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An Intelligent Energy Management Strategy for Grid-Connected and Islanded Microgrids

P. Prathyusha, MTech
Assistant Professor,
Electrical and Electronics Engineering
Sanskrithi School of Engineering,
Puttaparthi (A.P)

M. Malleswari
Electrical and Electronics Engineering,
Sanskrithi School of Engineering
Puttaparthi (A.P)

K. Sai Keerthana
Electrical and Electronics Engineering
Sanskrithi School of Engineering
Puttaparthi (A.P)

N. Prathyusha
Electrical and Electronics Engineering,
Sanskrithi School of Engineering,
Puttaparthi (A.P).

E. Mahesh,
Electrical and Electronics Engineering
Sanskrithi School of Engineering,
Puttaparthi (A.P).

G. TejaVardhan
Electrical and Electronics Engineering
Sanskrithi School of Engineering,
Puttaparthi (A.P).

***Abstract*— A microgrid is a localized energy system that integrates distributed generation sources, energy storage units, and loads, capable of operating in both grid-connected and islanded modes. With the growing penetration of renewable energy sources such as solar photovoltaic and wind power, efficient and coordinated energy management has become critical for ensuring reliability, economic viability, and sustainability. This paper presents the design and implementation of an intelligent Energy Management System (EMS) for optimal microgrid operation. The proposed EMS continuously monitors renewable generation, load demand, and battery state of charge, and dynamically regulates power flow among renewable sources, energy storage systems, and the utility grid. Priority is assigned to maximizing renewable energy utilization to minimize fuel consumption and carbon emissions while maintaining system stability and power quality. Surplus energy during periods of high renewable generation is stored and subsequently utilized during peak load conditions or low renewable availability. The EMS enables seamless transitions between grid-connected and islanded operating modes, thereby ensuring uninterrupted power supply under varying operating conditions. Simulation results validate the effectiveness of the proposed strategy, demonstrating enhanced energy efficiency, reduced operational costs, and improved reliability of the microgrid.**

***Keywords*— Microgrid, Energy Management System, Renewable Integration, Energy Storage, Power Quality.**

I. INTRODUCTION

The rapid transformation of conventional power systems into decentralized and low-carbon energy networks has accelerated the deployment of microgrids as a viable solution for future electricity infrastructure. A microgrid is a localized energy system that integrates distributed energy resources (DERs), energy storage systems, and local loads, and is capable of operating either in grid-connected mode or autonomously in islanded mode. The increasing penetration of renewable energy sources (RES) such as solar photovoltaic (PV) and wind power is primarily driven by growing concerns over fossil-fuel depletion, greenhouse gas emissions, climate change, and the need for sustainable development. While RES significantly reduce carbon emissions and operating costs, their intermittent and stochastic nature introduces new challenges in maintaining power balance, system stability, and reliable supply.

Consequently, microgrids have gained attention due to their ability to enhance system resilience, improve power quality, reduce transmission losses, and support high renewable penetration at the distribution level.In addition to environmental benefits, microgrids offer strong economic and operational advantages. By locally utilizing renewable generation and energy storage, microgrids can reduce dependency on the utility grid, mitigate peak demand charges, and improve energy cost efficiency. Furthermore, the capability of islanded operation enhances resilience against grid disturbances, natural disasters, and faults, ensuring uninterrupted power supply to critical loads such as hospitals, data centres, and industrial facilities. However, the coexistence of multiple energy sources, bidirectional power flows, and varying load demands makes microgrid operation inherently complex. Without proper coordination, excessive grid imports, renewable curtailment, battery overuse, and power quality degradation may occur, thereby offsetting the intended benefits of microgrids. To address these challenges, an Energy Management System (EMS) plays a pivotal role in the optimal operation of microgrids. The EMS acts as the supervisory control layer that continuously monitors generation, load demand, battery state of charge (SOC), electricity tariffs, and grid availability, and makes intelligent decisions regarding power dispatch. Effective coordination among PV, wind, battery energy storage systems (BESS), and the utility grid is essential to maximize renewable utilization, minimize operational costs, and ensure reliable power supply. In grid-connected mode, the EMS must determine optimal import and export schedules while responding to time-of-use tariffs and reducing peak grid dependency. In islanded mode, the EMS must maintain power balance using limited local resources while respecting battery SOC and power constraints. Therefore, a robust EMS is critical for enabling seamless and reliable microgrid operation under varying operating conditions. Despite significant advancements in microgrid control, several operational challenges remain. Renewable generation is inherently intermittent and uncertain, leading to frequent power imbalances between supply and demand. Battery energy storage, while providing flexibility, is constrained by SOC limits, charging/discharging power ratings, efficiency losses, and degradation concerns. Improper battery dispatch can reduce battery lifetime and compromise system reliability. Moreover, transitions between grid-connected and islanded modes introduce additional complexity, as sudden loss of grid support requires fast and coordinated control actions to avoid load shedding or instability. Many existing approaches rely on centralized optimization or forecast-dependent techniques, which may be computationally intensive or unsuitable for real-time implementation. Consequently, there is a growing need for intelligent, practical, and constraintaware EMS strategies that can operate effectively under realworld uncertainties. In this context, intelligent EMS strategies based on SOC-aware and priority-based dispatch logic have emerged as promising solutions. Such strategies emphasize the use of renewable energy as the primary power source, supported by battery storage and the grid when necessary. By incorporating SOC thresholds and operating mode awareness, the EMS can prevent overcharging and deep discharging of batteries while ensuring sufficient reserve capacity for islanded operation. Grid import minimization during high-tariff periods further enhances economic performance, while controlled export during surplus conditions improves renewable utilization. Compared to purely optimization-based methods, intelligent rule-based EMS approaches offer simplicity, transparency, and robustness, making them well suited for real-time microgrid control and practical deployment. This paper presents an intelligent energy management strategy for grid-connected and islanded microgrids that explicitly addresses renewable intermittency, battery SOC constraints, and mode switching requirements. The proposed EMS dynamically regulates power flow among PV, wind, BESS, and the utility grid with the objective of maximizing renewable energy utilization, minimizing grid import and operational cost, and ensuring reliable supply under both operating modes. The strategy prioritizes renewable generation, employs SOC-aware battery dispatch, and enables seamless transition between grid-connected and islanded operation without violating system constraints. The effectiveness of the proposed EMS is validated using MATLAB-based simulations under realistic load, renewable generation, and tariff scenarios. Quantitative performance metrics, including energy cost, renewable utilization, SOC trajectory, grid power exchange, and islanding performance, are analyzed through comprehensive result plots.

The main contributions of this work are summarized as follows. An intelligent energy management system is developed to support dual-mode microgrid operation, enabling seamless and reliable transitions between gridconnected and islanded modes under varying operating conditions. The proposed strategy incorporates an SOCaware battery dispatch mechanism that prioritizes renewable energy utilization while minimizing grid power import, thereby protecting battery health, reducing operational energy costs, and enhancing overall system reliability. In addition, the effectiveness of the proposed EMS is comprehensively validated using MATLAB-based simulations, where detailed quantitative performance metrics and result plots demonstrate notable improvements in energy efficiency, cost savings, and resilient microgrid operation. Overall, the presented EMS framework offers a structured and practical solution that provides a reliable foundation for future microgrid deployments with high renewable energy penetration and serves as a scalable approach for smart distribution systems.

II. MICROGRID SYSTEM DESCRIPTION

The microgrid considered in this study comprises a hybrid renewable energy architecture integrating solar photovoltaic (PV) generation, wind energy conversion systems, a battery energy storage system (BESS), local loads, and the utility grid through a point of common coupling (PCC) breaker. This configuration represents a typical low-voltage distributionlevel microgrid designed to support high renewable energy penetration while ensuring operational flexibility and supply reliability. The PV system primarily contributes daytime generation based on solar irradiance availability, whereas the wind generation unit provides complementary power that may extend into non-solar hours, thereby enhancing overall renewable availability. The BESS acts as a key balancing component by absorbing surplus renewable energy during low-demand or high-generation periods and supplying power during renewable deficits or peak load conditions. The PCC breaker enables controlled connection and disconnection between the microgrid and the utility grid, facilitating both grid-connected and islanded operation. To enable effective supervisory control and decision-making, the Energy Management System continuously monitors a set of critical measurement signals within the microgrid. These include the PV power output P_{pv} , wind power output P_w, total load demand P_L, battery state of charge (SOC), and grid power exchange P_g. The available generation signals P_{pv} and P_w provide real-time information on available clean energy and energy supply. While the load demand P_L reflects the instantaneous consumption requirements of connected loads, the SOC serves as a vital indicator of the battery's available energy capacity and directly influences charging and discharging decisions to prevent overcharging or deep discharging. The grid power signal P_g indicates the magnitude and direction of power exchange with the utility grid, where positive values represent grid import and negative values indicate grid export. Collectively, these measurements form the core input set for the proposed EMS and allow coordinated power flow control across all microgrid components. The microgrid operates under two distinct modes depending on grid availability and operational requirements. In the grid-connected mode, the PCC breaker remains closed, allowing bidirectional power exchange between the microgrid and the utility grid. In this mode, the EMS prioritizes renewable energy utilization to supply local loads, while surplus renewable energy may be used to charge the BESS or exported to the grid based on SOC limits and tariff conditions. During periods of renewable shortfall or high load demand, the EMS intelligently schedules battery discharge and grid import to maintain power balance and minimize operational cost. This mode provides economic benefits through peak shaving, tariff-based optimization, and improved renewable integration.

In the islanded mode, the PCC breaker is opened, electrically isolating the microgrid from the utility grid. Under this condition, the microgrid must rely entirely on local renewable sources and the BESS to meet load demand. The EMS plays a critical role in ensuring uninterrupted supply by dynamically dispatching the battery while strictly enforcing SOC and power constraints. If renewable generation and battery capacity are insufficient to fully satisfy load demand, optional load shedding strategies may be employed to preserve system stability and prioritize critical loads. The ability to transition smoothly between grid-connected and islanded modes without violating system constraints highlights the resilience and reliability of the proposed microgrid configuration. Overall, this microgrid system architecture, combined with comprehensive measurement feedback and clearly defined operating modes, provides a robust platform for implementing and evaluating the proposed intelligent energy management strategy under realistic operating scenarios.

III. MATHEMATICAL MODELING

This section presents the mathematical formulation of the hybrid microgrid and the proposed Energy Management System (EMS). The modeling focuses on renewable generation, power balance, battery dynamics, and the operational objective, which collectively govern the decisionmaking process of the EMS under both grid-connected and islanded modes. The total renewable power available within the microgrid at any instant is obtained as the sum of the solar

PV and wind generation, expressed as

$$P_{ren}(t) = P_{pv}(t) + P_w(t) \qquad (1)$$

This equation represents the aggregate clean energy available to supply local loads, charge the battery, or export power to the utility grid. The fundamental power balance of the microgrid is governed by

$$P_{ren}(t) + P_b(t) + P_g(t) = P_L(t) \qquad (2)$$

where $P_b(t)$ denotes the battery power and $P_g(t)$ represents the grid power exchange. A positive battery power (P_{b} > 0) corresponds to battery discharging, while a negative value (P_{b} < 0) indicates battery charging. Similarly, positive grid power denotes grid import and negative grid power denotes grid export. This equation ensures that the instantaneous load demand is always met by a coordinated combination of renewable generation, battery support, and grid interaction, subject to operating mode constraints. The solar PV power output is modeled using a simplified efficiency-based formulation given by

$$P_{pv}(t) = \eta_{pv} A_{pv} G(t) \qquad (3)$$

where η_{pv} is the PV conversion efficiency, A_{pv} is the effective PV array area, and $G(t)$ is the incident solar irradiance. This model captures the direct dependence of PV power on environmental conditions and system parameters and is suitable for system-level EMS studies. The wind turbine output power is represented using a standard piecewise model based on wind speed v, expressed as

$P_w(v) =$

$0,$ $amp;\, v$ $lt;\, v_{ci}$ or $v \geq v_{co}$

$\{P_r\,(v$ $amp;\, v_{ci} \leq v$ $lt;\, v_r$ (4)

$v_r - - v v_{ci} ci)3,$ $amp;\, v_r \leq v$ $lt;\, v_{co}$

$P_r,$

where v_{ci}, v_r, and v_{co} denote the cut-in, rated, and cut-out wind speeds, respectively, and P_r is the rated turbine power. This formulation reflects the nonlinear relationship between wind speed and generated power and allows realistic modeling of wind energy availability. The battery energy storage system dynamics are characterized through the state of charge (SOC) evolution, given by

$$SOC(t+1) = SOC(t) + \frac{\eta_c P_{ch}(t) - P_{dis}\,\eta_d(t)}{E_{bat}}\Delta t \qquad (5)$$

where $P_{ch}(t)$ and $P_{dis}(t)$ are the battery charging and discharging powers, η_c and η_d are the charging and discharging efficiencies, E_{bat} is the rated battery energy capacity, and Δt is the sampling interval. This equation ensures accurate tracking of the battery energy level over time and enables SOC-aware dispatch decisions within the EMS. To protect the battery and ensure safe operation, the battery power is constrained by

$$-P_{cmaxh} \leq P_b(t) \leq P_{dismax} \qquad (6)$$

where $P_{c}{}^{max}{}_{h}$ and $P_{dis}{}^{max}$ represent the maximum allowable charging and discharging power limits, respectively. These constraints prevent excessive current flow and mitigate battery degradation. The operational objective of the EMS is to minimize the total operating cost over the scheduling horizon, formulated as

$$J = \sum_{Tt=1}(c_{buy}(t)P_{g+}(t) - c_{sell}(t)P_{g-}(t) + c_{deg}|P_b(t)|)\,\Delta t \qquad (7)$$

where $c_{buy}(t)$ and $c_{sell}(t)$ are the grid electricity purchase and selling prices, respectively, and c_{deg} represents a battery degradation cost coefficient. The terms $P_g{}^{+} = \max(P_g, 0)$ and $P_g{}^{-} = \max(-P_g, 0)$ denote grid import and export power.

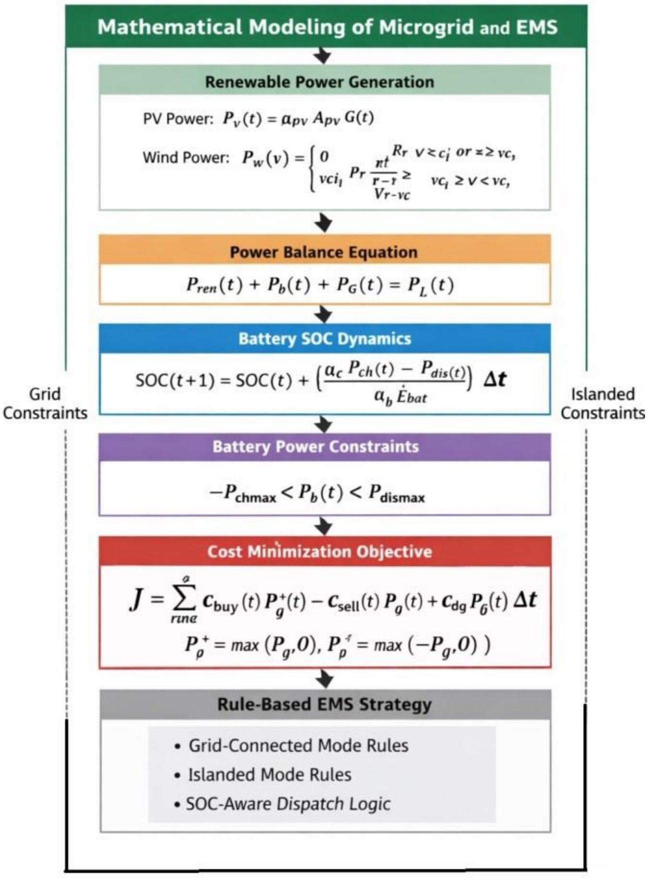


Fig. 1. Mathematical Modelling of Microgrid

This cost function simultaneously accounts for energy trading costs and battery usage, encouraging economical and sustainable operation. Rather than solving a computationally intensive optimization problem, the proposed EMS employs a rule-based intelligent strategy to achieve a near-optimal reduction of the objective function JJJ. The EMS enforces the power balance equation, SOC dynamics, and battery power limits while incorporating operating mode constraints associated with grid-connected and islanded conditions. This approach provides a practical and robust solution for realtime microgrid energy management while maintaining performance close to optimal solutions.

IV. PROPOSED INTELLIGENT EMS STRATEGY

The proposed intelligent Energy Management System (EMS) is designed to coordinate power flow among renewable energy sources, battery energy storage, local loads, and the utility grid while ensuring reliable and economical microgrid operation under both grid-connected and islanded modes. The EMS operates in a supervisory control layer and executes a rule-based decision-making process using real-time system measurements and predefined operational constraints. This strategy emphasizes practicality, low computational complexity, and robustness, making it suitable for real-time microgrid applications. The EMS continuously acquires key input signals, including the solar PV power output P_{pv}, wind power output P_w, total load demand P_L, battery state of charge (SOC), and the grid status (grid-connected or islanded). Using these inputs, the total renewable power is first computed as $P_{ren} = P_{pv} + P_w$. The EMS then evaluates the power balance by comparing renewable generation with load demand to determine whether the system is operating under a power surplus or power deficit condition. This surplus/deficit assessment forms the basis for all subsequent dispatch decisions. When the microgrid operates in gridconnected mode, the EMS allows bidirectional power exchange with the utility grid and follows a priority-based dispatch logic. Renewable energy sources are always given the highest priority to supply local loads, ensuring maximum utilization of clean energy and reduced dependence on the grid. If the available renewable generation exceeds the load demand, the EMS checks the battery SOC. When the SOC is below its maximum allowable limit (SOC < SOC_{max}), the surplus renewable power is used to charge the battery. This strategy not only stores excess energy for future use but also reduces renewable curtailment. If the battery is already fully charged ($SOC \geq SOC_{max}$), the remaining surplus energy is exported to the utility grid, enabling economic benefits through energy trading. During periods of renewable energy deficit in grid-connected mode, the EMS determines whether the shortfall should be supplied by the battery or the grid. Battery discharge is prioritized during high-tariff periods or peak load intervals, provided that the SOC remains above the minimum threshold (SOC > SOC_{min}). This SOC-aware discharge strategy minimizes expensive grid imports, supports peak shaving, and preserves battery health. If battery discharge is not permitted due to low SOC or operating constraints, the remaining deficit is met through grid import, thereby maintaining uninterrupted power supply. In islanded mode, the PCC breaker is opened and the microgrid is electrically isolated from the utility grid. Under this condition, grid import and export are strictly prohibited, and the EMS must rely solely on local renewable generation and the battery energy storage system. As in grid-connected mode, renewable energy is used first to supply the load. If renewable generation exceeds load demand, the EMS charges the battery within its allowable SOC limits. Any surplus renewable power that cannot be absorbed by the battery is curtailed to maintain system stability. When a power deficit occurs in islanded mode, the EMS dispatches the battery to supply the deficit, provided that the SOC remains above the minimum limit. The battery power is constrained by its maximum discharge capability to ensure safe operation. If the deficit persists due to insufficient renewable generation and low battery SOC, the EMS may activate an optional load shedding mechanism. In such cases, non-critical or lowpriority loads can be disconnected to preserve supply to critical loads and prevent system collapse. This feature enhances microgrid resilience during prolonged islanding conditions or extreme operating scenarios.

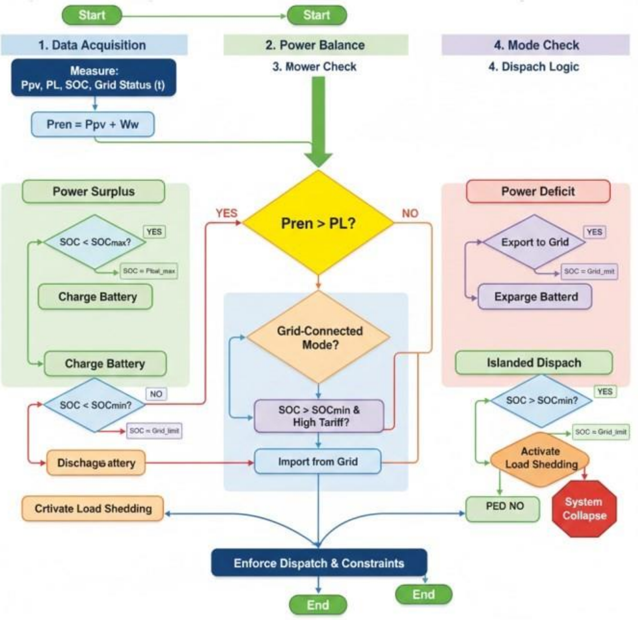


Fig. 2. Proposed Method

The overall EMS logic can be represented using a flowchart consisting of the following sequential steps: measurement acquisition, renewable power calculation, surplus/deficit evaluation, operating mode identification, rule-based dispatch decisions, and constraint enforcement. Although the detailed flowchart is presented separately, the described strategy clearly demonstrates how intelligent rule-based control enables near-optimal energy management while satisfying system constraints. By integrating SOC-aware battery dispatch, renewable prioritization, and modedependent control actions, the proposed EMS ensures efficient, reliable, and resilient microgrid operation across diverse operating conditions.

V. SIMULATION SETUP

The proposed intelligent Energy Management System (EMS) is evaluated using a MATLAB-based time-domain simulation conducted over a 24-hour operating horizon. The simulation time step is fixed at $\Delta t = 15$ minutes, resulting in 96 discrete intervals per day. This resolution is sufficient to capture variations in renewable generation, load demand, and battery state of charge (SOC) while maintaining computational efficiency suitable for EMS-level studies. At each time step, the EMS processes real-time measurements and executes rule-based dispatch decisions in accordance with system constraints and operating mode. Realistic profiles are used to represent the variability of renewable resources and load demand. The solar photovoltaic (PV) system is driven by a typical daily irradiance profile, characterized by zero generation during nighttime, a gradual increase during morning hours, peak output around midday, and a decline toward evening. Wind generation is modeled using a time-varying wind speed profile with moderate fluctuations to reflect practical operating conditions and to complement PV generation during non-solar periods. The load demand profile follows a typical residential-commercial pattern, exhibiting morning and evening peaks, thereby creating both surplus and deficit operating conditions throughout the day. The battery energy storage system (BESS) is modeled using an energy-based SOC formulation.

The battery is characterized by its rated energy capacity E_{bat}, predefined minimum and maximum SOC limits, maximum charging and discharging power limits, and charging/discharging efficiencies η_c and η_d . These constraints ensure safe operation, prevent excessive battery degradation, and enable SOC-aware dispatch decisions within the EMS. Battery charging is prioritized during renewable surplus periods, while discharging is scheduled during renewable deficits or high-tariff intervals. A time-ofuse (TOU) tariff model is incorporated to assess the economic effectiveness of the EMS in grid-connected mode. Electricity prices vary across off-peak, mid-peak, and peak periods, encouraging grid import minimization during high-cost intervals. To validate dual-mode operation, an intentional islanding event is introduced between 18:00 and 20:00 hours, during which the microgrid operates autonomously without grid support. During islanding, the EMS relies solely on renewable sources and the BESS to meet load demand, with optional load shedding applied if necessary.

Table I. Simulation Parameters of the Microgrid System

Parameter	**Value / Description**
Simulation horizon	24 hours
Time step, (\Delta t)	15 minutes
PV system input	Daily irradiance profile
Wind system input	Time-varying wind speed profile
Load profile	Residential–commercial with peak demand
Battery capacity, (E_{bat})	40 kWh
SOC limits	20% – 90%
Max charge/discharge power	±10 kW
Battery efficiencies	(η_c = 0.95, η_d = 0.95)
Tariff model	Time-of-use pricing
Islanding interval	18:00 – 20:00

V. RESULTS AND DISCUSSIONS

This fig.3 shows the time-varying PV output over the 24h horizon. The PV power follows the expected daytime irradiance pattern, reaching a maximum around midday and dropping to zero during nighttime. The profile confirms that solar generation mainly supports mid-day load and battery charging.

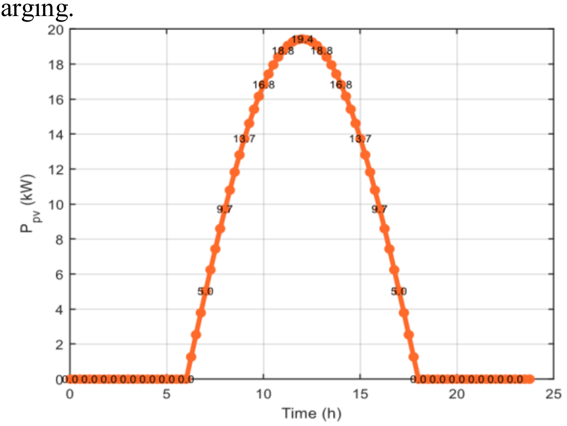


Fig. 3 PV power profile

The wind power output exhibits stochastic variation across the day due to changing wind speed. Unlike PV, wind generation can contribute during evening and night hours, providing complementary support to reduce renewable deficit periods and improve overall renewable availability as shown in Fig. 4.

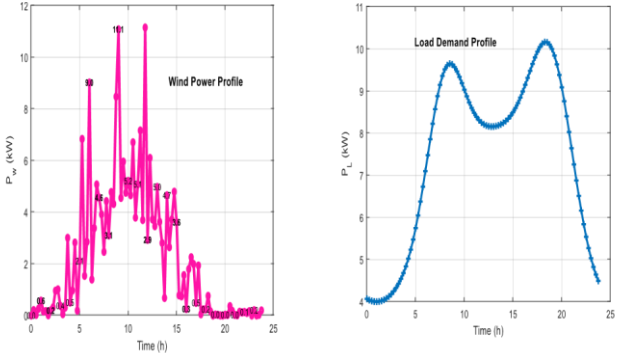


Fig. 4 Wind power and load demand profile

The load curve represents a typical daily demand pattern with notable morning and evening peaks. These peak intervals create high-stress operating conditions where battery discharge and grid support become critical to maintain power balance and reduce cost.

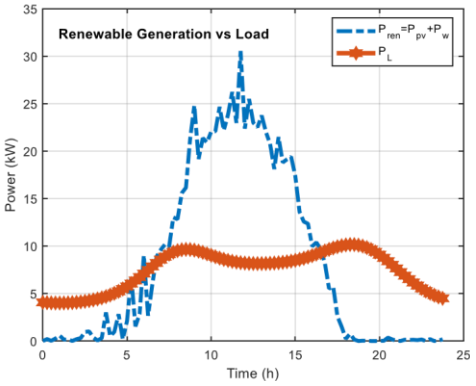
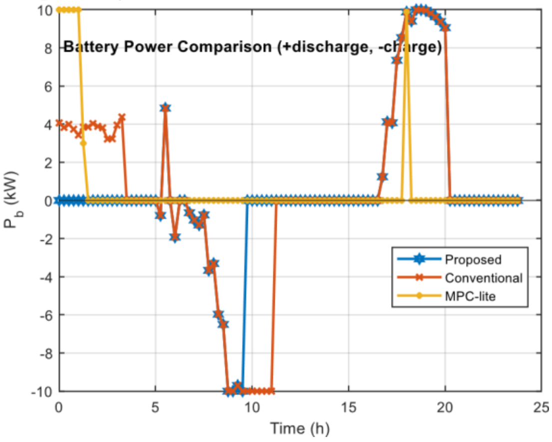


Fig. 4. Renewable Generation vs. Load Comparison

This Fig.4 compares total renewable power P_{ren} with the load demand P_L . Surplus intervals ($P_{ren}>P_L$) indicate opportunities for battery charging or grid export, while deficit intervals ($P_{ren}< P_L$) require battery discharge and/or grid import depending on SOC and mode constraints.



Battery power illustrates EMS-controlled charge/discharge behavior, where negative power indicates charging and positive power indicates discharging. The EMS charges the battery during renewable surplus and discharges it during renewable deficits and high-tariff/peak periods, demonstrating SOC-aware dispatch and peak-shaving capability as shown in Fig. 5.

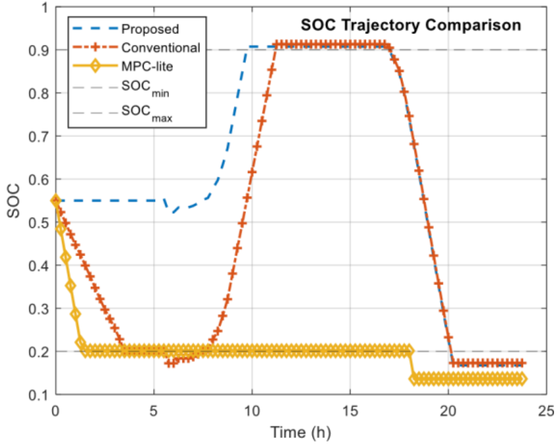


Fig. 6. SOC Trajectory

The Fig. 6 SOC plot shows how battery energy evolves throughout the day under EMS decisions. SOC remains within the defined limits [SOC_{min}, SOC_{max}] , validating constraint enforcement and safe battery operation. The SOC trend also reflects charging during surplus renewable periods and discharging during peak demand or islanding.

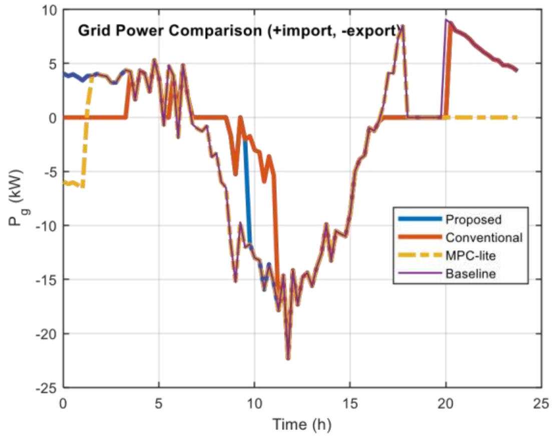


Fig. 7. Grid Power Exchange (Import/Export)

Grid power indicates bidirectional interaction with the utility grid in grid-connected mode, where positive values represent import and negative values represent export as shown in Fig. 7. The EMS reduces imports during high-tariff periods through battery support and enables export only when renewables exceed load and storage capacity.

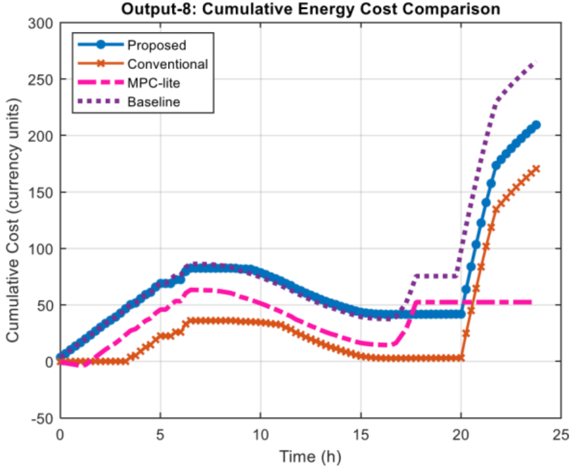


Fig. 8. Energy Cost Over Time / Total Cost Comparison

This figure presents cumulative operating cost over time, typically comparing the proposed EMS with a baseline or recent technique. The proposed strategy yields a lower cumulative cost by shifting energy usage via storage, reducing peak-tariff imports, and improving renewable utilization, thereby demonstrating economic effectiveness. Curtailment power represents unused renewable energy when generation exceeds load and battery charging limits. The renewable utilization percentage highlights how effectively the EMS converts available renewable generation into useful energy (load supply + charging). Reduced curtailment indicates better renewable harvesting and improved sustainability as shown in Fig. 8.

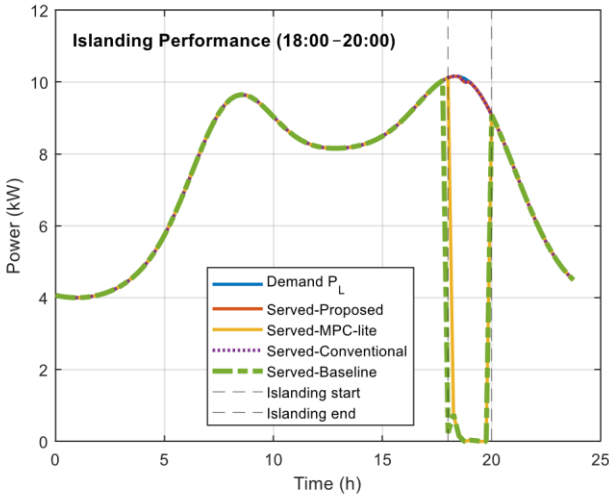


Fig. 10. Islanding Event Performance

This Fig.9 evaluates microgrid reliability during the islanded interval (e.g., 18:00–20:00). Served load tracks the portion of demand satisfied using renewables and the battery, while unmet load (if any) indicates load shedding or shortage due to limited storage/SOC constraints. Minimal unmet load confirms resilient islanded operation.

VII. CONCLUSION AND FUTURE WORK

This paper presented an intelligent Energy Management System (EMS) for reliable and economical operation of renewable-integrated microgrids under both grid-connected and islanded modes. The proposed EMS employs a rulebased, SOC-aware dispatch strategy that prioritizes renewable energy utilization while dynamically coordinating battery energy storage and grid interaction. Simulation results demonstrate that the EMS effectively reduces grid power import during high-tariff and peak demand periods, leading to a noticeable reduction in overall operating cost. In addition, improved renewable utilization and reduced curtailment confirm the capability of the proposed strategy to harvest available clean energy more efficiently. During islanded operation, the EMS maintains power balance using local renewables and battery support, ensuring reliable load supply and minimizing unmet demand, thereby enhancing microgrid resilience. The SOC-constrained battery management ensures safe operation and prevents excessive degradation, while seamless transitions between gridconnected and islanded modes highlight the robustness of the proposed approach. Compared with conventional and recent EMS techniques, the proposed strategy achieves a favorable trade-off between performance and computational simplicity, making it well suited for real-time microgrid applications. Future work will focus on extending the proposed framework using advanced control and optimization techniques. Model Predictive Control (MPC) and Reinforcement Learning (RL)–based EMS strategies can be explored to further improve decision-making under uncertainty and dynamic operating conditions. Incorporation of short-term renewable generation and load forecasting will enhance proactive energy scheduling and cost optimization. Real-time validation using hardware-in-the-loop (HIL) platforms such as OPAL-RT or Typhoon HIL is planned to assess practical implementation feasibility. Additionally, multi-objective optimization frameworks considering cost, emissions, battery aging, and power quality can be developed to further enhance sustainable and resilient microgrid operation.

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