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A Systematic Review of Energy Management Strategies in Hybrid Off-Grid Systems: The Role of Battery Storage Systems in Minimizing Diesel Generator Operation Hours and Enhancing Sustainability

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ABSTRACT

Energy Management Systems (EMS) are pivotal in increasing the efficiency of Hybrid Renewable Energy Systems (HRES) and decreasing diesel generator usage. This study aims to perform a Systematic Literature Review (SLR) on advanced EMS strategies, providing insights into the impact of EMS on reducing diesel consumption, cost-effectiveness, and operational efficiency of off-grid hybrid solar-diesel systems. Recent progress on predictive control, real-time observations, and optimization algorithms has been reviewed along with battery storage integration for better energy dispatch. Using a systematic search method across multiple databases, 28 relevant articles published from 2022 to 2025 were identified and analyzed based on strict inclusion criteria. The findings show that rule-based and algorithm-driven EMS approaches, including Fuzzy Logic Control (FLC), Marine Predator Algorithm (MPA), and Deep Deterministic Policy Gradient (DDPG), contribute to a substantial decrease in reliance on diesel while enhancing renewable energy utilization. Battery storage optimizes EMS performance by shifting energy and minimizing operating costs. Nevertheless, challenges such as high upfront costs, complexities in system integration, and the need for standardization remain. This review emphasizes the importance of EMS as a key component in sustainable energy transitions for off-grid applications and proposes an optimization framework for battery energy storage. Future research should emphasize real-world implementation, scalability, and policy frameworks to facilitate broader adoption and long-term economic viability of HRES.

Keywords: Energy Management Systems; battery storage; diesel generator reduction; Solar Photovoltaic Systems (PV); rural electrification, optimization algorithm

INTRODUCTION

Access to energy in rural areas remains a significant challenge and is mainly done through hybrid energy systems combining renewable energy sources with conventional diesel generators (Figure 1) (Ganjei et al. 2022). Diesel generators are often used as the main electricity supply asset or backup power in remote areas. However, their operation has high fuel costs, logistical constraints, and significant carbon emissions, and therefore, in the long term, is economically and environmentally unsustainable (Ali et al. 2023). Furthermore, according to Ali et al. (2023) and Ismail et al. (2023), the increasing demand for sustainable and reliable energy solutions in an affordable way has translated into the integration of renewable energy sources, mainly solar Photovoltaic (PV) and wind power, along with Battery Storage Systems (BESS) that enhance dependability while reducing diesel dependence. By implementing advanced Energy

Management Systems (EMS), these hybrid configurations can provide benefits for power generation and energy efficiency and work toward reducing diesel consumption, enabling cleaner energy and cost savings, and ultimately helping with sustainable rural electrification (Abdullah et al. 2023; Menzri et al. 2024; Shamsuddin et al. 2025).

The main research question addressed in this study is "How do energy management systems reduce the usage of diesel generators?" The literature review is guided by three main objectives to address this question. First, it assesses the effectiveness of EMS in optimizing hybrid energy system operation, maintaining a balance between renewable power and backup diesel generation. Second, the study seeks to assess battery storage's role in reducing diesel generator usage, emphasizing how energy storage enhances grid stability and mitigates reliance on fossil fuels. Lastly, this review aims to understand how various EMS algorithms, such as predictive control and real-time monitoring, reduce diesel use and assess how advanced optimization strategies improve energy efficiency and sustainability in off-grid hybrid systems.

This study focuses on off-grid hybrid energy systems combining solar PV and battery storage to ensure energy reliability and sustainability across remote areas. The focus is on energy management approaches proposed to enhance the operation of such hybrid systems, including system optimization strategies, battery energy storage integration, and advanced control algorithms (Neeraj et al. 2023; Rodriguez et al. 2023). Moreover, this study is focused on how EMS affects the usage of diesel generators, including the operational hours, fuel consumption, and emissions (Zigman et al. 2024). This review aims to bring together recent research findings to provide a comprehensive understanding of EMS-driven approaches that enhance the efficiency and sustainability of off-grid hybrid energy systems.

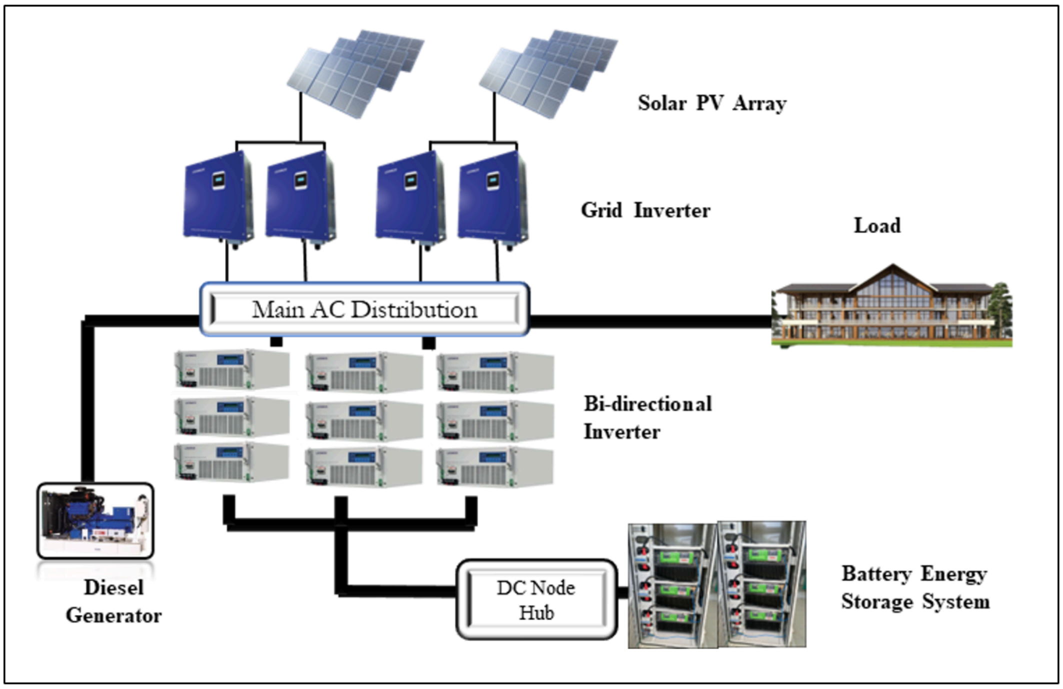

FIGURE 1. Typical diagram for off-grid solar hybrid system components

This paper is organized into four sections. The Methodology section outlines a systematic methodology for collecting and analyzing relevant literature on EMS and diesel generator reduction in off-grid hybrid systems, along with specifying selection criteria and a filtering process. The Result section discusses key findings from the reviewed studies and highlights significant patterns, inconsistencies, and the impacts of specific EMS approaches on energy efficiency and fossil fuel reduction. Meanwhile, the article's Discussion section discusses the role of battery storage, EMS optimization, and hybrid system configurations in reducing diesel dependence. Finally, the conclusion consolidates the study's significant contributions and describes limitations and future research recommendations for establishing more sustainable and cost-effective EMS-based off-grid hybrid systems.

However, locating articles that satisfied the study's parameters and objectives was challenging. Out of 1,725 articles, only 27 met the study's requirements and criteria. The chosen databases were limited to those accessible through university subscriptions, and the selected articles focused on open-access publications.

METHODOLOGY

This study's Systematic Literature Review (SLR) process is systematic and transparent in identifying, evaluating, and synthesizing research regarding EMS strategies for hybrid off-grid systems, as illustrated in Figure 2. The first stage of the review involved an extensive search of four principal academic databases, with the subsequent number of articles found: ScienceDirect (1,464 articles), IEEE Xplore (50 articles), Scopus (188 articles), and Web of Science (23 articles), resulting in a total of 1,725 articles. These databases were selected due to their extensive coverage of renewable energy, hybrid systems, and optimization techniques.

The specific search strings were crafted based on keywords associated with diesel generators, battery storage, solar PV systems, and EMS. The final search strategy combined these terms with Boolean operators (AND, OR) to identify relevant studies regarding off-grid hybrid systems satisfying our search criteria. The search strings are shown in Table 1.

In the first round of screening, specific inclusion criteria were developed to narrow the selection to research articles published from 2022 to 2025, written in English, appearing as peer-reviewed journal papers, and open access to guarantee transparency and accessibility. This resulted in 239 articles after the filtering step. Further refining based on abstract relevance excluded those not within the study scope, leaving 127 full-text articles for revision. To ensure an emphasis on hybrid off-grid energy systems, articles that covered electric vehicle topics, grid-connected urban systems, or non-related technologies were eliminated.

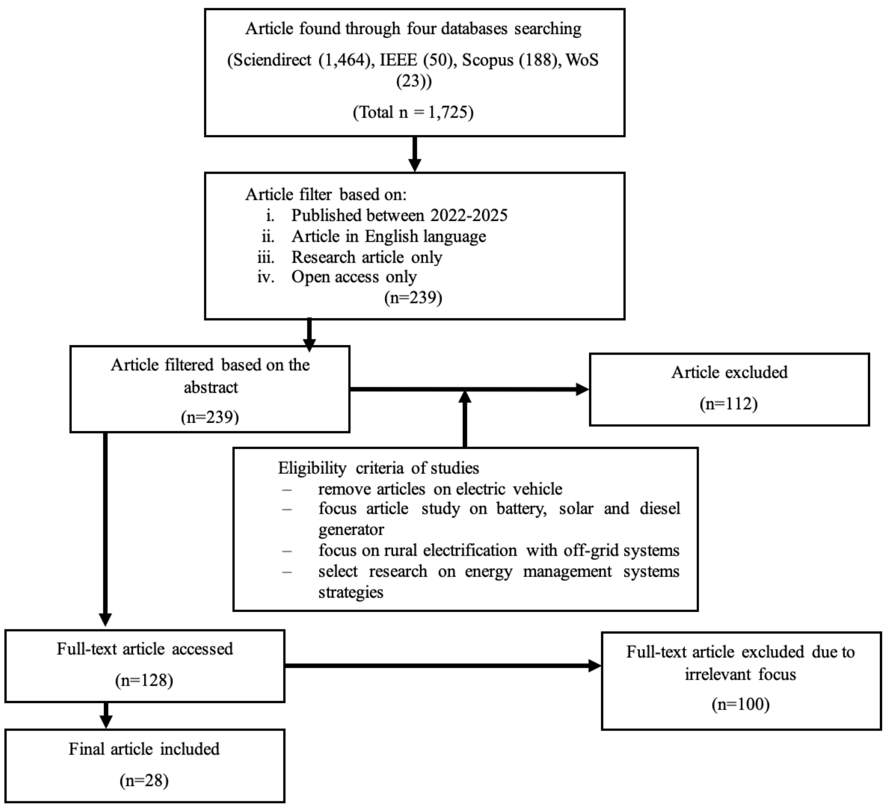

FIGURE 2. The systematic literature review process flow

The inclusion and exclusion criteria were used to select which studies would be included in the results. The focus was on research on integrating battery storage, solar, and diesel generators in rural electrification contexts. Studies on energy management approaches, including real-time optimization, predictive control, and load dispatch algorithms, were also prioritized. After excluding 100 articles due to irrelevant focus, a final dataset of 28 studies was left. These selected articles provide a valuable understanding of the role of EMS in diesel reduction and battery storage optimization in hybrid off-grid settings.

The literature review method is built on consistency, replicability, and bias reduction. The review narrows from a wide net of publications to 28 excellent articles covering current developments and findings in energy management of off-grid hybrid systems. The refined dataset laid the groundwork for evaluating the effects of EMS on diesel generator utilization reduction, conducting economic feasibility studies, and determining gaps for future research on hybrid energy systems optimization.

RESULTS

The papers discussed in this review reflect various methodologies, such as optimization, system designs, and simulation-based methodologies, that combine to improve hybrid energy systems and reduce the use of diesel generators. Table 2 summarizes and describes the major themes and associated studies discussed in this study and their relevance to each theme.

The evidence from the selected studies indicated that EMS plays a crucial role in optimizing diesel generator usage in hybrid off-grid systems. Different EMS strategies, such as rule-based energy management, real-time State-of-Charge (SoC) monitoring, and predictive control, have been utilized in different studies to perform the dispatch from renewable sources efficiently, reducing diesel generator reliance. For example, Ab Ghani et al. (2022) designed an economic EMS that enhances the performance of diesel-powered microturbines and aims to minimize total costs while maximizing renewable energy use. Similarly, Aziz et al. (2022) presented a more advanced dispatch strategy using Hybrid Optimization Model for Electric Renewables (HOMER) software with 12-hour foresight, enhancing renewable energy penetration and significantly reducing Carbon Dioxide (CO_2) emissions through lower diesel dependency. These studies emphasize that EMS-driven load scheduling and real-time monitoring reduce diesel generators' operational hours, translating into better energy efficiency in hybrid systems. However, previous studies may be subject to bias due to the absence of large-scale validation and limited adaptability to dynamic load fluctuations.

TABLE 1. Database search strategy (keywords and Boolean operators)

	Database	Search String
1.	ScienceDirect	("Diesel Generator" OR "Diesel Consumption") AND ("Energy Storage Systems" OR "Battery Storage") AND ("Solar PV" OR "Photovoltaic") AND ("Energy Management Systems" OR "EMS")
2.	Scopus	("Diesel Generator" OR "Diesel") AND ("Energy Storage Systems" OR "Battery") AND ("Solar Photovoltaic" OR "PV") AND ("Energy Management Systems" OR "EMS")
3.	IEEE Xplore	("Diesel") AND ("Battery") AND ("Solar" OR "Photovoltaic") AND ("Energy Management Systems" OR "Energy Dispatch")
4.	Web of Science	("Diesel Generator" OR "Diesel Consumption") AND ("Battery" OR "BESS" OR "Energy Storage Systems" OR "Battery Storage") AND ("Solar" OR "PV" OR "Photovoltaic") AND ("Energy Management Systems" OR "Energy Optimization")

Integrating battery storage with EMS further reduces diesel consumption by allowing excess renewable energy to be stored and utilized during the low generation time. For example, See et al. (2022) report battery integration as a key technology for cost-effectiveness and emissions reduction in hybrid PV/wind/diesel systems. Furthermore, Bambokela et al. (2022) discovered that a biogas-solar PV hybrid system coupled with lithium-ion battery storage allows electricity autonomy, eliminating diesel dependence even more. A study by Coban (2024) demonstrated that system reliability improves with solar, wind, diesel, and battery storage, and fuel consumption declines. These findings propose that effective EMS strategies and adequate battery storage create a more stable and fuel-efficient hybrid power system for rural and isolated areas. Nevertheless, previous studies still lack analysis of system scalability and might not consider integration complexity, especially in different geographical settings.

Optimization algorithms have also improved EMS performance for diesel generator reduction. Belboul et al. (2022) used the Multi-objective Salp Swarm Algorithm (MOSSA) that achieved the Cost of Energy (COE) and optimal diesel generator operation of 0.255 USD/kWh compared to other algorithms optimizing hybrid system configurations. Similarly, Elmetwaly et al. (2022) implemented the Marine Predator Algorithm (MPA) in combination with EMS and the Adaptive Dynamic Voltage Restorer (ADVR), which resulted in a reduced maintenance cost, as well as better power quality and a decrease in diesel generator operation time.. These studies illustrate that advanced optimization methods enhance system efficiency by adapting diesel generator operations based on the changing availability of renewable energy. However, the study by Tightiz et al. (2023) considers real-time responsiveness of system efficiency, which other studies do not. The framework must also address rapidly changing renewable energy inputs to reduce diesel dependency effectively.

TABLE 2. Categorization of studies by themes

Theme	Corresponding Studies
Energy Management Strategies (EMS) in Hybrid Systems	(Ab Ghani et al. 2022), (Atoui et al. 2022), (Tightiz et al. 2023), (Elmetwaly et al. 2022), (Coban, 2024), (Yao et al. 2024)
Optimization Algorithms for EMS	(Belboul et al. 2022), (Elmetwaly et al. 2022), (Tightiz et al. 2023), (Zhou et al. 2024), (Younis et al. 2024)
Techno-Economic Feasibility of Hybrid Systems	(See et al. 2022), (Aziz et al. 2022), (Singh & Rizwan, 2022), (Wali et al. 2023), (Roy et al. 2025)
Battery Storage Integration in Hybrid Systems	(Ab Ghani et al. 2022), (Aziz et al. 2022), (Bambokela et al. 2022), (Kumar et al. 2024), (Mukhtar et al. 2024)
Diesel Generator Reduction Strategies	(Atoui et al. 2022), (Aziz et al. 2022), (Cabrera et al. 2024), (Nurdiana et al. 2024), (Ahmed et al. 2024)
Microgrid Design and Energy Management for Rural Electrification	(Bambokela et al. 2022), (Cabrera et al. 2024), (Mukhtar et al. 2024), (Alam et al. 2025), (Wamalwa et al. 2025)
Hybrid Renewable Energy Systems (PV/Wind/Diesel/Battery)	(See et al. 2022), (Coban, 2024), (Kumar et al. 2024), (Wali et al. 2023), (Al-Sawalha et al. 2024)
AI and Machine Learning in Energy Management	(Alam et al. 2025), (Tightiz et al. 2023), (Elmetwaly et al. 2022), (Younis et al. 2024)
Green Hydrogen and Alternative Storage Technologies	(Younis et al. 2024), (Roy et al. 2025)

Moreover, techno-economic analysis of hybrid systems confirms they are a financially viable solution for decreasing diesel reliance in EMS. Wali et al. (2023) and Nurdiana et al. (2024) also highlighted the substantial reduction in Net Present Costs (NPC) and Levelized Cost of Energy (LCoE) for optimized hybrid energy systems, supporting long-term economic sustainability. Similarly, Alam et al. (2025) demonstrated that Artificial Intelligence (AI)-based microgrid design, integrating machine learning clustering and Mixed-Integer Linear Programming (MILP) optimization, could achieve a maximum carbon emission reduction of 98.23% while reducing reliance on diesel generators. These findings show that a hybrid system combining EMS and battery storage provides both environmental advantages and long-term economic benefits, proving to be a prospective option for rural electrification.

Overall, aggregated results from these studies show that EMS strategies and integration and optimization of the BESS with the generation from renewable energies improve the performance of hybrid off-grid systems by minimizing the dependence on diesel generators. Real-time monitoring, predictive dispatch, and intelligent load management contribute to less fuel consumption, enhanced system reliability, and reduced environmental impact. The financial prospects of diesel reduction strategies based on EMS favor their implementation on larger scales, especially in rural and disadvantaged areas. Nonetheless, further investigation into optimizing EMS adaptability and cost-efficiency will be essential to maximize their value for off-grid renewable energy systems.

Comparative studies show that the advanced EMS reduces fuel consumption from diesel generators, enhancing hybrid off-grid systems' operational performance. Multiple EMS approaches have been investigated in the literature, including rule-based EMS, real-time SoC monitoring, and predictive dispatch control to achieve optimal energy allocation with minimized fuel consumption. For example, Ab Ghani et al. (2022) presented a rule-based EMS integrating the real-time SoC monitoring system, achieving optimal microturbine operational cost reduction and maximizing renewable energy consumption. Similarly, Aziz et al. (2022) employed an enhanced dispatch approach using HOMER software with a 12-hour foresight, resulting in a higher share of renewable energy and lower CO_2 emissions. It brings out how significant the role of EMS is in managing energy flows seamlessly to minimize the reliance on diesel, particularly in off-grid and rural regions. The study by Yao et al. (2024) focuses on enhancing the economic viability of solar projects in China by forecasting power consumption from photovoltaic power stations. The researchers developed a Long Short-Term Memory (LSTM) neural network model to predict both power consumption and solar irradiance, critical factors for operational planning. However, previous studies are based only on mathematical models with limited empirical verification and insufficient real-world implementation.

Integrating battery storage with renewable energy sources compounds the ability of EMS to mitigate diesel use by ensuring energy availability during low renewable energy generation periods. See et al. (2022) proposed that integrating storage battery systems with solar PV, wind turbines, and diesel generators significantly improved cost-effectiveness and emission reductions, making rural electrification projects more viable. Bambokela et al. (2022) demonstrated this further by showing that a biogas-solar PV system with lithium-ion battery storage allowed for independent electricity on-site, reducing reliance on diesel backup generation. Similarly, Kumar et al. (2024) highlighted the significance of battery storage in stabilizing hybrid systems relying on solar and hydro energy sources, subsequently decreasing diesel consumption and enhancing system reliability. These studies also indicate that, when controlled through EMS, battery storage lowers fuel costs and enhances the system's efficiency by storing excess renewable charge for future use.

Furthermore, optimization algorithms have played a crucial role in improving energy dispatch to minimize diesel consumption and thus assist EMS operations. Belboul et al. (2022) proposed the MOSSA, which improved the other techniques for optimizing system designs to minimize the COE, achieving a COE equal to 0.255 USD/kWh. A study by Elmetwaly et al. (2022) utilized the MPA with an ADVR that successfully minimized diesel maintenance costs and enhanced power quality. Moreover, Tightiz et al. (2023) proposed using a DDPG for a real-time optimization of EMS that also addresses the minimization of load shedding and diesel usage in microgrids. These studies proposed that integrating AI-driven and heuristic-based optimization methods improves EMS capabilities, leading to greater fuel efficiency and cost reductions in off-grid hybrid systems. Although previous studies have shown that integrating EMS with optimization algorithms can improve system efficiency, exploration has been limited to combining it with other EMS algorithms that might yield better results.

Considering economic feasibility, several researchers have estimated hybrid energy management strategies' Return on Investment (ROI). Singh & Rizwan (2022) and Wali et al. (2023) assessed that systems integrating EMS and battery storage achieved lower NPC and COE, making them financially viable. Cabrera et al. (2024) highlighted that cost-effective containerized microgrids with little reliance on diesel are most economically suited for emergency and off-grid applications. Besides, Roy et al. (2025) pointed out that hydrogen-based systems were more expensive than battery-based systems, providing greater flexibility, showing that, for hybrid systems, battery storage was the least expensive option for reducing dependence on diesel. These findings indicate that EMS and battery storage investments provide significant long-term financial benefits, including lower operational costs and enhanced system sustainability.

With these consistent results, some discrepancies exist regarding the economic viability of different energy storage technologies. Roy et al. (2025) revealed that hydrogen integration offered more operational flexibility at a higher cost, while BESS could avoid the overproduction of electricity at a lower price. Likewise, Wamalwa et al. (2025) emphasize the importance of subsidies in the affordability of hybrid mini-grids and indicate that economic viability heavily depends on policy support. While Coban (2024) and Ahmed et al. (2024) identified hybrid microgrids as a promising means to reduce energy costs by optimizing diesel use, Wassie & Ahlgren (2023) established that household size and appliance ownership are local determinants of electricity consumption patterns and, consequently, diesel reliance. This explains why EMS and battery storage provide consistent technical and economic benefits. However, differences in contextual factors such as location, policy incentives, or energy demand patterns may require tailored approaches to achieving optimal diesel reductions.

DISCUSSION

ROLE OF ENERGY MANAGEMENT SYSTEMS IN DIESEL REDUCTION

Implementing EMS is crucial for the efficiency of hybrid systems, as it allows for better utilization of renewable energy and reduces the reliance on diesel generators. Ab Ghani et al. (2022) demonstrated how rules-based energy management strategies, combined with real-time SoC monitoring, could lower microturbines' operating costs and optimize the use of renewable energy resources. Furthermore, Aziz et al. (2022) optimized energy allocation for a 12-hour outlook utilizing the HOMER software to minimize CO_2 emissions and improve the ratio of renewable energy to the total energy output of the hybrid system. Similarly, EMS has also proven effective for hybrid systems, according to Atoui et al. (2022), where they found the PV generator efficiency improved to 99.5% using a Fuzzy Logic Controller (FLC) in PV/Diesel/Battery power management system. This demonstrates that an efficient EMS can optimize diesel consumption and maximize the overall performance of the hybrid power system.

In terms of operational strategies, EMS uses load forecasting, demand management strategies, and battery storage optimization to perform a real-time equilibrium of energy demand and supply. Tightiz et al. (2023)

demonstrated that real-time EMS optimization using the DDPG can alleviate load shedding and stabilize microgrid operation. Moreover, Elmetwaly et al. (2022) also presented that MPA and ADVR usage improved power quality and reduced diesel maintenance costs in remote microgrids. Meanwhile, Cabrera et al. (2024) highlighted the need to develop customized container microgrid designs specifically for emergency and remote situations, which enables you to design an overall more efficient power system, resulting in significantly less diesel consumption. EMS empowered with real-time demand monitoring and reasonable energy distribution strategies can significantly lower fossil fuel consumption and enhance the economy and sustainability of hybrid energy systems. The categorization of EMS methods is illustrated in Figure 3.

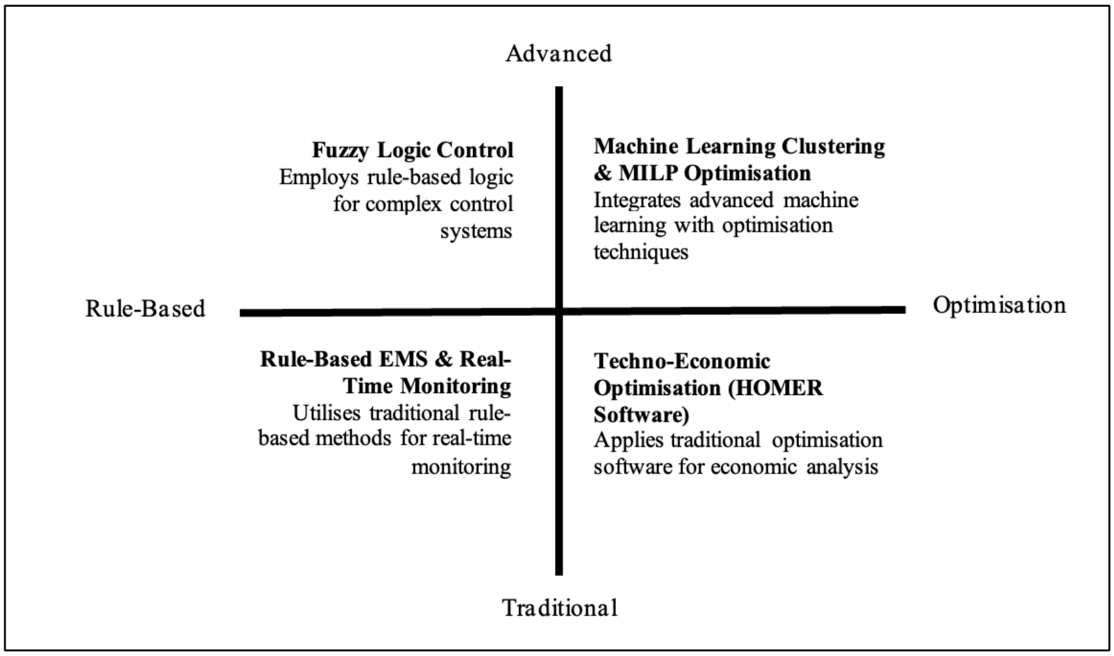

FIGURE 3. Categorization of EMS methods used to reduce diesel consumption

BENEFITS OF BATTERY STORAGE IN DIESEL REDUCTION

Battery storage plays an important role in reducing the dependency on diesel generators by storing excess amounts of renewable energy during peak hours or when renewable energy sources are insufficient. Ab Ghani et al. (2022) indicated that it is beneficial for EMS to derive the real-time SoC of the batteries to ensure the optimal usage of batteries, minimize the operating costs of microturbines, and enhance the performance of hybrid energy systems. Additionally, a study by Aziz et al. (2022) observed that enhanced energy separation strategies using HOMER could reduce carbon emissions and allow greater exploitation of renewable energy by storing excess energy in batteries for when there are excess energy demands. In an integrated system context, Bambokela et al. (2022) found that this solution was able to provide energy autonomously, avoiding the use of diesel generators, using lithium-ion battery storage coupled with a Biogas-Solar PV hybrid system, proving the relevance that energy storage has in increasing the reliability of off-grid energy systems.

From a cost-effective perspective, deploying battery storage paired with EMS has lowered the long-term operating expenditure of off-grid hybrid systems. See et al. (2022) discovered that the PV/WT/Battery/Diesel system configuration is the most cost-effective energy generation for rural areas, while the addition of batteries succeeds in decreasing carbon emissions and provides energy savings. Moreover, an investigation by Kumar et al. (2024) demonstrated that 100% renewable power system integration was possible, eliminating the need for diesel generators by combining batteries, solar, and hydropower. Concerning long-term costs, Roy et al. (2025) demonstrated that PV/BESS systems are less expensive than hydrogen-based power systems regarding energy costs and operational flexibility. In general, battery storage optimizes energy storage and reduces diesel consumption, resulting in significant savings in the long-term operation cost of off-grid hybrid systems.

ENERGY MANAGEMENT SYSTEM ALGORITHMS AND METHODS

The effectiveness of various EMS algorithms in reducing diesel generator usage depends on the energy control approach and the geographical and climatic conditions where the systems operate. Ab Ghani et al. (2022) demonstrated that real-time SoC-based EMS strategies with real-time SoC monitoring can improve renewable energy consumption, significantly reducing microturbine operation costs. In a separate study, Coban (2024), Atoui et al. (2022) and Younis et al. (2024) discovered that EMS applied to PV, diesel, and battery solutions addresses the challenges of intermittent renewable energy sources while decreasing the reliance on diesel generators. Elmetwaly et al. (2022) applied a conventional MPA with ADVR in isolated microgrids to reduce maintenance costs and enhance power quality. A study by Tightiz et al. (2023) also determined that DDPG can be applied to EMS to provide real-time load management to alleviate interruptions in power supply and enhance grid stability. Belboul et al. (2022) established that the MOSSA achieved a COE of $0.255 per kWh and a Loss of Power Supply Probability (LPSP) of 27.079%, outperforming other optimization techniques in this study. Similarly, a study by Cabrera et al. (2024) proposed a five-step design methodology for containerized microgrids aimed at remote areas and regions highly exposed to emergencies in Colombia. Their approach effectively reduced reliance on diesel and maintained energy reliability, providing a viable blueprint for areas suffering from energy insecurity (Cabrera et al. 2024). Meanwhile, Zhou et al. (2024) employed the Improved Aquila Optimization (IAO) algorithm to optimize the design of Hybrid Renewable Energy Systems (HRES). This resulted in a 25% cost savings and a 15% improvement in energy efficiency, reinforcing the sustainability and feasibility of utilizing renewable energy in off-grid regions (Zhou et al. 2024).

However, a review of related articles found that most studies rely on simulation-based approaches that do not adequately reflect real-world situations. Factors such as long-term climate variability, component degradation (especially batteries), and cyber-physical vulnerabilities in algorithmic control strategies are poorly explored. In addition, scalability across diverse infrastructure settings and standardized integration protocols are rarely addressed, posing challenges to the generalizability and repeatability of these EMS solutions. As summarized in Table 3, while each EMS algorithm offers a unique approach to reducing diesel consumption, its effectiveness depends on factors such as the uncertainty of renewable energy sources, grid stability requirements, and the ability of energy storage systems to accommodate excess energy for peak-time use.

TABLE 3. EMS algorithm and methods used for system efficiency and diesel reduction

	EMS Algorithm & Method	Study Related	Research Finding	Research Gap & Limitation
1.	Rule-Based EMS & Real-Time Monitoring	(Ab Ghani et al. 2022)	The study proposed the rule-based EMS with real-time monitoring to minimize the utilization of diesel-powered microturbines.	Lack of validation in a large-scale environment and a lack of dynamic adaptability to changing load profiles.
2.	Fuzzy Logic Control (FLC); Nelder-Mead Simplex Method; and Reduced Fractional Gradient Descent (RFGD)	(Atoui et al. 2022) (Coban, 2024) (Younis et al. 2024)	EMS resolves the challenges of intermittent renewable energy sources by improving solar PV efficiency and reducing diesel generator operation.	Integration complexity and a lack of analysis on scalability and long-term performance across different geographical settings.
3.	Marine Predator Algorithm (MPA) & Adaptive Dynamic Voltage Restorer (ADVR)	(Elmetwaly et al. 2022)	The EMS algorithm lowered the operational costs of diesel generators within a network of interconnected microgrid systems.	Lack of real-time responsiveness and consideration for rapidly inconsistent renewable inputs.
4.	Deep Deterministic Policy Gradient (DDPG)	(Tightiz et al. 2023)	EMS with the DDPG algorithm performs more accurately and efficiently when supplying loads with battery and diesel generators when renewable energy resources are absent.	The high computational load in resource-limited off-grid applications could limit the practical utility of the approach.

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5.	Multi-Objective Salp Swarm Algorithm (MOSSA)	(Belboul et al. 2022)	The proposed EMS approach aims to manage energy flow between system components and to minimize the COE.	Insufficient real-world implementation; mainly based on mathematical models with limited empirical validation.
6.	Five-Step Design Method	(Cabrera et al. 2024)	This study applies EMS in containerized microgrids to provide electricity from solar generation, store surplus energy, and minimize the use of diesel generators.	Not tested under alternate emergency or geographic conditions to verify universal applicability.
7.	Improved Aquila Optimization (IAO)	(Zhou et al. 2024)	EMS increases renewable energy utilization and lowers costs by reducing dependence on diesel power.	Limited exploration of combining with other EMS algorithms and real-time in large-scale systems

CHALLENGES IN INTEGRATING ENERGY MANAGEMENT SYSTEM

Integrating Energy Management Systems (EMS) and battery storage with hybrid off-grid systems has remained difficult, particularly in rural and developing areas. The significant challenges are high initial costs, technological complexities, and non-standardized systems. However, the cost of investing in complex EMS and advanced battery storage systems still constitutes a significant barrier to adoption, especially in regions with constrained financial resources (Ab Ghani et al. 2022; Mukhtar et al. 2024). Financial incentives and subsidies can potentially reduce them; however, according to Wamalwa et al. (2025), their allocation and access vary by region, which limits their potential impact.

Technical hurdles are also associated with the development and widespread use, particularly due to problems with system compatibility, real-time data processing, and optimization algorithms, as reported by Atoui et al. (2022) and Roy et al. (2025). Several EMS strategies, including fuzzy logic controllers and predictive algorithms, have been designed in controlled simulation environments using tools such as HOMER and MATLAB and employing dedicated Artificial Intelligence (AI) models (Atoui et al. 2022; Roy et al. 2025). However, such theoretical models may not accurately reflect the deployment reality, where renewable generation and battery health can vary over time. Furthermore, according to Elmetwaly et al. (2022), the lack of EMS communication and operational standards for hybrid microgrids leads to inefficiencies in energy dispatch, inconsistent operations, and challenges in integrating various renewable sources, diesel generators, and storage technologies.

To address these challenges, collaborative industry efforts and regulatory frameworks are imperative. Bambokela et al. (2022) and Cabrera et al. (2024) reported that pilot-scale demonstrations and field trials are required to validate EMS and battery systems long-term, which must be prioritized to assess scalability and performance under real-world conditions. Furthermore, according to Younis et al. (2024), innovations in storage expansion through technologies such as lithium-ion and hydrogen-based systems can also provide some flexibility. However, they are understudied and require further empirical exploration. Addressing these concerns is crucial for enabling the development of EMS-based integrated hybrid energy systems that promote sustainable electrification.

LIMITATION AND RECOMMENDATION

While findings from previous studies seemed promising, some limitations need to be noted, especially concerning implementation in the real world and scalability. Most studies rely on simulations utilizing HOMER, MATLAB, and AI-based optimizations. While these are enlightening, they do not always mirror the real-world deployment challenges when setting up such systems. Theoretical predictions of uncertainties in renewable energy generation, battery degradation over time, and grid stability concerns must be validated through long-term field trials. Research has shown great potential for diesel reduction. However, scalability is a concern in the analysis focused on small, microgrid-scale projects that cannot easily be expanded to larger, more complex energy networks. Addressing these limitations through comprehensive pilot projects, industry collaborations, and policy-driven standardization efforts will ensure that hybrid EMS-driven energy systems are scalable and reliable on a large scale.

Hence, to work on these impending issues, future research should focus on the development of cost-effective EMS strategies that adhere to the requirement of the system from the point of view of the energy demand of the off-grid communities, where the reliance on diesel remains high in the rural areas as reported by Singh & Rizwan (2022) and Wali et al. (2023). Based on studies by Cabrera et al. (2024) and Ahmed et al. (2024), where economic viability turned out to be the most relevant indicator for success, policymakers should also consider the introduction of subsidies and financial incentives for hybrid solar-diesel systems. According to Coban (2024) and Kumar et al. (2024), standardizing EMS protocols and BESS facilitate inter-system coordination, lowering the implementation barriers and guaranteeing that renewable energy sources are optimally deployed to reduce the reliance on fossil energy. Thus, innovative energy storage technologies, including lithium-ion batteries and hydrogen-based storage, could enable greater system flexibility, and their large-scale implementation in hybrid microgrids remains underexplored (Bambokela et al. 2022; Roy et al. 2025).

In addition, hybrid system optimization should prioritize real-time demand forecasting and load management to enhance system efficiency and reduce unnecessary diesel consumption, as shown in research by Younis et al. (2024) and Al-Sawalha et al. (2024). Data-driven design methodologies, including machine learning clustering and MILP optimization, have yielded promising outcomes for optimizing renewable energy and minimizing carbon emissions, making them valuable areas for future research (Alam et al. 2025). In the same vein, it has been reported that metaheuristic optimization procedures, such as Cuckoo Search Algorithm (CSA), Mayfly Algorithm (MFA), Flower Pollination Algorithm (FPA), Constraints Particle Swarm Optimization (CPSO), and Harmony Search Algorithm (HSA), are better than conventional EMS methods in remote applications in terms of cost reduction and efficiency (Roy et al. 2025). The results indicate that further integrating AI-driven algorithms with EMS could provide more accurate energy predictions and optimize energy distribution, particularly in regions with intermittent renewable energy supply.

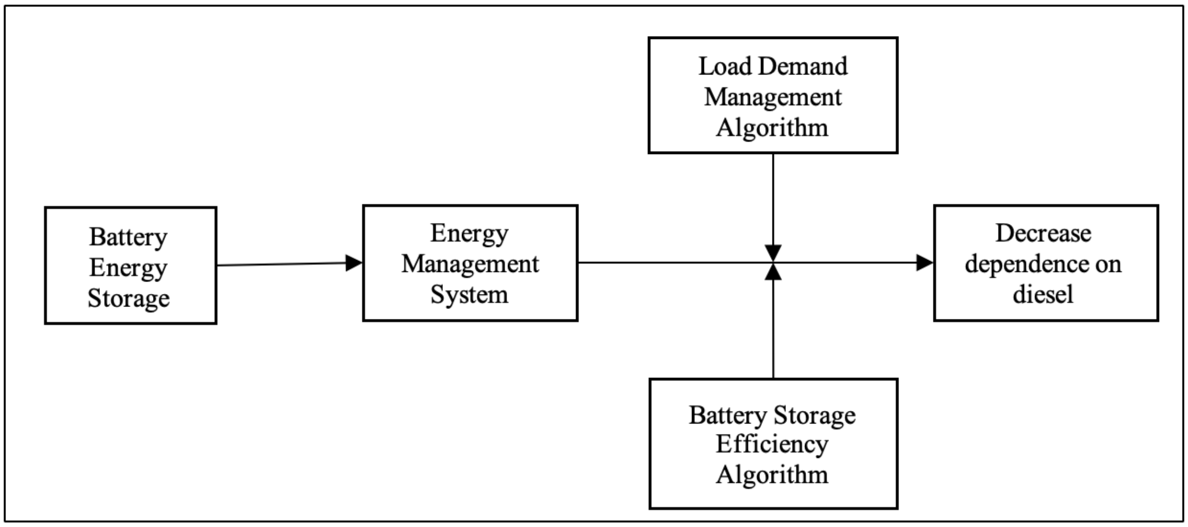

FIGURE 4 Energy management optimization framework for battery storage systems in minimizing diesel dependency

This study contributes by proposing an "Energy Management Optimization Framework for Battery Storage Systems in Minimizing Diesel Dependency," which provides a structured approach to enhance the efficiency of off-grid solar systems (Figure 4). It combines optimization techniques such as artificial intelligence (AI), machine learning (ML), and advanced control algorithms within EMS to improve energy efficiency in hybrid solar systems. The framework emphasizes real-time monitoring, energy demand forecasting, and the optimal dispatch of renewable resources and battery storage to reduce reliance on diesel generators. By integrating predictive models, battery storage management, and multi-objective optimization, the framework aims to balance energy supply and demand, extend battery life, lower operating costs, and decrease carbon emissions in off-grid solar systems for rural electricity supply.

CONCLUSION

In conclusion, the reviewed studies collectively propose that advanced EMS approaches and optimized BESS are crucial in reducing diesel generator dependency in off-grid solar-diesel hybrid systems. Though these techniques have shown improvement, challenges remain regarding economic feasibility, scalability, and technical implementation. Future research should also focus on developing more affordable EMS solutions, improving energy storage integration, and fostering supportive policies that enable extensive adoption of hybrid renewable systems in off-grid settings.

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DECLARATION OF COMPETING INTEREST

None.

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