

COMPREHENSIVE REVIEW ON RULE-BASED ENERGY MANAGEMENT SYSTEM FOR HYBRID RENEWABLE ENERGY SOURCES WITH BATTERY BANK

Shehu Abubakar^{1*}, Ibrahim Abdulwahab², Gadaffi Sani Shehu³, David Enemali Abah⁴

^{1,2,3,4}Department of Electrical Engineering, Ahmadu Bello University, Zaria, Nigeria

*Corresponding author: bakrsmgee@gmail.com

Abstract

Keywords:

Battery Energy Storage System (BESS), Decision Rule Control, Hybrid Renewable Energy Sources (HRES), Microgrid Control, Optimization Algorithms, Rule-Based Energy Management System (RBEMS).

This paper presents a comprehensive review of Rule-Based Energy Management Systems (RB-EMS) applied to hybrid renewable energy systems integrated with battery storage. As hybrid configurations—typically combining photovoltaic (PV), wind, diesel generators, fuel cells, and battery banks—continue to gain prominence in both standalone and grid-connected microgrids, effective energy management becomes essential for achieving reliability, operational efficiency, and cost optimization. The review synthesizes recent advancements in RB-EMS architectures, control strategies, decision-making rules, and their applications in microgrid scenarios. Particular focus is placed on operational thresholds, mode-switching logic, battery state-of-charge (SOC) constraints, and real-time power flow coordination. The study also examines hybrid approaches where RB-EMS is integrated with optimization algorithms such as genetic algorithms, simulated annealing, deep learning models, and dynamic programming to enhance decision quality and economic performance. Strengths and limitations of existing RB-EMS solutions—including scalability challenges, rule-rigidity, and computational trade-offs—are discussed. Finally, the review highlights research gaps and future opportunities for intelligent, adaptive, and data-driven rule-based control frameworks capable of supporting next-generation resilient, low-carbon hybrid renewable energy systems.

1. INTRODUCTION

The global energy landscape is undergoing a fundamental shift driven by increasing electricity demand, depletion of fossil fuel resources, rising fuel prices, and the urgent need to mitigate greenhouse gas emissions Abdulwahab et al., (2024). These trends have accelerated the adoption of Hybrid Renewable Energy Systems (HRES), which integrate diverse renewable sources such as photovoltaic (PV) systems, wind turbines, fuel cells, microturbines, and backup diesel generators with Battery Energy Storage Systems (BESS) (Khalil et al., 2023). Such hybrid architectures leverage the complementary characteristics of individual renewable sources, enhancing overall system reliability, power quality, cost-effectiveness, and sustainability Hafis et al., (2023). However, the intermittent and stochastic nature of renewable energy sources introduces complexities in maintaining a stable energy supply, particularly in remote or rural microgrids Adefarati and Bansal, (2016). This challenge underscores the importance of an efficient Energy Management System (EMS) capable of coordinating power generation, storage, and consumption in real time. Among various EMS strategies David et al., (2025), (Garc and Dufo-l, 2019), the Rule-Based Energy

Management System (RB-EMS) has emerged as one of the most widely implemented due to its simplicity, transparency, computational efficiency, and ease of integration with distributed control platforms. RB-EMS operates using predefined decision rules often derived from expert knowledge, operational experience, or heuristic logic to determine power-sharing, mode switching, battery charging/discharging, and grid interaction. These rules are typically based on system state indicators such as battery state of charge (SOC), renewable generation availability, load demand, peak tariff periods, and grid conditions. Unlike mathematical optimization methods, RB-EMS offers fast execution and minimal computational burden, making it suitable for embedded controllers and real-time operation Sharma et al., (2016).

Despite its advantages, RB-EMS faces notable limitations. Rigid rule structures may not fully capture nonlinear system behaviors or dynamic interactions among multiple energy sources. Fixed thresholds can lead to suboptimal performance under varying conditions such as seasonal changes, rapid load fluctuations, or battery degradation. Recent studies therefore integrate RB-EMS with advanced optimization techniques, including genetic algorithms, simulated annealing, linear programming, mixed-integer nonlinear programming, and deep learning models, to enhance decision accuracy and adaptiveness. These hybrid approaches help overcome rule rigidity while retaining the practical implementation benefits of RB-EMS (Baba et al., 2023). Given the rapid expansion of HRES deployments and the evolving landscape of EMS technologies, a comprehensive review of RB-EMS is essential. Existing literature tends to focus on optimization-based or model predictive control approaches, while the unique contributions, strengths, and evolving capabilities of rule-based systems remain underrepresented. This review seeks to bridge that gap by systematically examining the architecture, operational strategies, decision logic, scalability, performance evaluation methods, and implementation challenges of RB-EMS in hybrid renewable energy systems supported by battery banks. The contribution of this review is as follows:

1. Analyze the fundamental principles, structure, and operational characteristics of RB-EMS in HRES applications.
2. Evaluate recent advancements, trends, and hybridization strategies combining rule-based logic with optimization and artificial intelligence.
3. Identify limitations, research gaps, and future perspectives for developing intelligent, adaptive, and self-learning rule-based EMS frameworks.

The remainder of this review is organized as follows: Section 2 presents an overview of existing approaches, Section 3 discusses energy management, and Section 4 concludes with a discussion of future work.

2. OVERVIEW OF EXISTING APPROACHES

Hybrid Renewable Energy Systems (HRES), typically integrating photovoltaic (PV), wind, micro-hydro, fuel cell, or diesel backup with battery storage, have emerged as a promising solution for reliable, low-carbon power supply. The intermittency and stochastic nature of renewable resources make energy management a central requirement for achieving stable and economical operation. Battery banks play a critical role in smoothing power fluctuations, ensuring energy continuity during low-generation periods, and mitigating voltage and frequency deviations within the local network. In Sharma et al. (2016), developed a Grey Wolf Optimization (GWO) algorithm to minimize the operational costs of grid-connected microgrids (MGs) comprising components such as wind turbines (WTs), photovoltaic (PV) arrays, microturbines (MTs), battery storage devices (BSDs), and fuel cells (FCs). The operational cost model specifically targeted MTs and FCs, incorporating operation and maintenance (O&M) expenses, fuel costs, as well as start-up and shut-down costs. In contrast, WTs, PVs, and BSDs were assumed to have zero start-up and shut-down costs. Additionally, the optimization process accounted for determining the optimal size of the BSD, which played a key role in reducing the overall operational expenses of the MG system. While GWO is effective for optimization, it may converge prematurely or fall into local minima in highly complex or non-convex problem spaces. This could affect the accuracy or optimality of the solution, especially when dealing with large-scale or multi-objective systems. Musa et al. (2023) designed and modeled a Hybrid PV-Micro Hydro Power Generation for the Jimma Zone of MenkoToli, Ethiopia. The work discussed the optimization and operational approach of a hybrid renewable energy system. This work aims to prove that

renewable energy can be used to provide electricity to remote areas. The procedures undertaken provided a promising result in terms of capital, maintenance, operating, and other related costs with comparable supply ratings. For instance, the net present cost (NPC), etc. In conclusion, the study encourages private investors and local community residents, especially in Ethiopia, to take advantage of renewable energy and be convinced that there is sustainability in investing in hybrid power systems. The results obtained in the projected work were carried out on NASA and SWERA data. HOMER software had been used for modeling optimized results of the hybrid power generation system and was observed to be cost-effective design. However, the designed renewable system did not consider the unmet load power, which turns the system into be unsustainable means of power supply. In Khalil et al., (2023) , tidal energy's influence on a hybrid system's optimal parameters was investigated. To evaluate such an approach, a framework has been modified to obtain the minimum cost of a hybrid energy system, where the reliability has been specified. Crow search optimization algorithm (CSA) was used to find said parameters. Accordingly, it is observed that the union of PV/wind and tidal energy resources could reach the best, most cost-efficient system when looked at in the context of other energy sources or a combination of the same. Furthermore, by using battery storage, an excess cost reduction results as a byproduct, and furthermore, augments the reliability of the system. However, model assumes static environmental and economic parameters over the simulation period, which may not reflect real-world variability in factors such as energy prices, resource availability, or load demand In Ahmed et al., (2017), an optimal sizing of renewable power system components has been studied. A comparison study between several renewable systems configurations (individual PV with battery, individual WT with battery, and combined PV-WT with battery) to supply agricultural irrigation pumps and housing for farmers with the electricity in two different locations have been studied. HOGA program is the core part of this study, and its results show effective solutions for all proposed configurations. NPC (net present cost) and COE (cost of energy) for all proposed configurations are compared and the best configurations is selected for each location based on the minimum NPC & COE that gives an indication to the optimum solution for such places. The study results proved that for the El-Arish location, standalone PV with battery configuration is the optimal solution for such a place with the minimum system cost. Meanwhile, the hybrid PV-WT-Battery approach is found as the optimal solution for the other location in Abu-Rudies region, which has the minimum NPC & COE values as compared with other configurations. However, the analysis does not incorporate potential grid connection options or backup systems, which may be viable in certain rural areas In (Toa et al., 2018), it is shown that the power supply of such systems, especially in combination with wind or solar battery storage, can replace the diesel generator for remote areas. Result shows that the proposed renewable hybrid system is a reasonably cost-efficient and dependable option for far-flung areas. Moreover, such a system's cost is anticipated to be decreased shortly due to an extensive improvement in renewable system components manufacturing. This can result in substantial fall in the renewable systems' costs and accordingly renewable systems will be more committed in remote areas. Accordingly, DG will be rarely used in remote areas in the future. In Fulzele et al., (2018). The study results verify that for different factors, the system composed of PV, WT, battery and converter provides best frugal and reliable settlement-based case study of the selected location. The sensitivity analysis could help to predict in advance for the proper future planning of hybrid renewable energy system. Optimization of hybrid renewable system for rural areas, should consider the economic feasibility as an essential objective in the planning of such system. Thus, economic feasibility is the most priority factor to be considered in design of the hybrid renewable system for rural regions in a developing country, the reason is that the consumers in such places normally not able to pay for expensive rates of power due to the modest economic conditions. In (Adesanya and Schelly, 2019) presented an assessment of the impact of solar PV-diesel hybrid systems on Nigeria's private sector. The work focused on assessing the viability of the hybrid solar PV-diesel generator system economically in Nigerian private companies. A case study of forty companies across the country was considered. The survey was carried out by designing a standard survey questionnaire to collect quantitative data in the companies to examine fuel savings that can be achieved. These data were then used as input to model design, design, and simulate using HOMER software. Energy and fuel consumption costs and sources of electricity and load profile represent the data collected. The data obtained were then analyzed and results were presented for the system. The results obtained showed that

the current energy cost (LCOE) with DG is less economically efficient for Nigerian businesses compared to the cost when PV was added. In Hemeida et al., (2020) worked on the optimum design of a hybrid wind/PV energy system for the remote area at Makadi Bay, Red Sea, Hurghada, Egypt. This study offered a workable approach that combined battery energy storage (BES) with a hybrid energy system that included renewable wind energy (WES) and photovoltaic (PVS). The wind speed was measured accurately and recorded. The temperature and sun irradiation were also measured during that time and took into account when calculating the output power of the suggested hybrid renewable energy system. During the same time period, the city's demand load data was also recorded in order to assess the system's viability. Utilizing the linear TORSCH optimization technique, the optimal solution for the suggested crossbred renewable energy system was achieved. In the presence of BES, individual PVS and WES configurations have been examined and contrasted with hybrid PV/WT. Moreover, arguments for the optimal economic system have been made using economic analysis. The obtained results show that installing such a hybrid system consisting of WES, PVS and BES is cheaper than installing each one individually. However, the optimization applied is linear, it may not be able to accommodate more than two sources of energy.

Nugroho et al., (2020), presented a techno-economic analysis of a hybrid PV/diesel/battery in a rural setting. The assessment was carried out in six randomly selected geo-political zones in Nigeria. HOMER software was used in evaluating the economic effect of different micro-grid component configurations (solar array, wind turbine, and diesel generator) in the six areas. The work targeted the net present cost, cost of energy, and sizing of the hybrid renewable configurations. The result obtained after the evaluation showed that the PV/diesel energy generator/ battery hybrid system is the best configuration based on the cost and CO₂ emission reduction.

Mutumbi et al., (2021) developed a techno-economic feasibility analysis of an interactive grid system using the solar system for South African residential load. The work shows the economic benefit of battery storage coupled directly to a grid-connected PV generation system. Factors considered in the study are as follows: net present cost, cost of energy under time of use, and feed-in tariff incentive. Data on annual real-time load demand from a typical residential consumer was acquired using HOMER software. Obtained results show an annual average electricity production from PV of about 70% of the total generation. The remaining 30% was obtained from the grid. Obtained results can still be improved, especially with the use of a metaheuristic algorithm.

Shufian and Mohammad, (2022), utilizes forecasted energy costs and load conditions to manage energy storage and dispatch from an integrated grid-connected battery system. Two distinct approaches are introduced: a heuristic method based on a state flow (chart flow) strategy, and a more advanced optimization method employing linear programming (LP). The LP-based approach is designed to minimize overall operational costs while adhering to system operational constraints. Results demonstrate that the LP optimization method achieves approximately 19% cost savings compared to the heuristic approach and enables the reduction of excess grid energy consumption by approximately 3.44–5.01%. These findings highlight the potential of predictive optimization techniques for improving the economic efficiency of battery-integrated energy systems. However, the linear programming (LP) approach assumes linear relationships between variables and does not capture non-linear system behaviors, such as battery degradation dynamics, inverter efficiency variation, or fluctuating grid tariffs.

Hafis et al., (2023), investigate the economic performance of a hybrid standalone energy system composed of small hydropower, photovoltaic (PV), and diesel generator components integrated with battery storage. The objective is to minimize the Cost of Energy (COE) by optimizing a defined cost function using the Dragonfly Algorithm (DA), a nature-inspired metaheuristic optimization technique. The decision variables in the optimization process include the number of small hydropower turbines (NSHP), number of PV panels (NPV), number of batteries (NBATT), and the capacity of the diesel generator (PDG). The proposed method is applied to a case study based in Kiri village, located in the Shelleng Local Government Area of Adamawa State, Nigeria. The results offer valuable insights into the optimal sizing of hybrid systems for remote, off-grid rural communities. However, the environmental impact of diesel fuel usage and battery disposal is not evaluated, limiting the sustainability assessment of the system.

(Jamal et al., 2024), utilized MATLAB Simulink software to model a grid-connected nanogrid (NG) incorporating hybrid renewable energy sources (HRES), specifically wind turbines and photovoltaic (PV) systems, along with three battery storage devices (BSDs). The objective was to design an effective Energy Management System (EMS) capable of reducing the overall operational costs of the NG system. To achieve this, a Rule-Based EMS (RB-EMS) was developed using State flow (SF) to ensure safe, reliable, and consistent power flow within the NG. Furthermore, the study introduced two optimization techniques Genetic Algorithm (GA) and Simulated Annealing Algorithm (SAA) to determine cost-effective operational strategies that satisfy the system's constraints, thereby minimizing the total cost of energy management within the nanogrid. The Genetic Algorithm (GA) and Simulated Annealing Algorithm (SAA) were effective but may not represent the optimal or most efficient algorithms for every operating scenario. Both methods can be computationally intensive and prone to local minima, especially in high-dimensional search spaces.

3. ENERGY MANAGEMENT SYSTEM

Designing an Energy Management System (EMS) involves addressing the challenge of balancing multiple competing objectives, often requiring trade-offs between conflicting needs. For example, optimizing fuel efficiency may need to be balanced against providing sufficient power for acceleration, or energy regeneration might conflict with preserving battery life. The goal is to identify an optimal solution that adapts to diverse driving conditions and operational demands, leading to various approaches in EMS design (Yu et al., 2022).

Energy Management Systems (EMSs) have traditionally been categorized into two main types: rule-based and optimization-based strategies. However, with the rapid advancements in computational technologies, driven largely by the growth of AI techniques, a new category has emerged learning-based EMSs. This classification, along with potential control strategies, is illustrated in Figure 1. Each approach offers unique methods for managing the complex dynamics of powertrains in hybrid electric vehicles (HEVs), enabling more efficient power distribution and system operation, while presenting distinct advantages and limitations (Gómez-barroso et al., 2025). Figure 1 presents a hierarchical classification of Energy Management Strategies into three primary categories: Rule-Based, Optimization-Based, and Learning-Based approaches. Rule-Based strategies include Deterministic methods (like Thermostat ON/OFF, Power Follower) and Fuzzy Logic variants (Basic, Adaptive, Predictive). Optimization-Based strategies are divided into Global Optimization (Like Dynamic Programming, Metaheuristics) and Real-Time Optimization such as Model Predictive Control, Robust Control). Learning-Based strategies encompass Machine Learning, Deep Learning (Supervised and Unsupervised), and Reinforcement Learning, including advanced techniques like Deep Reinforcement Learning and Artificial Neural Networks. This taxonomy provides a structured overview of the diverse methodologies employed in energy management systems, highlighting their operational logic and computational sophistication.

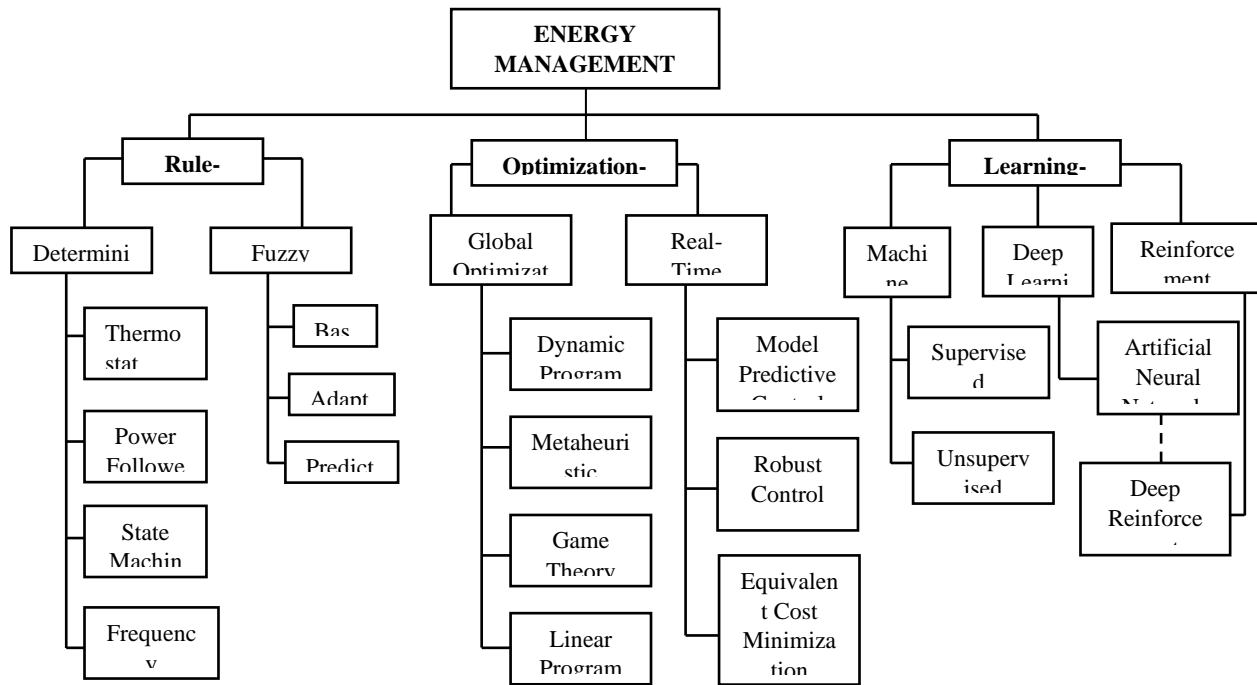


Figure 1: Energy Management System Classification (Gomez-Barroso et al., 2025)

3.1 Energy Management based on Optimization

In the study by Sharma et al. (2016), a Grey Wolf Optimization (GWO) algorithm was employed to reduce the operational cost of a grid-connected microgrid (MG) consisting of wind turbines (WTs), photovoltaic (PV) arrays, microturbines (MTs), battery storage devices (BSDs), and fuel cells (FCs). Their cost model focused primarily on MTs and FCs and included fuel expenditures, operation and maintenance (O&M) costs, and the start-up and shut-down costs associated with these units. In contrast, the PV, WT, and BSD components were assumed to have negligible start-up or shut-down costs. The optimization framework also estimated the appropriate capacity of the battery storage system, which proved essential in minimizing the total operational cost of the microgrid. Although GWO has strengths in handling engineering optimization tasks, it may still suffer from premature convergence or entrapment in local minima, particularly when applied to complex, large-scale, or highly non-convex optimization problems potentially compromising the optimality of its results in multi-objective scenarios.

Similarly, Musa et al. (2023) developed and analyzed a hybrid PV–micro-hydro power system for the MenkoToli area in the Jimma Zone of Ethiopia. Their work focused on the operational strategy and optimization of a hybrid renewable energy configuration to demonstrate its viability for supplying electricity to remote communities. The evaluation revealed favorable outcomes concerning capital investment, operating and maintenance costs, and overall economic performance, including metrics such as net present cost (NPC). Their conclusions encouraged both private investors and local inhabitants to adopt renewable-based hybrid systems due to their long-term sustainability and cost-effectiveness. The study utilized NASA and SWERA datasets, and HOMER software was applied to derive the optimal design configuration. However, a notable limitation of the proposed system was its failure to account for unmet load, which ultimately challenges the reliability and long-term sustainability of the solution.

In another related work, Oskovei et al. (2016) examined the impact of tidal energy on the optimal operational parameters of a hybrid renewable energy system, highlighting how marine resources can influence system design and energy management performance.

To assess this methodology, the authors adapted an evaluation framework to determine the minimum-cost configuration of a hybrid energy system while meeting predefined reliability criteria. The Crow Search Optimization Algorithm (CSA) was applied to identify the optimal system parameters. Their findings indicated that a combination of PV, wind, and tidal resources produced the most economical solution when compared with other single-source or multi-source configurations. The inclusion of battery storage further contributed to reducing overall costs while simultaneously enhancing system reliability. However, the model assumes constant environmental and economic conditions throughout the simulation period, which may not accurately represent real-world fluctuations in resource availability, market prices, and load demand.

In the work of Ahmed et al. (2017), optimal sizing of renewable energy components was explored. Their study compared different system configurations—including standalone PV with battery storage, standalone wind turbine (WT) with battery storage, and combined PV–WT–battery systems—to supply electricity for agricultural irrigation pumps and farmers' households across two different geographical locations. Using the HOGA optimization program, the study generated effective solutions for each configuration. The researchers evaluated the Net Present Cost (NPC) and Cost of Energy (COE) for all proposed systems, selecting the optimal configuration based on the lowest values of these indicators. The results showed that for the El-Arish location, a standalone PV–battery system offered the lowest system cost. Conversely, in the Abu-Rudies region, the hybrid PV–WT–battery option presented the most cost-effective solution, yielding the minimum NPC and COE among the tested alternatives. Nonetheless, the study did not consider the possibility of grid connection or backup power systems, which could be feasible in certain rural settings.

Similarly, Toa et al. (2018) demonstrated that renewable hybrid systems—particularly those integrating wind or solar power with battery storage—have the potential to fully replace diesel generators in remote regions. Their results confirmed that such systems are both cost-effective and reliable for electrifying distant communities. Furthermore, ongoing technological advancements and large-scale manufacturing of renewable energy components are expected to drive down system costs, making hybrid renewable solutions even more attractive and practical for remote-area deployment in the near future.

Consequently, the reliance on diesel generators (DGs) in remote regions is expected to diminish significantly in the future. In the work of Fulzele et al. (2018), the authors demonstrated that a hybrid configuration consisting of PV, wind turbines (WT), battery storage, and a power converter offered the most economical and reliable solution for the selected case-study location. Their findings also highlighted the value of sensitivity analysis, which enables planners to anticipate system performance under varying conditions and supports informed long-term decision-making. The study emphasized that, in rural regions—particularly within developing countries—economic feasibility must remain a primary consideration when planning hybrid renewable energy systems. This is largely due to the limited financial capacity of consumers in such areas, who are often unable to afford high electricity tariffs, making affordability a critical design requirement.

Similarly, Adesanya and Schelly (2019) examined the economic performance of solar PV–diesel hybrid systems within Nigeria's private sector. Their research evaluated the financial viability of integrating PV technology with existing diesel generator systems in forty private companies across the country. Quantitative data were collected through a standardized survey questionnaire that assessed fuel consumption, energy usage patterns, and existing electricity sources. These data were subsequently used as inputs for modeling and simulation in HOMER. The analysis revealed that the levelized cost of energy (LCOE) associated with diesel-only systems was less economical than the hybrid PV–DG configuration, demonstrating substantial cost savings for Nigerian businesses when PV was incorporated.

In a related study, Mutumbi et al. (2021) conducted a techno-economic feasibility assessment of a grid-interactive solar PV system designed for South African residential consumers. Their work illustrated the financial advantages of integrating battery storage with grid-connected PV systems. The parameters

considered included net present cost, cost of energy under time-of-use tariffs, and feed-in tariff incentives. Using real-time annual load data and HOMER simulations, the study found that approximately 70% of the total electricity generation came from PV, with the remaining 30% supplied by the grid. While the results were promising, the authors noted that further improvements could be achieved by incorporating metaheuristic optimization algorithms to enhance system performance and cost-effectiveness.

In the study by Hafis et al. (2023), the authors examined the economic performance of a standalone hybrid energy system comprising small hydropower, photovoltaic (PV) modules, and a diesel generator, all supported by battery storage. Their primary aim was to minimize the Cost of Energy (COE) by optimizing a specified cost function using the Dragonfly Algorithm (DA), a nature-inspired metaheuristic optimization method. The optimization considered several key decision variables, including the number of small hydropower turbines (NSHP), the number of PV modules (NPV), the battery bank size (NBATT), and the diesel generator capacity (PDG). The methodology was applied to a rural case study in Kiri village, located within the Shelleng Local Government Area of Adamawa State, Nigeria, and the findings provided practical guidance on optimal system sizing for off-grid communities. However, the study did not assess the environmental implications of diesel consumption or end-of-life battery disposal, which limits the comprehensiveness of the sustainability evaluation.

Figure 2 illustrates a structured taxonomy of Optimization Techniques commonly employed in energy systems and engineering applications. The diagram categorizes eight distinct methodological approaches: Linear and Nonlinear Programming, Metaheuristics, Multi-Agent Systems, Dynamic Programming, Stochastic and Robust Programming, Predictive Control, Artificial Intelligence, and a general category for Other Techniques. This classification highlights the diversity of optimization paradigms, ranging from classical mathematical formulations to intelligent, adaptive frameworks, thereby providing a comprehensive overview of the tools available for solving complex, multidimensional optimization problems.

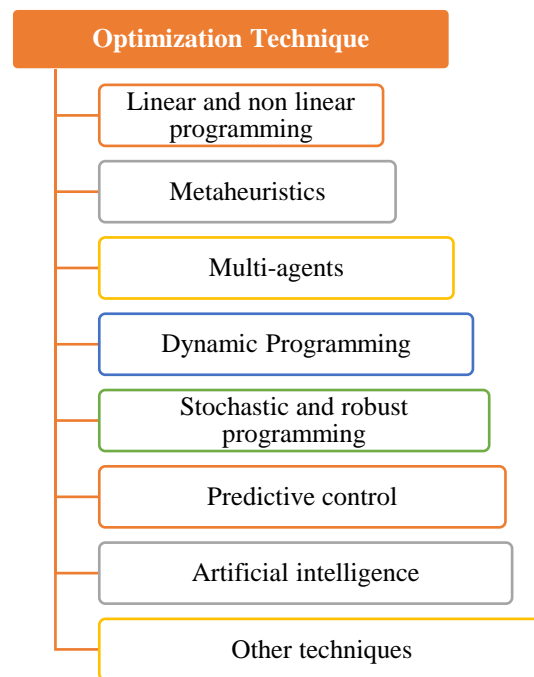


Figure 2: Optimization technique in energy management

3.2 Energy management based of Linear and non-linear programming

In the study by Shufian and Mohammad (2022), the authors employed forecasted energy prices and load profiles to regulate energy storage and power dispatch in a grid-connected battery system. They

proposed two management strategies: a heuristic method derived from a state-flow (flowchart-based) decision process, and an advanced optimization strategy based on linear programming (LP). The LP formulation seeks to minimize total operational costs while respecting all system constraints. Their findings revealed that the LP-based strategy achieved roughly 19% cost reduction compared with the heuristic method and lowered unnecessary grid energy usage by 3.44–5.01%. These results underscore the effectiveness of predictive optimization in enhancing the economic performance of battery-supported energy systems. Nevertheless, the LP model is limited by its assumption of linearity among system variables, making it unsuitable for representing non-linear behaviors such as battery degradation, inverter efficiency fluctuations, or dynamic tariff structures.

In a related contribution, Hemeida et al. (2020) developed an optimized hybrid wind–PV energy system for Makadi Bay in Hurghada, Egypt, aimed at powering remote areas. The study integrated battery energy storage (BES) with wind energy systems (WES) and photovoltaic systems (PVS). Accurate measurements of wind speed, temperature, and solar irradiance were collected and incorporated into the power generation calculations, while real demand-load data from the region were used to evaluate system feasibility. Using the linear TORSCHÉ optimization tool, the authors identified the optimal configuration of the proposed hybrid system. Performance analyses were conducted for standalone PVS, standalone WES, and the combined PV–WT system with BES, followed by economic comparisons to determine the most cost-effective option. The results demonstrated that the hybrid configuration with BES was more economical than installing either wind or solar systems individually. However, because the applied optimization approach was linear, it lacked the flexibility to effectively model scenarios involving more than two renewable sources or non-linear system interactions.

In the study conducted by Nugroho et al. (2020), a techno-economic evaluation of a hybrid PV–diesel–battery system for rural electrification was performed across six randomly selected geopolitical zones in Nigeria. Using HOMER software, the researchers assessed the economic implications of various microgrid component combinations, including solar PV arrays, wind turbines, and diesel generators. Key performance indicators such as net present cost (NPC), cost of energy (COE), and optimal component sizing were analyzed for each location. The findings indicated that the PV–diesel–battery hybrid configuration offered the most cost-effective solution while also yielding significant reductions in CO₂ emissions compared with the other examined alternatives.

3.3 Energy management based on Rule-based

Satish and Rao (2014) developed a rule-based energy management system (RB-EMS) for a standalone DC microgrid consisting of photovoltaic (PV) generation, a fuel cell, and a battery bank. Their work demonstrated the use of threshold-based rules and decision flows that enable coordinated operation under islanded conditions.

Similarly, Kumar and Bhongade (2017) proposed a rule-driven control framework for long-term planning and operation of off-grid microgrids. Their scheme combined queuing theory with rule-based logic to support optimal sizing and operational scheduling of hybrid energy systems.

In another contribution, Hasanien and El-Fergany (2019) introduced a modular RB-EMS designed to dynamically adjust to microgrid reconfigurations and different component combinations, including electric vehicles (EVs), battery energy storage systems (BESS), and microturbines (MTs). The authors highlighted the scalability and adaptability of their approach, emphasizing its suitability for microgrids that evolve over time.

More recently, Jamal et al. (2024) utilized MATLAB/Simulink to model a grid-connected nanogrid (NG) integrating wind turbines, photovoltaic (PV) generators, and three battery storage units. The goal was to design an EMS capable of minimizing the operational cost of the hybrid system. A Rule-Based EMS (RB-EMS) was developed using Stateflow to ensure safe, stable, and coordinated energy flow within the nanogrid. In addition, the researchers applied two metaheuristic optimization techniques Genetic Algorithm (GA) and Simulated Annealing Algorithm (SAA) to derive cost-effective operational strategies that maintain compliance with system constraints. While GA and SAA yielded improved cost efficiency, both

methods are computationally demanding and susceptible to getting trapped in local minima, particularly in complex or high-dimensional optimization spaces.

Figure 3 illustrates a cyclic framework for Energy Management, comprising five interdependent stages that form a continuous improvement loop. The process begins with Defining Rules, where operational criteria and energy usage guidelines are established. This is followed by Monitoring Energy Usage, enabling real-time tracking of consumption patterns. Next, Controlling Energy Resources involves adjusting energy flows based on predefined rules to maintain efficiency. The fourth stage, Optimizing Energy Consumption, focuses on minimizing costs and enhancing sustainability. Finally, Adapting to Needs ensures the system remains responsive to evolving operational requirements. This closed-loop structure emphasizes dynamic control, feedback integration, and adaptive optimization in modern energy systems.

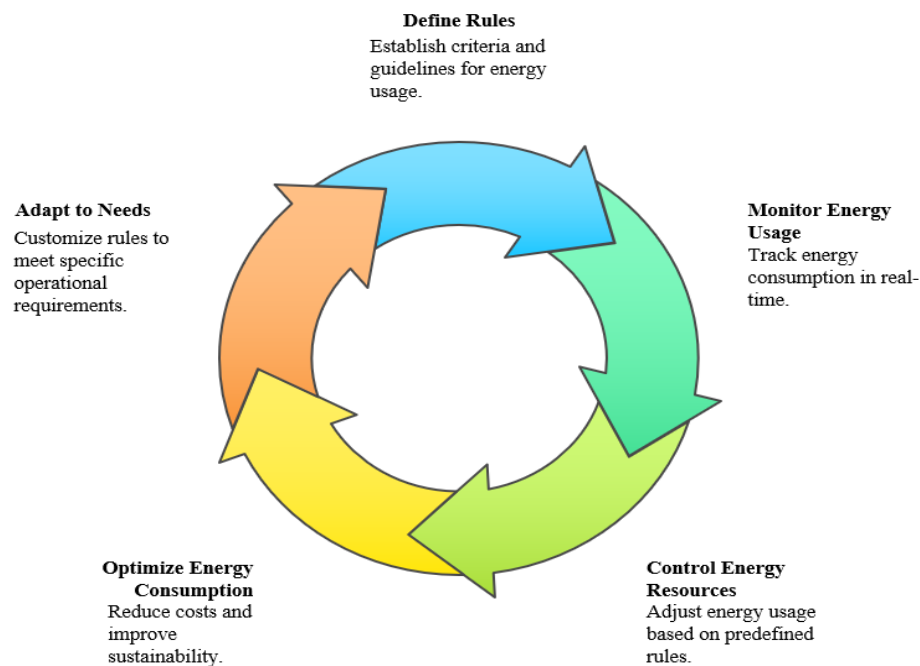


Figure 3: Rule-based Energy Management Cycle

Figure 4 presents a systematic flowchart for achieving Sustainable and Reliable Energy Management, emphasizing the interplay between forecasting, storage control, and adaptive distribution. The process initiates with Energy Demand Forecasting, which informs whether the current demand is met. If affirmative, the system proceeds to charge the Battery Bank; otherwise, it triggers Discharge of the Battery Bank to maintain supply continuity. Both pathways converge at Efficient Energy Distribution, enabling the prioritization of Maximum Renewable Energy Use. This leads to a reduction in dependence on conventional sources through the Minimization of Conventional Energy Reliance, and supports Adaptability and Responsiveness to dynamic load profiles and operational conditions. The framework culminates in the overarching objective of Sustainable and Reliable Energy Management, aligning with the broader goals of resilient, low-carbon power systems.

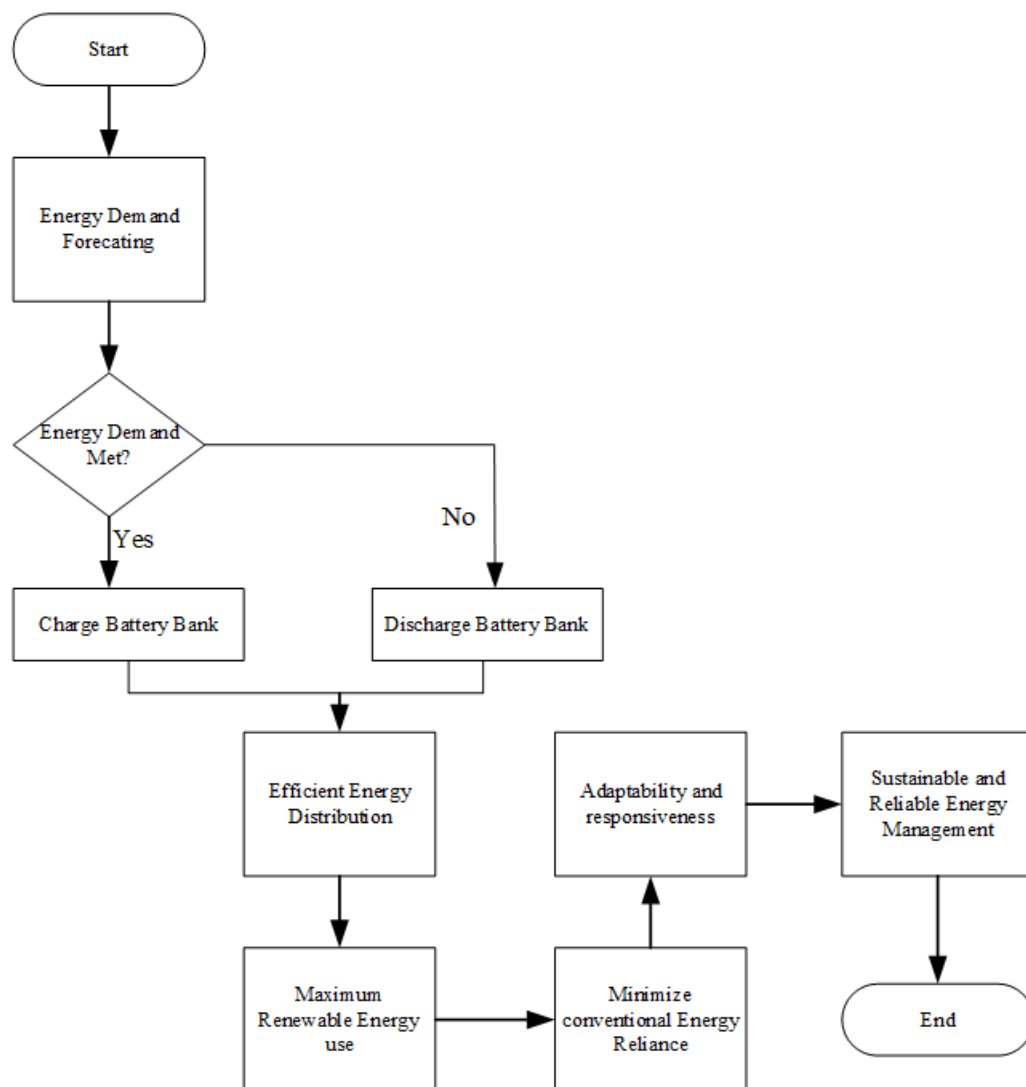


Figure 4: Rule-based Energy Management System flowchart

3.4 Energy management based on dynamic programming

Trivedi et al., (2016) developed an EMS framework for microgrids using a hybrid optimization approach that integrates dynamic programming with mixed-integer nonlinear programming (MINLP). The system, linked to the main utility grid, performs decision-making based on the Bellman equation, where historical data are utilized for offline optimization considering power flow and battery capacity constraints. The study also highlights the potential scalability of the proposed algorithm for coordinated energy management across multiple interconnected microgrids.

Baba et al., (2023) proposed a centralized EMS capable of managing microgrids in both stand-alone and grid-connected modes. In standalone operation, the fuel cell is dispatched only when the battery state of charge (SOC) falls below 80%, ensuring prolonged battery life and supply reliability. Under grid-connected conditions, a reduced SOC threshold of 60% is adopted to optimize energy exchange with the utility grid while maintaining system stability.

Khalil et al., (2023) presented an EMS approach based on dynamic programming combined with deep learning for real-time control of stand-alone microgrids. The system enables intra-day scheduling and continuously updates optimal control strategies in response to varying renewable generation and load conditions. The framework also integrates communication signals from local controllers, thus supporting a coordinated, centralized microgrid management architecture.

Iliyasu et al., (2024) introduced an energy management model that incorporates both battery SOC and ultra-capacitors to enhance transient performance and energy balancing. The proposed hierarchical management strategy defines four distinct operational modes—normal operation, photovoltaic (PV) limitation, recovery, and stand-alone mode—allowing the microgrid to adapt dynamically to resource availability, load variations, and system disturbances.

3.5 Energy management based on other miscellaneous techniques

Joseph et al. (2025) introduced an optimization framework aimed at identifying the most economically viable configuration of a stand-alone microgrid incorporating lithium battery storage. Their study assessed multiple energy management control strategies, while battery lifespan was evaluated through an advanced electrochemical model to ensure durability and long-term performance.

Magaji et al. (2023) carried out a comparative analysis of diverse optimization objectives for stand-alone microgrid management. Their methodology primarily employed linear programming and genetic algorithms. Results revealed that optimizing controllable loads not only reduces operational expenses but also facilitates greater integration of renewable energy sources.

Musa et al. (2023) focused on the design and optimization of microgrids by applying mixed-integer programming for energy management. To address uncertainties in photovoltaic generation, they utilized a probabilistic Markov model, complemented by a linear model to estimate the overall lifetime of the microgrid system.

Das et al. (2011) proposed a hierarchical energy management framework tailored for interconnected residential microgrids serving prosumers. Their approach combined local control mechanisms with a central supervisory controller, enabling coordinated energy management through information exchange between distributed units.

4. CONCLUSION AND FUTURE RESEARCH

This comprehensive review has critically examined the role, structure, and evolution of Rule-Based Energy Management Systems (RB-EMS) within Hybrid Renewable Energy Systems (HRES) integrated with battery storage. As hybrid microgrids become increasingly central to global energy transitions, particularly in rural electrification, decentralized power systems, and smart grids, RB-EMS remains one of the most widely implemented control strategies due to its simplicity, transparency, modularity, and low computational requirements. The review demonstrates that RB-EMS continues to serve as the foundational EMS approach in systems requiring robust and real-time decision-making without dependence on high-performance computing infrastructure. Findings from the literature confirm that RB-EMS effectively coordinates multiple renewable energy sources such as photovoltaic (PV), wind, micro-hydro, fuel cells, and diesel generators, while ensuring safe battery operation through SOC-based logic. Its rule-oriented structure makes it suitable for embedded controllers, low-resource environments, and remote microgrids where reliability and predictability take precedence over optimization complexity. In addition, the adaptability of RB-EMS enables integration with new DER components such as electric vehicles and ultra-capacitors, providing scalable and modular EMS architectures for evolving microgrid configurations. However, despite its strengths, this review highlights several inherent limitations of conventional RB-EMS. These include restricted adaptability to fast-changing environmental conditions, difficulty in handling nonlinear system behaviors, and performance degradation under uncertainty. The deterministic threshold rules used in RB-EMS often struggle to capture stochastic variations in renewable generation, dynamic pricing, battery aging effects, and fluctuating grid constraints. Moreover, as hybrid systems grow in size and complexity, traditional rule bases become unwieldy and challenging to tune manually, leading to suboptimal operational efficiency compared to optimization-based or intelligent EMS approaches. Recent research trends show a growing shift toward hybrid RB-EMS frameworks, which integrate metaheuristic

optimization, machine learning, dynamic programming, and predictive models to overcome these limitations. These hybrid approaches retain the interpretability and operational safety of rule-based logic while enhancing adaptability, economic performance, and resilience under uncertainty. This evolution reflects a broader paradigm shift in EMS design—moving from fixed heuristic rules to intelligent, adaptive, and data-driven strategies. Overall, the review concludes that RB-EMS will continue to play a vital role in the design and operation of HRES, especially for developing countries and remote communities where simplicity, cost-effectiveness, and ease of implementation remain top priorities. However, the future of RB-EMS lies in its integration with advanced optimization and learning-based techniques. Future research should therefore focus on developing adaptive RB-EMS, incorporating real-time forecasting, battery degradation models, uncertainty quantification, and self-learning algorithms to ensure reliable and economically optimal operation. In this way, RB-EMS can maintain its relevance while contributing to the next generation of intelligent, resilient, and sustainable microgrids.

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