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Review on "Energy Management System for Small Scale Hybrid Wind-Solar-Battery Based Micro Grid."

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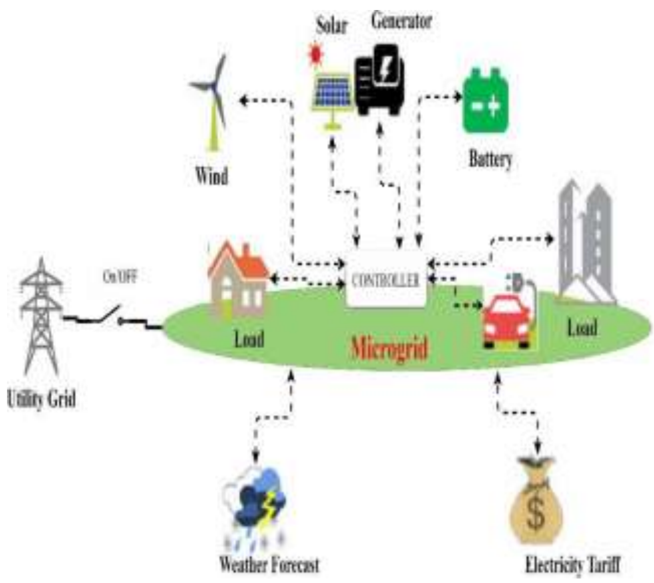
Abstract -.

The integration of renewable energy sources into distributed generation systems has accelerated interest in hybrid micro-grids that combine solar photovoltaic (PV), wind, and battery storage technologies. Among these, small-scale hybrid wind–solar–battery micro-grids represent a promising solution for rural electrification, off-grid applications, and enhancement of local energy resilience. However, the intermittency of renewable resources, variability of load demand, and limitations of battery storage necessitate an effective Energy Management System (EMS) to ensure reliable, efficient, and economical operation. This review paper provides a comprehensive overview of EMS strategies designed for small-scale hybrid micro-grids. It discusses fundamental system components, operational modes, and control architectures, with emphasis on rule-based, optimization-based, and intelligent approaches for power flow management. Recent developments in forecasting, converter control, and supervisory algorithms are summarized, highlighting their strengths and limitations in practical deployment. The review also identifies key challenges such as forecasting uncertainty, battery degradation, computational complexity, and transition between grid-connected and islanded modes. Finally, future research directions are outlined, including the integration of advanced storage technologies, adaptive and learning-based EMS frameworks, and real-time hardware validation. The insights from this study aim to guide researchers and practitioners in developing efficient EMS frameworks for reliable and sustainable operation of small-scale hybrid wind–solar–battery micro-grid.



1. INTRODUCTION

The growing demand for clean, reliable, and sustainable energy has accelerated the adoption of renewable energy technologies across the globe. Solar photovoltaic (PV) and wind energy are among the most promising renewable sources due to their abundance, scalability, and declining costs. However, the intermittent and unpredictable nature of these resources poses significant challenges for ensuring stable power supply, particularly in isolated and small-scale applications. To overcome this limitation, hybrid renewable energy systems that integrate multiple energy sources with energy storage have emerged as an An EMS plays a critical role in hybrid micro-grids by balancing generation, storage, and demand while maintaining system stability, optimizing efficiency, and effective solution.

Small-scale hybrid micro-grids that combine solar, wind, and battery storage are gaining increasing attention for applications in rural electrification, remote communities, off-grid households, and resilience enhancement in weak-grid areas. The complementarity of solar and wind resources, coupled with the energy-buffering capability of battery storage, makes such systems capable of delivering continuous and reliable power. Nonetheless, their efficient operation requires advanced coordination of power flows among different components, which is achieved through an Energy Management System (EMS).

extending the lifetime of components such as batteries. Depending on the design and application, EMS strategies may range from simple rule-based controls to sophisticated optimization and intelligent algorithms. Key functions typically include maximum power point tracking (MPPT) for renewable sources, state-of-charge (SoC) management for batteries, real-time power allocation, and mode transition handling between islanded and grid-connected operation.

In recent years, considerable research has been devoted to developing EMS frameworks for hybrid micro-grids. However, most studies face practical challenges including uncertainty in renewable generation forecasting, computational complexity of optimization techniques, limited consideration of battery degradation, and lack of large-scale experimental validation. These issues highlight the need for a systematic review of existing EMS approaches, their strengths and limitations, and potential pathways for future development.

This paper reviews the state of the art in EMS strategies for small-scale hybrid wind–solar–battery micro-grids. The discussion covers system architecture, operational modes, and different categories of EMS approaches, followed by a critical analysis of their performance and challenges. Finally, future research opportunities are identified to support the design of efficient, cost-effective, and sustainable EMS frameworks for small-scale hybrid renewable micro-grids.

2. RELATED STUDY

Numerous studies have explored Energy Management Systems (EMS) for hybrid renewable energy-based microgrids, with a focus on balancing supply, storage, and demand under varying environmental and operational conditions.

Rule-Based and Heuristic Approaches
Early works often relied on simple rule-based strategies to manage charging and discharging cycles of batteries. For instance, Alfred et al. (2025) applied a fuzzy logic-based EMS for a PV–wind–battery hybrid system serving health facilities, demonstrating improved reliability with low computational burden. Similarly, Kabouri et al. (2025) presented an optimized fuzzy logic control scheme for hybrid PV–wind microgrids, showing enhanced system stability and robustness. These approaches remain attractive for small-scale systems due to their simplicity and ease of implementation.

Techno-Economic and Sizing Studies
Several works have also examined the sizing and economic optimization of hybrid wind–solar–battery systems. Mishra et al. (2025) proposed a multi-objective al. (2024) and
Hassan et al. (2023), highlight that EMS design is strongly influenced by local resource availability, component costs, and demand patterns.

Optimization-Based Methods
To improve efficiency and reduce operational costs, advanced optimization frameworks have been developed. Joshal et al. (2023) critically reviewed the application of Model Predictive Control (MPC) in micro grids, highlighting its ability to incorporate forecasts and constraints into scheduling. Hu et al. (2023) demonstrated economic MPC for microgrids, achieving cost-effective operation through predictive decision-making. Ali et al. (2023) extended this concept to consensus-based distributed EMS, showing scalability for multiple distributed energy resources.

Battery Degradation-Aware EMS
Since battery life strongly affects system sustainability, several studies have incorporated degradation models into EMS design. Shamarova et al. (2022) reviewed battery degradation modeling and its integration into scheduling strategies, emphasizing the trade-off between short-term efficiency and long-term asset preservation. Wang et al. (2020) demonstrated that neglecting degradation models can lead to suboptimal operation and increased lifecycle costs. Li et al. (2022) proposed a degradation-aware MPC framework for PV–battery microgrids, extending battery lifetime without significant performance losses.

Artificial Intelligence and Learning-Based EMS
Recent studies have applied artificial intelligence (AI) techniques to improve adaptability and handle uncertainties. Kouihi et al. (2025) reviewed classical and AI-driven EMS frameworks, highlighting machine learning and reinforcement learning as promising tools for dynamic and uncertain environments. These approaches are particularly relevant for small-scale systems where forecasting errors and stochastic fluctuations are significant.

Real-Time Implementations
Practical deployment of EMS remains limited, though some studies have addressed real-time challenges. Bipongo et al. (2024) presented a real-time EMS for hybrid micro-grids, emphasizing hardware-in-the-loop validation. Kumar et al. (2023) and Balasundaram et al. (2024) demonstrated MATLAB/Simulink-based EMS designs for wind–solar–battery microgrids, confirming effective voltage stabilization and battery state-of-charge management under varying conditions.

optimization framework for designing sustainable micro-grids, balancing economic, environmental, and reliability indices. Similar feasibility studies, such as those reviewed by Ahmad et

Overall, the literature demonstrates significant progress in EMS strategies for hybrid wind–solar–battery microgrids. However, most studies remain simulation-based, with limited real-world deployment and validation.

3. Body of Paper

Hybrid micro-grids integrate solar PV and wind with battery storage, managed by an Energy Management System (EMS) to ensure reliable power. The EMS balances generation, storage, and load, supporting standalone (islanded) or grid-connected operations, with strategies ranging from simple rule-based methods to complex AI or optimization approaches. Key challenges include intermittency, battery degradation, and computational complexity, while future research focuses on degradation-aware EMS, robust strategies, and field validation.

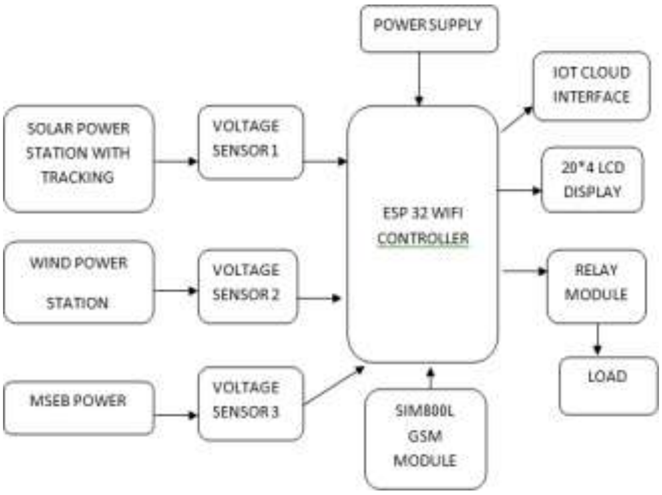


Fig -2: Block diagram of the system

- **Generation:**

Solar PV panels and wind turbines capture renewable energy, while power electronic converters maintain grid stability.

- **Storage:**

Battery energy storage systems (BESS) store excess power and discharge it when renewable generation is insufficient.

- **Energy Management System (EMS):**

This is the central decision-making component that:

- **Maintains Power Balance:** Ensures generation matches demand.
- **Manages Battery Health:** Prevents overcharging/deep discharging to extend battery life.
- **Optimizes Resource Use:** Maximizes renewables and minimizes reliance on other sources.

Types of EMS Strategies

1. **Rule-Based/Heuristic:**

Inverters, and bidirectional converters maintain voltage/frequency stability.

The integration of these elements requires a supervisory system — the EMS — to coordinate energy flows.

2. Role of Energy Management Systems (EMS)

Battery life.

Development of uncertainty-aware and robust

Simple if-then rules based on thresholds, easy to implement but less efficient for fluctuating conditions.

2. **Optimization-Based:**

Uses mathematical techniques like Model Predictive Control (MPC) to optimize costs and resources but requires accurate forecasts and more processing power.

3. **Intelligent/AI-Based:**

Employs machine learning and fuzzy logic for adaptive, robust control but needs significant data and computational resources.

4. **Hybrid Approaches:**
Combines simpler rules with optimization or AI for a balanced solution.

Operational Modes

- **Stand-Alone (Islanded) Mode:**

Operates independently from the main grid, requiring precise energy management for reliability.

- **Grid-Connected Mode:**

Exchanges power with the main grid, allowing for cost optimization and grid services.

- **Mode Transition:**
The ability to switch seamlessly between islanded and grid-connected operations, crucial for resilience.

Key Performance Metrics

- **Reliability:** Ability to meet load without interruption.
- **Renewable Fraction:** The proportion of load met by renewables.
- **Battery Health:** Management of State of Charge (SoC) and Depth of Discharge (DoD).
- **Economic Performance:** Levelized Cost of Energy (LCOE).
- **Power Quality:** Voltage and frequency stability.

Challenges & Future Directions

- **Challenges:**

Renewable intermittency, battery degradation, high computational demands of advanced EMS, and limited real-world validation.

- **Future Research:**
Developing degradation-aware EMS, robust optimization strategies for uncertainty, hybrid EMS, hardware-in-the-loop (HIL) demonstrations, and cost-effective designs for small-scale systems.

optimization strategies.

Hybrid EMS frameworks that blend heuristic simplicity with optimization/AI intelligence.

Hardware-in-the-loop (HIL) and pilot-scale demonstrations for validation.

Incorporation of demand-side management and smart load scheduling.

Cost-effective EMS designs tailored for small-scale, rural,

4. CONCLUSIONS

Small-scale hybrid micro-grids integrating wind, solar, and battery storage have emerged as a promising solution to address energy access, reliability, and sustainability challenges, particularly in remote and off-grid applications. However, the inherent variability of renewable sources and the operational limitations of battery storage demand a robust Energy Management System (EMS) to ensure reliable, efficient, and cost-effective operation.

This review has highlighted the fundamental roles of EMS in coordinating generation, storage, and load through strategies ranging from simple rule-based methods to advanced optimization and intelligent algorithms. Rule-based and fuzzy logic controllers remain attractive for their simplicity and ease of implementation, while model predictive control (MPC), mixed-integer optimization, and other advanced methods offer improved performance at the expense of computational complexity. Recent developments in artificial intelligence and machine learning have shown strong potential to enhance adaptability and decision-making under uncertainty, but require further validation in real-time environments.

A critical challenge across most studies is the limited consideration of battery degradation, forecasting uncertainties, and system scalability. In addition, many EMS approaches remain confined to simulation environments, with relatively few implementations in real-time hardware or field-deployed systems. Addressing these limitations is essential to ensure the practical applicability of EMS frameworks.

Future research directions should focus on integrating degradation-aware and uncertainty-aware control strategies, combining demand-side management with generation scheduling, and validating EMS approaches through hardware-in-the-loop and pilot-scale demonstrations. Moreover, cost-effective EMS designs tailored for small-scale systems will be key to enabling widespread adoption in rural and resource-constrained settings.

In conclusion, effective EMS design remains central to unlocking the full potential of hybrid wind–solar–battery micro-grids. By bridging the gap between advanced control techniques and practical deployment, future EMS solutions can enhance the resilience, sustainability, and affordability of decentralized energy systems worldwide.

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