMS must maintain a power factor of approximately 0.94 or better and limit power output if reactive power demand increases. The transformer serves the functions of voltage matching and galvanic isolation; it does not regulate frequency or primary-side voltage.

3.2. Discussion

The integration of a hybrid PV-wind-battery system on the FSO Gagak Rimang offers strategic benefits for energy management.

3.2.1 Optimization of Load Management and Reduction of DG Auto-Starts

The integrated hybrid system has a maximum continuous AC output capacity of 60 kW. When the vessel's total load is detected rising above the EMS trigger threshold (764 kW), the battery storage system begins discharging to shave the load peaks. The success in avoiding the need to start backup generators depends heavily on the final residual load borne by the main generator. The residual load is calculated using the following power balance formula:

$$P_{\text{residual DG}} = P_{\text{Load Spike FSO}} - P_{\text{Hybrid Support}} \quad \dots(9)$$

In the event of an extreme transient load spike recorded in the refinery's historical data—reaching a peak value of 916.1 kW—the hybrid EMS control system will command a maximum auxiliary power injection of 60 kW. The evaluation of the power balance calculation is as follows:

$$P_{\text{residual DG}} = 916,1 \text{ kW} - 60 \text{ kW} = 856,1 \text{ kW}$$

Based on these calculations, the residual load experienced by the single generator is 856.1 kW. Since this residual load of 856.1 kW exceeds the PMS auto-start safety threshold (824.4 kW), the hybrid system is

classified as operating in a partial peak-shaving mode. In this scenario, the PMS automation unit retains final decision-making authority and proceeds to execute the startup and synchronization commands for the backup generator as normal, thereby ensuring operational reliability and preventing a total blackout.

3.2.2 Analysis of Discharge Inhibit Conditions and Fail-Safe Responses (Inhibit and Fail-Safe Scenarios)

The energy management system is designed with the safety of offshore operations as the top priority. Consequently, the battery bank's power discharge function for peak support is not permitted to operate continuously. In the event of an operational anomaly within the hybrid circuit or the FSO's internal network, the EMS controller immediately blocks or suspends battery support (discharge inhibit/fail-safe standby). Under such disconnection conditions, the handling of the remaining electrical load reverts entirely to the main diesel generator units and the PMS.

The matrix of hybrid system operational outcomes and fail-safe actions is outlined in the following critical scenarios:

- **Low Battery Charge Limit Scenario (SoC $\leq 50\%$):** When the battery bank's charge level drops to the routine operational lower limit—specifically, a State of Charge (SoC) of 50% or less—the EMS controller automatically activates the discharge inhibit function to protect the chemical composition of the VRLA OPzV battery cells from the risk of deep discharge.
- **Grid Loss / Dead Bus Scenario:** Three hybrid inverter units are configured to operate exclusively in grid-following mode. In the event of a main generation system failure resulting in a total loss of voltage on the 440 VAC busbar (dead bus), the inverters automatically perform a fail-safe disconnection to prevent the risk of islanding and are prohibited from independently energizing the de-energized busbar.
- **Ship Emergency Shutdown (ESD) System Activation Scenario:** If an ESD Level 1 or Level 2 signal activates due to a refinery emergency, the main contactor relay in the hybrid interconnection panel will immediately open mechanically (normally-open fail-safe) via a hardwired path within less than 100 milliseconds to cut off all power flow.
- **Abnormal Voltage/Frequency Scenario:** If the voltage parameters of the MCC-1 POI bus fluctuate beyond the $\pm 5\%$ tolerance limit—specifically, $440 \text{ V} \times (1 \pm 0.05)$, resulting in a range of 418 V–462 V—or if the frequency shifts beyond the $\pm 2\%$ limit—specifically, $60 \text{ Hz} \times (1 \pm 0.02)$, resulting in a range of 58.8 Hz–61.2 Hz—the inverter's internal protection unit will isolate its own circuit.
- **Reverse Power Risk Scenario:** To prevent the risk of motoring on active diesel generators, zero export logic in the EMS will monitor POI metering and cut the inverter duty cycle instantly to maintain reverse power flow at 0 kW.
- **Inverter Fault and Battery Abnormality Scenario:** If the monitoring module detects a battery cell temperature spike exceeding the critical threshold of 25 degrees Celsius, or if an internal hardware modulation failure (inverter fault) occurs, the controller circuit will immediately trigger a common alarm status and switch to safe mode.
- **Communication Line Failure Scenario (Communication Failure and Restart Inhibit):** If Modbus TCP/IP data communication between the hybrid controller and the PMS is interrupted, the loss of the heartbeat signal will force the inverter to stop operating. In all such failure scenarios, the hybrid system will lock into a "Restart Inhibit" state (preventing automatic restart) and can only be restarted following manual authorization (reset/authorization) by an operator once normal conditions are restored.

3.2.3 Renewable Energy Contribution and System Stability Analysis

Integrating hybrid power electronic devices into the ungrounded Gagak Rimang FSO distribution network requires special attention to power quality aspects. Based on the AC distribution system design, the physical interconnection is facilitated by an 80 kVA dry-type isolation transformer with a Dyn5 vector group configuration. Within this electrical structure, the primary technical functions of the isolation transformer are outlined as follows:

- **Voltage Matching:** Transforming the AC output voltage from the hybrid inverter (400 VAC) to the operating voltage of the ship's distribution busbar (440 VAC).
- **Galvanic Isolation:** Provides physical magnetic circuit separation between the renewable hybrid generation domain and the main FSO electrical grid domain. Through a Delta (D) winding configuration on the primary side, the transformer confines zero-sequence harmonic currents (triplen harmonics) to circulate solely within its internal windings, thereby preventing the injection of waveform distortion into the FSO circuit.

It must be emphasized as a fundamental engineering principle that an isolation transformer is neither a primary frequency stabilizer nor a primary voltage stabilizer. The operational dynamic stability of this offshore electrical system remains entirely dependent on the performance of the generator engine governor system, the diesel generator (DG) excitation system, the existing Power Management System (PMS) automation controls,

the MCCB protection coordination, and the operation of inverter components within their permissible operating limits [37], [38].

The findings of this study have important practical and methodological implications for the integration of hybrid renewable energy systems into constrained power systems. The results demonstrate that a hybrid system with a relatively small capacity compared with the main diesel generator can still provide meaningful operational support when its power is strategically dispatched around the PMS threshold. Rather than being designed to supply the overall load, the hybrid system can be utilized as a supplementary resource to manage short-duration load excursions and maintain generator loading within an acceptable operating range [12], [39]. This finding highlights the importance of aligning hybrid-system operation with the characteristics of the existing generation-control strategy rather than evaluating its value solely based on its installed capacity.

The results also indicate that EMS design should distinguish between nominal equipment ratings and actual dispatchable power. Although the hybrid inverters have a combined nominal capacity of 60 kW, the battery-only output is conservatively limited to approximately 43.1 kW under the minimum operating voltage and maximum allowable discharge-current conditions considered in this study. Consequently, the available peak-support capacity cannot be determined solely from the inverter rating but must account for renewable-energy availability and battery operating constraints [40]. Incorporating these constraints into the EMS is important to prevent excessive battery discharge, operation beyond allowable current or voltage limits, and overestimation of the system's peak-shaving capability. From a system-integration perspective, the findings support the application of hierarchical control for hybrid-system retrofit projects in which an established PMS already governs the primary generation system. Retaining PMS authority minimizes interference with existing generator protection and operating logic, while the EMS operates as a supplementary permissive layer for peak support. This architecture provides a practical pathway for integrating renewable generation and battery storage without requiring fundamental modifications to the existing PMS philosophy, thereby supporting safer and more traceable implementation [41], [42].

The proposed framework also provides a quantitative basis for determining the hybrid capacity required to address specific load excursions. The required effective hybrid support can be estimated from the difference between the expected peak load and the PMS threshold. For the observed 916.1 kW load spike, at least 91.7 kW of effective support would be required to reduce the residual generator load to 824.4 kW. Because the present hybrid system has a maximum inverter capacity of 60 kW, it cannot completely prevent the PMS threshold from being exceeded during this extreme event. The implication is that the current configuration should be regarded as a partial peak-shaving system, while higher hybrid capacity would be required if the operational objective were to maintain the residual generator load below the PMS threshold for larger load excursions.

The novelty of this study lies in the development of a constraint-based hierarchical Energy Management System (EMS) that enables peak shaving while preserving the existing Power Management System (PMS) as the primary authority in an isolated power system. Rather than replacing or modifying the established generator-control logic, the proposed framework positions the EMS as a supplementary control layer that provides early peak support according to the operating condition and actual capability of the hybrid system [41], [43]. This approach addresses the practical challenge of integrating renewable energy and battery storage into an existing power-system architecture where generator protection, PMS authority, and operational reliability must remain unchanged.

The proposed EMS integrates the PMS load-dependent start threshold with an independently defined EMS dispatch trigger, allowing hybrid power to be dispatched before the generator reaches the PMS threshold. The dispatch decision is constrained by the actual available power from PV and wind generation, inverter capacity, battery State of Charge (SoC), minimum battery voltage, allowable discharge current, and system-level fail-safe conditions. Consequently, the proposed framework does not assume that the nominal inverter capacity is continuously available but dynamically limits hybrid support according to the most restrictive operating constraint [44], [45]. This provides a direct link between load-spike characteristics, component-level capability, and generator-control requirements.

The distinctive contribution of the proposed framework is therefore its PMS-preserving and constraint-based control architecture for short-duration peak shaving. The framework establishes a quantitative relationship between the PMS threshold, EMS trigger, available hybrid power, and residual generator load, enabling the system to distinguish between operating conditions in which complete peak shaving is feasible and those in which only partial peak shaving can be achieved [46], [47]. In the studied configuration, this approach demonstrates that a nominal 60 kW hybrid capacity can theoretically extend the PMS-compatible load boundary from 824.4 kW to 884.4 kW, while the battery-constrained condition limits battery-only support to approximately 43.1 kW. These relationships provide an engineering basis for evaluating the adequacy of hybrid capacity before implementation.

Thus, the contribution of this study extends beyond the integration of PV, wind, and battery resources. It provides a transparent and practically implementable EMS framework that coordinates limited hybrid resources with an existing PMS without bypassing its authority. The framework is particularly applicable to

industrial, offshore, remote, and other isolated power systems where renewable-energy integration must be achieved while maintaining established generation-control, protection, and fail-safe requirements.

Despite the technical insights provided by this study, several limitations should be considered when interpreting the results and their applicability. The study is based on an analytical case study and numerical simulation rather than a full-scale field demonstration. Consequently, the results demonstrate the technical feasibility of the proposed constraint-based hierarchical EMS but do not yet verify the dynamic interaction among the actual inverter, battery, PMS, and diesel-generator controls during real load transients. Further validation through hardware-in-the-loop, controller-in-the-loop, or real-time digital simulation is therefore recommended to evaluate the EMS response under representative operating and disturbance conditions, including load steps, inverter faults, communication loss, low SoC, abnormal voltage and frequency, emergency shutdown, reverse-power conditions, and simultaneous reductions in renewable generation [48], [49]. The availability of representative operational data is another limitation. The analysis primarily uses recorded load characteristics from August 13, 2025, which may not fully represent the variability of different operating modes, maintenance activities, seasonal conditions, or abnormal events. A longer-duration, higher-resolution dataset should therefore be collected to characterize the statistical distribution of load-spike magnitude, duration, frequency, and recurrence. Such data would enable the EMS trigger and peak-shaving boundaries to be evaluated using probabilistic or event-based analysis rather than relying predominantly on deterministic operating scenarios.

The renewable-energy contribution also introduces uncertainty into the actual hybrid support capability. The 15 kW wind capacity represents the installed nameplate rating rather than continuously available power, while PV generation varies with solar irradiation, temperature, shading, and conversion efficiency. Therefore, the 60 kW hybrid output should be interpreted as a conditional maximum rather than a continuously dispatchable capacity [3], [50]. Future implementation should incorporate real-time measurements of PV and wind generation, battery SoC, battery voltage and current, inverter operating status and temperature, and equipment availability into the available-power estimator. This would enable the EMS to dynamically determine the actual dispatchable support rather than relying on nominal equipment ratings. The battery model also represents a further limitation because battery aging, temperature-dependent capacity, internal resistance, degradation, and end-of-life performance were not fully incorporated into the present analysis [51], [52]. The estimated peak-support capability and number of support events should consequently be regarded as nominal beginning-of-life estimates. Future studies should incorporate battery degradation models and temperature-dependent electrical characteristics to determine how peak-shaving performance changes over the battery lifetime. This is particularly relevant for assessing the long-term operational and economic feasibility of repeated short-duration discharge events.

The fuel-saving analysis obtained from HOMER should likewise be interpreted with caution. The current results provide a comparative estimate rather than a fully validated prediction because the model requires re-evaluation using the final PVsyst production time series, validated diesel-generator fuel-consumption characteristics, final EMS dispatch logic, and consistent simulation time resolution. Future analysis should integrate these finalized inputs and evaluate not only fuel consumption but also generator operating hours, standby-generator starts, renewable-energy utilization, battery cycling, and associated carbon emissions. This would provide a more comprehensive assessment of the operational benefits of the proposed EMS.

Another limitation concerns the validation of the proposed protection and fail-safe mechanisms. Although the EMS framework incorporates grid-health, emergency-shutdown, reverse-power, battery, temperature, and communication permissives, these functions have not been experimentally validated under all possible fault and abnormal operating conditions. Before field implementation, detailed engineering verification should therefore be conducted, including inverter and battery vendor approval, transformer and MCCB coordination, reverse-power protection testing, harmonic assessment, communication-failure testing, emergency-shutdown verification, and integration testing with the existing PMS. These activities are essential to confirm that supplementary hybrid-power dispatch does not compromise the reliability, selectivity, or safety of the primary power system [46], [53].

The present study also provides an opportunity for methodological extension. The proposed rule-based EMS offers a transparent and relatively straightforward approach for implementation in an existing PMS-controlled system; however, its performance has not been systematically compared with alternative EMS approaches. Future research could compare the proposed strategy with optimization-based, fuzzy-logic, model-predictive, or adaptive EMS methods under identical operating scenarios. Such comparisons should consider not only fuel savings and renewable-energy utilization but also response time, computational requirements, explainability, battery degradation, protection compatibility, robustness to uncertainty, and operational acceptance.

4. CONCLUSION

Based on the harmonization of reference documents, load profile analysis, energy production simulation, evaluation of energy management strategies, and verification of equipment adequacy, the study concludes that a rule-based control energy management strategy is feasible for implementation on the FSO Gagak Rimang. It serves as a limited energy-support system designed to reduce diesel generator (DG) loading, utilize renewable energy, assist in battery State of Charge (SoC) recovery, and potentially lower fuel consumption and CO₂ emissions. This feasibility is contingent upon the technical verification—prior to system operation—of power capacity limits, battery operating windows, EMS–PMS coordination, protection functions, and all fail-safe requirements. The study’s primary contribution lies not merely in the addition of renewable capacity, but in the formulation of a hierarchical and constraint-based EMS. This framework integrates load spikes during Single DG Mode, PMS thresholds, available hybrid power, battery power-energy constraints, residual DG load, and fail-safe permissives into a unified decision-making structure, all without altering the existing PMS operating philosophy.

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AUTHOR CONTRIBUTIONS

Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review & Editing, Visualization, Supervision, Project Administration, Funding Acquisition, SR.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

INFORMED CONSENT STATEMENT

Prior to participation, each subject was provided with a detailed explanation of the study’s objectives, procedures, potential risks, and benefits. All participants voluntarily agreed to participate and signed a written informed consent form. All images in this article have been authorized and are the property of the authors.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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