Cureus Journal of Engineering
https://doi.org/10.7759/s44388-025-00041-y

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Part of SPRINGER NATURE

Review Article

A Critical Review of Microgrid Technologies: Storage and Control Systems with Effective Optimization Techniques for Modeling Wind, Solar, Biomass, and Battery Energy Storage Systems

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Received: September 05, 2025 | Review began: October 30, 2025 | Review ended: January 04, 2026 | Published: March 25, 2026

Abstract

This study provides an integrated and quantitative assessment that jointly examines energy storage technologies, control architectures, optimization algorithms, and capacity-demand matching in renewable-based microgrids. A distinctive contribution of this review is the comparative evaluation of optimization techniques in terms of convergence speed, accuracy, and real-time applicability, along with a unified analysis of how different renewable sources and storage systems collectively influence demand matching, system reliability, and cost-effectiveness. The study systematically examines centralized, decentralized, and distributed control frameworks, emphasizing their roles in maintaining system stability, enhancing energy efficiency, and ensuring resilient microgrid operation. Various optimization algorithms are critically compared in terms of convergence rate, computational efficiency, and accuracy to evaluate their suitability for real-time control applications. The review further analyzes key performance metrics - such as efficiency, capacity factor, and cost-effectiveness - across different renewable energy technologies, including photovoltaic, wind, biomass, and energy storage systems. Also, the study discusses potential solutions such as hybrid energy storage systems, multi-agent and hierarchical control, and AI-driven predictive energy management. Moreover, an in-depth analysis of capacity-demand matching is presented to assess how effectively renewable generation profiles align with fluctuating load demands over time.

Categories: Power Electronics and Renewable Energy

Keywords: renewable energy, energy storage, control system, optimization, cost analysis

Introduction And Background

Fossil fuel-based conventional energy generation resources such as coal, oil, and gas have been the primary sources of energy for human activities. However, the use of these resources has been linked to negative environmental impacts such as air and water pollution, climate change, and global warming [1]. Renewable energy resources, on the other hand, are considered a sustainable alternative to address the high energy demand. These resources include solar, wind, biomass, hydro, geothermal, and others. Unlike conventional energy resources, they are naturally replenished and have a minimal impact on the environment. Moreover, renewable energy resources can provide a reliable source of energy in remote areas where conventional energy infrastructure is limited or nonexistent [2]. Microgrids are an emerging concept in the field of electricity generation and distribution, which are designed to provide a local and reliable source of electricity to consumers. A microgrid can operate independently of the main power grid in the event of an outage or other disruption.

A microgrid typically consists of a mix of distributed energy resources (DERs), such as solar panel, wind turbines, biomass and battery storage systems as shown in Figure 1. These resources are integrated and managed using advanced control and monitoring systems, which allow the microgrid to operate efficiently and effectively [3]. Another important feature of microgrids is that they can be operated and controlled locally, which can help to improve the reliability and resilience of the electricity supply (Figure 1).

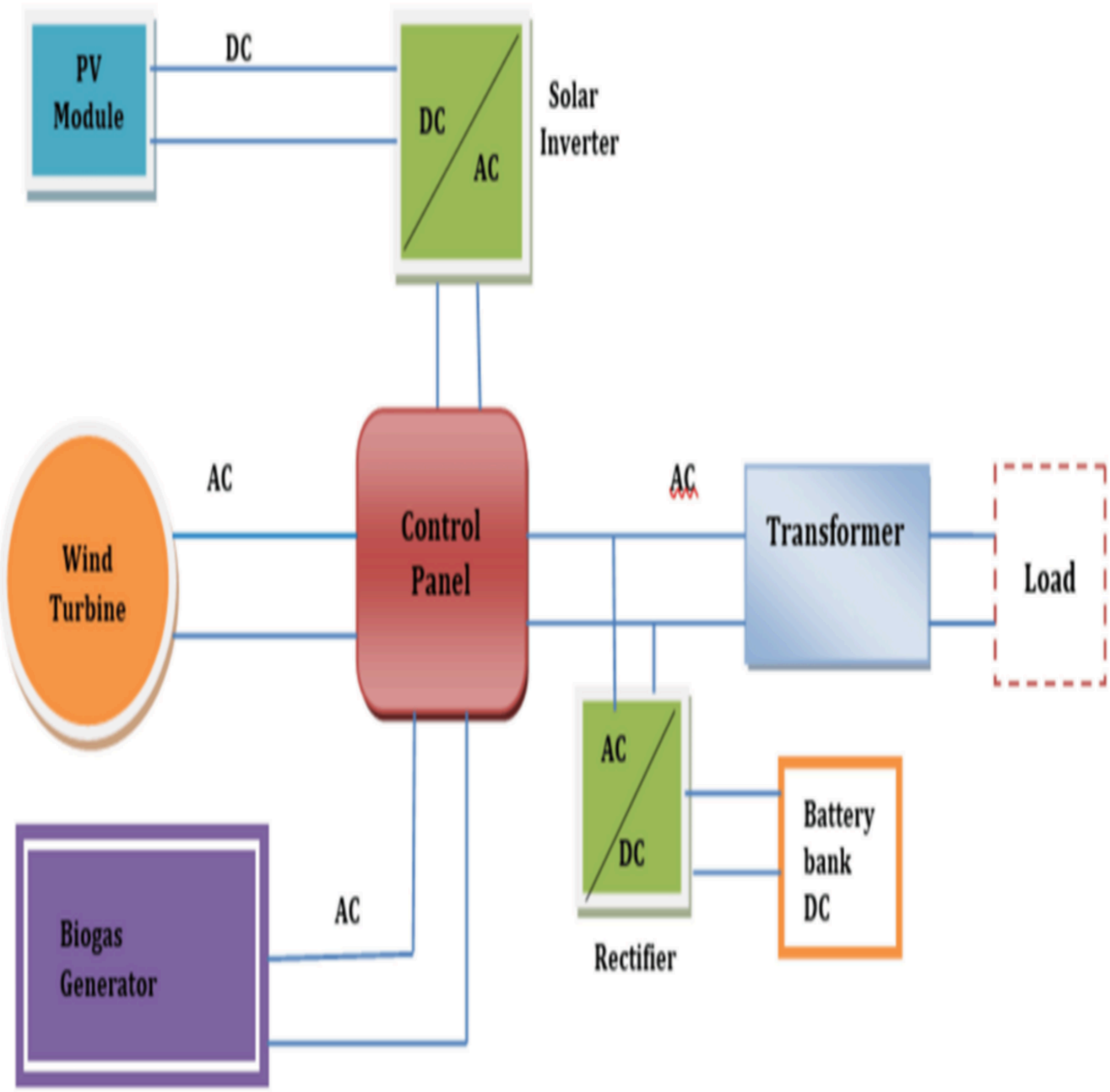

FIGURE 1: General Hybrid Model of a Microgrid-Based Renewable Energy Source

Several studies contribute valuable insights into the design, optimization, and implementation of hybrid renewable energy systems (HRESs) across diverse geographical locations and contexts. A study conducted by [4] and [5] employs multi-objective optimization algorithms to simultaneously address economic, environmental, and reliability objectives. In addition, the study in [5] integrates battery storage systems with solar and wind power to improve fuel efficiency and reduce reliance on diesel generators [6]. Advanced modeling techniques play a crucial role in optimizing HRES design and operation [7]. The use of genetic algorithms for system optimization [8] and MATLAB/Simulink for system simulation are employed to model and analyze HRES performance. In this context, various computer tools have emerged to assist researchers, policymakers, and stakeholders in analyzing, optimizing, and planning microgrid systems. These tools offer diverse functionalities to address specific challenges related to renewable energy integration, techno-economic analysis, and environmental sustainability within urban contexts [9]. Tools like HOMER offer an effective means of simulating microgrid configurations and assessing the feasibility of renewable energy deployment [10]. These tools are widely used for the design and optimization of off-grid and grid-connected power systems. It allows users to model various energy resources along with battery storage systems [11]. These tools employ optimization algorithms to find the optimal configuration of energy resources and system components based on user-defined objectives (e.g., cost minimization, reliability maximization). They can also be used to analyze the integration of battery storage systems within microgrids serving buildings or communities. Furthermore, energy management systems (EMS), battery storage technologies, and grid control strategies play a crucial role in balancing supply and demand, mitigating forecasting errors, and optimizing the utilization of energy storage systems (ESSs) [12]. These technologies include batteries, supercapacitors, compressed air storage, hydrogen storage, and more. Each of these storage options offers unique advantages in terms of power density, efficiency, scalability, and environmental impact. Significant advancements have been made in the development of novel materials and architectures for energy storage devices. For example, the synthesis of Sm_2O_3/rGO nanocomposites has demonstrated high specific capacitance and electrochemical efficiency, highlighting the potential of such materials for supercapacitor applications [13]. Also, to determine the appropriate capacity and size of battery energy storage (BES) for optimized operation cost minimization in a microgrid, several factors must be considered. The objective function can be formulated as the sum of the capital costs of the components and the operational costs over a certain period of time. These include the expected energy demand and supply profile of the microgrid, the size and capacity of wind turbines and PV units, and the efficiency and performance of the BES system itself. Various optimization algorithms can be used to determine the optimal size and capacity of the BES system [14]. The microgrid central controller can ensure that the microgrid operates optimally while minimizing operation costs. The microgrid sizing algorithm involves optimizing the size and configuration of various components in a microgrid, such as generation sources, storage systems, and control systems, to achieve a balance between cost, emission, and reliability. In microgrid sizing [15], constraints are an important aspect of problem-solving and decision-making. Some of the constraints in microgrid sizing are shown in Figure *3*. To optimize the size of a PV/Wind/biomass-integrated hybrid energy system with battery storage, various algorithms can be used to find the optimal sizes of the components that minimize the total cost of the system. The decision variables can include the size of the PV array, wind turbines, biomass, battery bank, and other components. The environmental sustainability of energy storage technologies is another critical consideration. More comprehensive life-cycle assessments are also required to evaluate the environmental impact of different storage options.

With the increasing integration of renewable energy sources, the need for advanced control methods in managing microgrid operations has become important. Researchers have investigated various control strategies to optimize microgrid operation, improve resource utilization, and ensure reliable performance. According to [16], centralized control methods have been proposed to coordinate system-wide operations from a single control center. However, challenges such as scalability and vulnerability to single points of failure may limit the applicability of centralized control in certain scenarios. The decentralized approach enhances system resilience, responsiveness, and scalability by enabling the autonomous operation of individual components. Decentralized control offers flexibility, adaptability, and fault tolerance, making it suitable for diverse microgrid configurations. Hybrid approaches combine elements of both control methods to leverage the strengths of each approach. The development of robust and adaptive control strategies that can effectively manage the battery state of charge (SoC) while considering dynamic operating conditions, battery degradation mechanisms, and grid integration requirements has been explored [17]. The major contributions of recent studies related to microgrid energy storage and control strategies are summarized in Table *1*.

Reference	Objective	Research Methodology	Key Results
Elalfy et al., Comprehensive review of energy storage systems (2024). [18]	Provide an up-to-date, cross-technology review of ESSs applicable to grids and microgrids.	Literature survey and techno-economic/technical synthesis of storage types (electrochemical, mechanical, thermal, electrical).	Summarizes maturity, application niches, performance trade-offs (efficiency, response time, scalability); highlights hybridization (e.g., batteries + long-duration storage) and need for standardized metrics for microgrid planning.
Choudhury et al., Review of energy storage system technologies integration (2022). [19]	Review ESS integration challenges and control methods for microgrid applications.	Structured review covering control, sizing, power electronics interfaces, and operational use-cases.	Identifies main challenges: SoC balancing, degradation modeling, control coordination; recommends advanced hierarchical control and combined sizing-control co-design.
Shamarova et al., BESS modeling in microgrids (Energies, 2022). [20]	Analyze battery models and lifetime/degradation modeling for microgrid BESS.	Comparative review of electrochemical, equivalent-circuit and data-driven models; links models to operational strategies.	Shows that accurate degradation-aware models are essential for realistic sizing and operation; emphasizes gap in field data for model validation.
Eskandari et al., BESS and the economy: applications/time-constants (2022). [21]	Classify BESS applications by time-scale and assess economic roles in microgrids.	Review + classification (synthetic inertia, frequency regulation, arbitrage, backup).	Finds that economic viability depends strongly on application portfolio and market/regulatory environment; multi-service stacking improves ROI.
Nagasri and Marimuthu, Review on advanced control techniques for microgrids (2023). [22]	Survey advanced controllers (MPC, multi-agent, sliding mode, adaptive) for microgrid stability and performance.	Thematic literature review organized by control objective (frequency, voltage, power sharing) and control class.	MPC and multi-agent methods show best performance for multi-objective optimization and uncertainty handling; however, computation/communication overhead and robustness under cyber/communication faults remain open issues.
Uddin et al., Microgrids: review, outstanding issues and future trends (2023). [23]	Holistic review of microgrid concepts including controls, EMS, protection, market integration.	Comprehensive literature review plus gap analysis.	Highlights need for standardized EMS architectures, V2G/DER integration, cybersecurity, and improved forecasting + scheduling algorithms for resiliency.
Makkiabadi et al., Performance Evaluation of Solar Power Plants: A Review & Case Study (Processes, 2021). [24]	Review performance metrics and methods for evaluating PV plants; include case study.	Survey of performance ratio, capacity factor, degradation assessment; applied case analysis.	Recommends harmonized KPIs and improved on-site monitoring/clearing of losses; shows how operational decisions affect long-term performance.
Al-Ghussain et al., Sizing renewable systems with storage: methodology (2020). [25]	Propose sizing methodology for RES components with various ESS scenarios for microgrids (techno-economic).	Simulation/optimization study comparing sizing results under different load profiles and storage options.	Demonstrates that inclusion of storage and sensitivity to load/solar profiles changes optimal component sizing; techno-economic tradeoffs depend on hourly demand and cost assumptions.
Balasubramanian and Balachandra, Effectiveness of demand response for supply-demand matching (R & SR, 2021). [26]	Evaluate demand response (DR) as a tool to match supply with variable renewables.	Modelling study (system simulations) comparing DR strategies vs storage-only strategies.	Finds DR can significantly reduce required storage capacity and system cost if participation

			is high; DR complements storage and grid flexibility solutions.
Ding et al., Distributionally robust capacity configuration for energy storage (Frontiers in Energy Research, 2022). [27]	Determine storage capacity configuration under uncertainty of renewable generation using robust optimization.	Distributionally robust optimization (DRO) applied to energy storage sizing in microgrids.	DRO yields conservative but more reliable capacity sizing under distributional uncertainty; improves resilience at modest cost increase.
NREL, Microgrids for Energy Resilience: Guide (2019, report). [28]	Practical guidance for microgrid analysis, design & resilience (DoD & energy stakeholders).	Best-practice guide synthesizing case studies, modelling approaches, and design workflows.	Provides design workflows integrating RES, storage, controls, and resilience metrics; emphasizes multi-year/horizon planning and stakeholder requirements.
Recent capacity configuration / sizing study (2023) — Capacity model and optimal scheduling of multi-microgrid energy storage sharing (Dai et al., 2024/2023). [29]	Explore multi-microgrid energy storage sharing and optimal scheduling to improve capacity utilization.	Mathematical modeling + optimization (scheduling + capacity allocation) and simulation.	Shows that shared ESS and coordinated scheduling reduce aggregate storage needed and increase renewable utilization; coordination algorithms needed for fair allocation.

TABLE 1: Comparative Review of Research on Energy Storage and Control Strategies in Microgrids

BESS, Battery Energy Storage System; ROI, Return on Investment; MPC, Model Predictive Control; EMS, Energy Management System; KPI, Key Performance Indicator; RES, Renewable Energy Source; ESS, Energy Storage System

A primary issue is the tendency of previous research to focus predominantly on limited combinations of renewable energy sources (RESs), primarily solar and wind. A more comprehensive exploration of various energy combinations could lead to enhanced energy efficiency, reduced costs, and greater system resilience in the face of fluctuating demand and supply conditions. Previous approaches often neglect the integration of demand response programs and real-time pricing, which are essential for maximizing the efficiency of energy systems. Another gap is the limited exploration of multi-objective optimization frameworks that simultaneously consider economic, environmental, and social factors. Most studies focus on a singular aspect, such as cost minimization or emission reduction. Moreover, traditional optimization techniques often require extensive manual parameter tuning, which can be both time-consuming and inefficient. Each storage technology has distinct characteristics, efficiencies, and costs, which can significantly influence its effectiveness in meeting fluctuating demands. The integration of energy sources with storage solutions and control systems is essential for optimizing modern energy systems, yet there are significant gaps in previous research and practice that limit the effectiveness of these integrations.

To complement the systematic literature review and to objectively assess the evolution of research in renewable-based microgrids, a bibliometric analysis was conducted focusing on scientific production trends and keyword relationships. The bibliometric study provides a quantitative overview of publication growth, dominant research themes, and emerging topic linkages within the field of microgrid energy storage, control strategies, and capacity-demand matching. The bibliometric dataset was extracted from the Scopus scientific database, covering peer-reviewed journal articles published between 2019 and 2025. The search was performed using Boolean combinations of keywords including “microgrid”, “energy storage system”, “battery energy storage”, “renewable energy integration”, “control strategy”, “energy management system”, and “optimization”. Only English-language articles relevant to distributed and microgrid-level applications were considered. Keyword co-occurrence and publication trend analyses were conducted using bibliometric mapping techniques. The results were used to identify the evolution of research interest and the structural relationships between major thematic areas. Tables *2* and 3 summarize the bibliometric findings, presenting annual publication trends and the thematic relationships among dominant keyword clusters in microgrid energy storage and control research.

Year	No. of Publications	Research Trend Interpretation	
2019	Low–Moderate	Early focus on basic microgrid architectures and battery integration	
2020	Moderate	Increased interest driven by renewable penetration and grid resilience	
2021	Moderate–High	Growth in optimization-based sizing and control strategies	
2022	High	Expansion toward distributed control, EMS, and hybrid storage	
2023	High	Strong emphasis on AI-based control, uncertainty handling, and degradation-aware models	
2024	Very High	Focus on real-time optimization, hybrid ESS, and capacity–demand matching	
2025*	Emerging	Shift toward intelligent, resilient, and sustainable microgrid frameworks	

TABLE 2: Bibliometric Summary of Scientific Production on Microgrid Energy Storage and Control (2019–2025)

EMS, Energy Management System; ESS, Energy Storage System; AI, Artificial Intelligence

The steady increase in annual publications highlights the growing global research interest in renewable-based microgrids, particularly in integrating energy storage, advanced control strategies, and optimization techniques to improve reliability and sustainability. The bibliometric findings confirm that recent research increasingly emphasizes integrated approaches combining energy storage technologies, control architectures, optimization algorithms, and demand-matching strategies.

Cluster No.	Keyword Cluster Theme	Representative Keywords	Research Focus	Linkages to Other Clusters		
1	Energy Storage Technologies	Battery Energy Storage, Supercapacitor, Hybrid ESS, Degradation, Lifecycle	Performance improvement, lifetime extension, hybridization	Strong link with control and optimization		
2	Microgrid Control and EMS	Centralized Control, Distributed Control, Multi-agent System, EMS	Stability, power sharing, real-time operation	Strong link with optimization and demand matching		
3	Optimization and Scheduling	MILP, PSO, GWO, ADMM, MPC, Multi-objective Optimization	Cost minimization, sizing, scheduling under uncertainty	Links storage and control clusters		
4	Capacity–Demand Matching and Renewable Integration	Capacity Factor, Load Matching, Demand Response, Peak Shaving	Aligning generation with variable demand	Strong link with storage and optimization		

TABLE 3: Keyword Cluster Analysis and Research Linkages in Microgrid Literature

EMS, Energy Management System; ESS, Energy Storage System; MILP, Mixed-Integer Linear Programming; PSO, Particle Swarm Optimization; GWO, Grey Wolf Optimizer; ADMM, Alternating Direction Method of Multipliers; MPC, Model Predictive Control

The paper is organized to first present a detailed review of storage technologies in microgrids, followed by an overview of advanced control technologies and strategies. It then discusses the performance analysis of renewable energy technologies along with proposed improvements in storage and control systems. The analysis also addresses capacity configuration and demand matching for renewable-based microgrids. Finally, the paper concludes with key findings and future research recommendations.

Review

Storage technology for microgrids

A storage system is being used to supply continuous power during peak hours. There are numerous power storage alternatives available at present, as shown in Figure *2*. Batteries, supercapacitors, hydroelectric pumped storage, hydrogen storage, compressed air storage, flywheel storage, and liquid air storage, among others, are all examples of energy storage devices. A battery can generate high power for short- and medium-length hours and has a quick dynamic response [30]. Some of the battery selection criteria are shown in Figure *3*.

Each energy storage technology presents specific limitations that must be considered for practical deployment. For example, Compressed Air Energy Storage (CAES) systems are highly dependent on suitable underground geological formations, such as salt caverns or aquifers, limiting their geographical applicability. Similarly, battery energy storage systems, particularly lithium-ion batteries, are prone to accelerated degradation in tropical climates due to high ambient temperatures, which affect both cycle life and safety. These constraints highlight the importance of selecting storage technologies based on regional conditions and application-specific requirements.

A power storage mechanism that bridges between rechargeable batteries and electrolytic capacitors is known as a supercapacitor (SC). This high-capacity capacitor [31] has an extremely high capacitance and a low voltage limit. Compared to electrolytic capacitors, approximately 10 to 100 times more power can be stored per unit of volume or mass. In comparison to a rechargeable battery, a supercapacitor also offers faster charging and more charge/discharge cycles [32].

Another storage technology is the CAES, which can store a large amount of power, ranging from 50 to 300 MW [33]. It has an extended shelf life of almost one year. Specific site capabilities, including depleted gas fields, rock mines, and others, are required for CAES deployment [34]. In order to store air in liquid form in a tank, a storage type called Liquid Air Power Storage (LAES) cools the air using electricity until it liquefies. Charging, power storage, and power recovery for the system are the three main activities that comprise LAES. A summary of recent research on energy storage and battery-related challenges is shown in Table *4*.

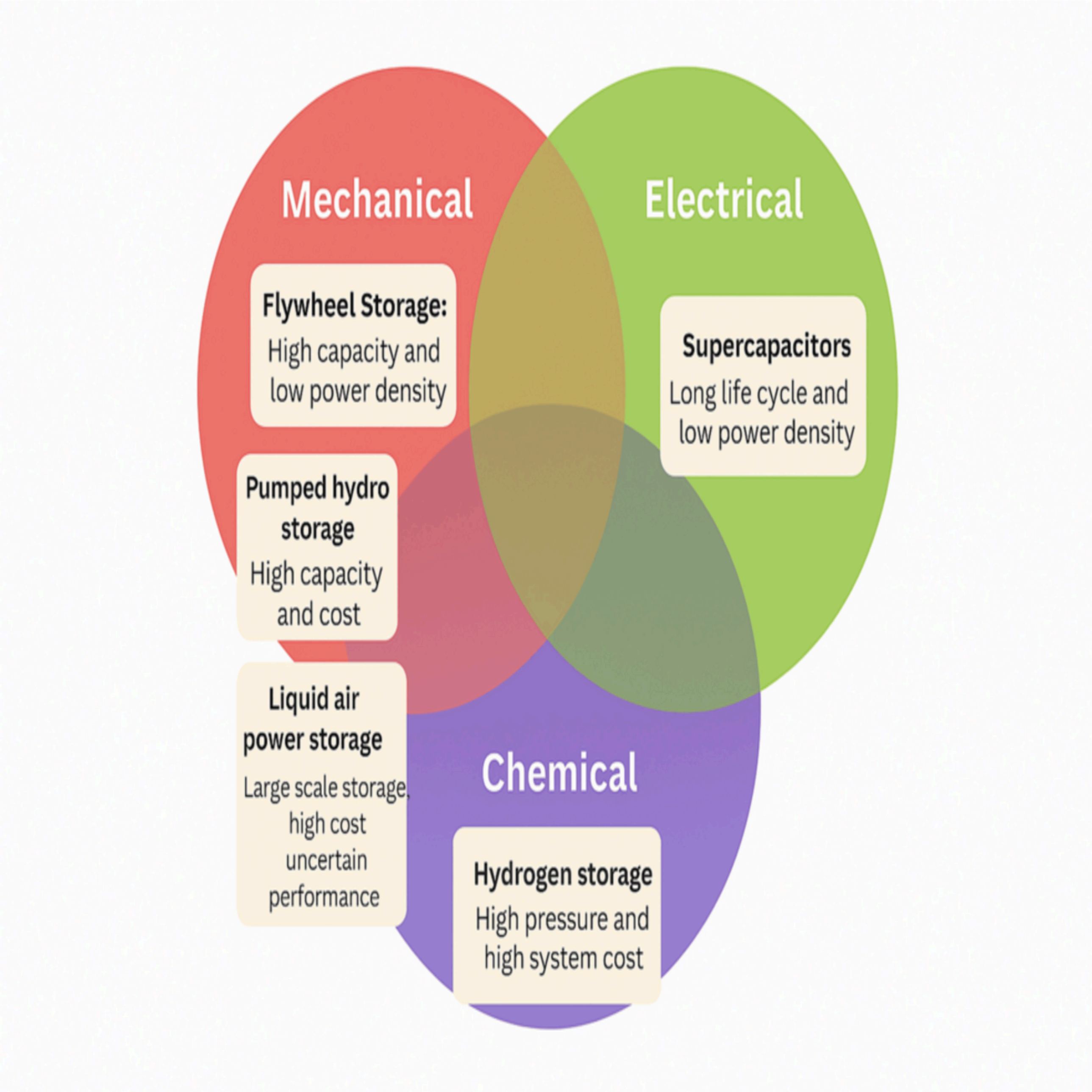

FIGURE 2: Energy Storage Technology

How to cite this article:
Srivastava A, Jha S, Gupta D, et al. (March 25, 2026) A Critical Review of Microgrid Technologies: Storage and Control Systems with Effective Optimization Techniques for Modeling Wind, Solar, Biomass, and Battery Energy Storage Systems. Cureus J Eng 3 : es44388-025-00041-y. DOI https://doi.org/10.7759/s44388-025-00041-y

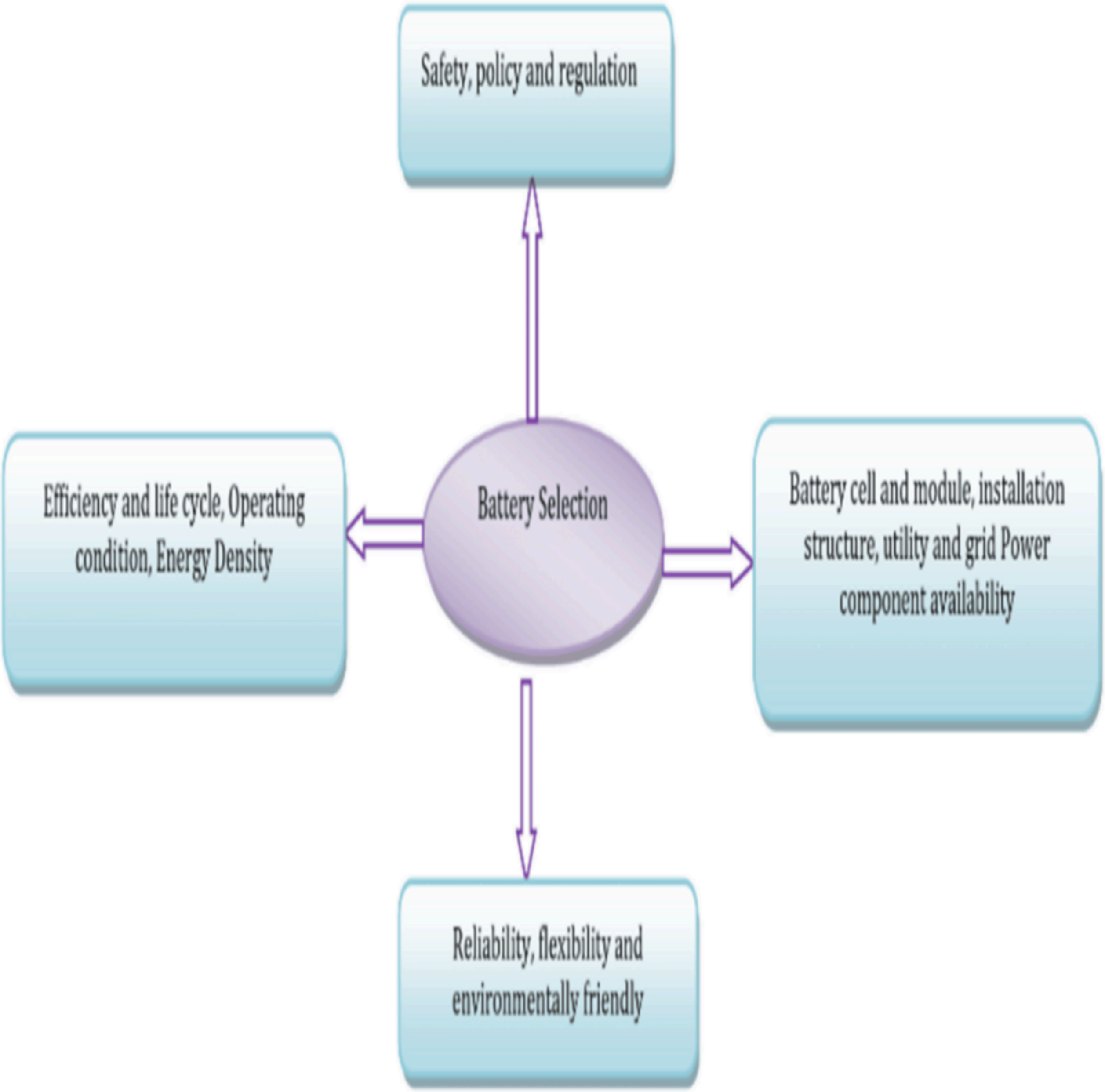

FIGURE 3: Battery Selection Criteria

Energy Storage and Battery Associated Problem	Objective	Method and Approach	Result and their Significance
Grid Integration and Control Strategy [35]	To develop a control strategy for a community battery bank within a grid-connected microgrid with significant photovoltaic generation. The aim is to minimize battery capacity by optimizing power transfer capacity between the microgrid and the external grid.	By employing empirical mode decomposition analysis, the study identifies daily and seasonal net power oscillations. These findings inform the development of a rule-based operational strategy for controlling the community battery bank.	A significant reduction of approximately 16% in the required battery capacity, achieved through the proposed control scheme. The scheme's independence from net power forecasting enhances its robustness in managing power buffering tasks, thereby offering a practical solution for grid-connected microgrids with photovoltaic generation.
Energy management system, control strategy [36]	To propose an effective power management control system for hybrid energy storage systems (HESS) in hybrid electric vehicles (HEV) and to provide backup energy generation from traditional sources through HESS.	By integrating wavelet transform, deep learning mechanisms, and fuzzy logic to effectively manage power storage and regulation. A long short-term memory-based machine learning technique is employed to address challenges with online forecasting.	The developed approach ensures optimal utilization of both batteries and supercapacitors, enhancing the reliability and performance of renewable energy sources in vehicle applications and improving efficiency in storing and regulating power, addressing challenges associated with online forecasting and calculation.
Life cycle, degradation and energy density, safety concern [37]	To fabricate and characterize Sm_2O_3/rGO nanocomposite for supercapacitor application, aiming to explore its electrochemical behavior and potential as a green energy storage technology.	The Sm_2O_3/rGO nanocomposite is synthesized via a hydrothermal method, followed by characterization of material properties using various analytical techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR).	The synthesized Sm_2O_3/rGO nanocomposite exhibits a high specific capacitance of 1356.36 F g^{-1} and a low charge transfer resistance (Rct) of 1.14 Ω, indicating excellent electrochemical efficiency. Stability analysis demonstrates the nanocomposite's stable behavior over 50 hours and after 5000 cycles, with structural stability maintained.
Energy management system and grid Integration [38]	To develop an energy management system (EMS) for nanogrids aimed at effectively balancing power supply and forecasted demand while mitigating forecasting errors.	Utilizes nanogrid sources like photovoltaics, fuel cells, and batteries, alongside a supercapacitor charging process, to meet forecasted demand.	By integrating a power-balancing optimization process and a reference power modulation strategy, leveraging nanogrid sources and a hybrid energy storage system, the EMS enhances reliability and efficiency. Evaluation with real data from the Korea Electric Power.
Energy Density, Safety Concerns, Cost and Life Cycle [39]	A comprehensive review of recent advancements in MXene materials for Zn-based rechargeable energy devices.	Summarizing synthesis techniques, emphasizing initial methods, and discussing emerging strategies such as surface termination and defect engineering to enhance MXene performance.	Developments in MXene materials for Zn-based rechargeable energy devices focus on their synthesis and application as electrodes. It highlights emerging strategies such as surface termination and defect engineering to enhance MXene performance.

TABLE 4: Summary of Recent Research in Energy Storage and Battery Technology

Advanced control and optimization strategies for microgrids

Control technology is essential for microgrids and essential specifications that must be controlled, i.e., equipment protection, power balancing, steady voltage and frequency, and stable voltage. By adjusting the system's voltage and frequency, stability can be increased [40]. Optimal load distribution should be used to maintain power flow.

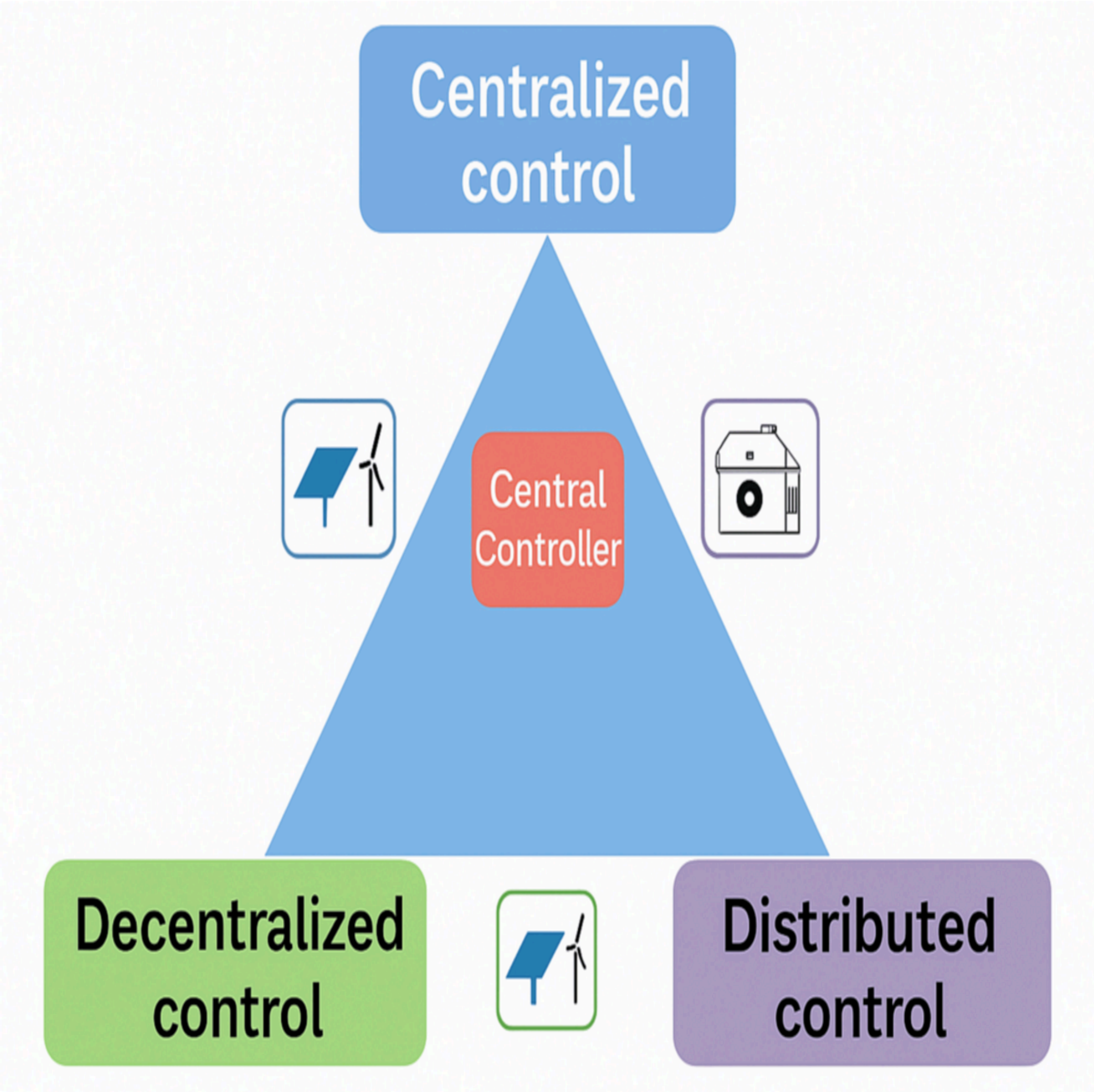

FIGURE 4: Control Strategy for Optimal Power Flow

The demand side and generation side must remain in balance. There are three various power flow schemes: distributed, centralized, and decentralized methods as shown in Figure *4*. In this work, a summary of the recent reviews of control strategies on MGs is briefly discussed and presented in Table *5*.

Centralized Control System

A centralized control system allows the integration of different renewable energy resources and technologies into the microgrid. By regularly monitoring and modifying the system parameters, the centralized control technique can also help to ensure that the microgrid is working efficiently and reliably [41]. There are several sensors and meters that collect data, and then the central controller uses this information to decide how to operate the various system components.

Decentralized Control System

Similar to a centralized system, a microgrid's decentralized control system manages and optimizes the functioning of the various system components to ensure efficient, dependable, and economical operation. In a decentralized control system, control decisions are made by multiple controllers each in charge of overseeing a subset of system components [42]. Each controller receives information from sensors and meters situated within its domain and bases control decisions on this information. Each controller must communicate and coordinate with each other to ensure that the microgrid operates efficiently and reliably.

Distributed Control System

The control and monitoring tasks in a DCS are divided among a number of processors or computers that are interconnected by a network [43]. Each processor or computer manages a certain aspect of the entire process, and they communicate with one another to make sure the process moves quickly and smoothly.

Control Method	Objective	Methodology	Result
Centralized and distributed [44]	To develop and implement a multi-agent model for an integrated energy system in a residential area, considering both centralized and distributed energy resources.	The research aims to harmonize the operating conditions of these diverse energy resources to prevent inefficiencies, reduce production costs, and ensure the optimal functioning of energy equipment and the overall energy system.	The proposed multi-agent structure and integrated system model serve the purpose of achieving coordinated management between energy facilities, balancing centralized and distributed energy generation for electricity and heat provision to consumers.
Distributed [45]	The aim is to demonstrate the microgrid's capability to maintain local stability, operate in island and grid-connected modes, handle resource variability, and provide grid services.	Utilize MATLAB-Simulink to create a high-fidelity model based on the identified conceptual framework. Implement individual components and their interactions, ensuring accuracy and realism in representing the behavior of a real-world distributed wind-hybrid microgrid.	The results underscore the resilience and versatility of distributed wind-hybrid microgrids and demonstrated capabilities, including fault tolerance, stable transitioning, and participation in grid services.
Distributed [46]	Contribute to the development of a distributed energy management solution for microgrids that optimally schedules HVAC and BESS, considering renewable energy sources, user satisfaction, and overall energy cost minimization.	This architectural framework incorporates solar energy forecasts, leveraging surplus-based consensus algorithms to address local power mismatches as surplus terms. It facilitates the cost scheduling of HVAC-BESS, specifically targeting the maximization of renewable energy efficiency during peak generation periods.	The formulation of convex cost functions further contributes to the success of the algorithm by minimizing HVAC user dissatisfaction and mitigating power losses during BESS operation. Minimizing total energy costs in a distributed manner, while adhering to individual load constraints and power balance constraints, is effectively achieved.
Distributed and Decentralized [47]	To design and simulate a distributed secondary control system based on a consensus algorithm for the efficient management of an isolated DC microgrid (MG-DC).	Implement the MPPT controller for the PV boost converter using the P & O method. Integrate Buck–Boost converters with local controllers and a primary droop control mechanism to manage power at loads. Analyze and quantify voltage deviations produced by the primary control on the DC bus.	The proposed distributed secondary control strategy has successfully compensated for this deviation. This strategy has simultaneously managed power sharing among batteries based on their individual capacities. Improvement in the life cycle of the batteries, as evidenced by the State of Charge (SoC).
Centralized and Decentralized [48]	To design a hierarchical cooperative optimization system for distributed economic dispatch within the microgrid.	Design a hierarchical cooperative optimization system for distributed economic dispatch within the microgrid. Integrate the centralized agent into the system to optimize the scheduling of the energy storage system.	Real-time simulation results reveal that the proposed hybrid strategy exhibits superior optimization performance compared to the purely centralized strategy.

TABLE 5: Overview of Recent Research on Microgrid System in the Field of Control Strategies

BESS, Battery Energy Storage System; HVAC, Heating, Ventilation, and Air Conditioning; MPPT, Maximum Power Point Tracking

Table *6* presents the convergence time and accuracy of each method. Mixed-Integer Linear Programming (MILP) achieved the best accuracy but required higher computation time, whereas metaheuristic techniques like Particle Swarm Optimization (PSO) and Grey Wolf Optimizer (GWO) provided near-optimal solutions with significantly faster convergence, making them more suitable for real-time or large-scale applications.

Optimization Technique	Converge Time (s)	Accuracy	Number of Iterations	Remarks
MILP	**9.2**	**100% (exact)**	**50**	**Optimal but slow for large-scale**
PSO	3.1	97.7%	80	Fast, may get stuck in local optima
GWO	2.8	98.0%	75	Balanced performance
FA	2.4	96.8%	90	Fewer parameters, slightly less accurate
ADMM	6.5	99.5%	40	Needs convexity assumption
HMOPSO	4.7	98.8%	100	Handles multi-objective well

TABLE 6: Quantitative Comparison of Optimization Techniques

MILP, Mixed-Integer Linear Programming; PSO, Particle Swarm Optimization; GWO, Grey Wolf Optimizer; FA, Firefly Algorithm; ADMM, Alternating Direction Method of Multipliers; HMOPSO, Hybrid Multi-Objective Particle Swarm Optimization

Performance of renewable energy technologies and proposed solutions in storage and control systems

In the assessment of renewable energy technologies, performance metrics such as efficiency, capacity factor, and cost are crucial for determining their viability and effectiveness as shown in Table 7. By comparing these indicators across different technologies, stakeholders can make informed decisions about which renewable energy solutions offer the best balance of performance and economic benefits [49]. This comprehensive evaluation helps in optimizing the integration of renewable energy sources into the existing energy systems.

Technology	Efficiency (%)	Capacity Factor (%)	Initial Capital Cost	Technology	Environmental Impact
Wind Turbines [49]	30-35	30-50	1,200-2,500	2-3	Minimal
Photovoltaic Systems [50].	15-22	15-25	1,000-3,000	1-2	Low
Biomass System [26]	20-30	70-85	4,000-8,000	3-5	Moderate
Energy Storage [29]	70-90	N/A	400-800 (per kWh)	Varies	Varies by type

TABLE 7: Comparison of Renewable Energy Technologies Based on Efficiency, Capacity Factor, Capital Cost, and Environmental Impact

The approach involves a comparative analysis of several renewable energy technologies, including photovoltaic systems, wind turbines, biomass systems, and energy storage solutions. Each technology is assessed based on defined performance metrics, allowing for a holistic view of their operational efficiency, cost implications, and environmental impacts. It highlights findings regarding the performance and economic feasibility of various renewable energy technologies. For instance, wind turbines demonstrate high efficiency and capacity factors, while energy storage solutions exhibit excellent efficiency but variable costs depending on the technology type. It provides a comprehensive assessment of renewable energy technologies, underscoring the trade-offs between efficiency, cost, and environmental impact.

Researchers have proposed diverse strategies ranging from hybrid energy storage systems, multi-agent and distributed control, to AI-driven predictive energy management. Table *8* summarizes the key problems identified in recent studies and presents corresponding potential solutions and emerging research directions aimed at improving microgrid performance, stability, and sustainability.

S. No.	Identified Issue/Problem	Description/Cause	Proposed Solution/Approach	Supporting References
1	Intermittency of Renewable Energy Sources	Fluctuations in solar and wind output cause voltage and frequency deviations	Integrate hybrid energy storage (battery + supercapacitor/flywheel); apply predictive control using weather and load forecasting	[51]
2	Limited Battery Lifetime and Degradation	Repeated cycling and high depth of discharge shorten battery life	Use hybrid storage (battery + hydrogen or SC); implement SoC-based charge optimization and degradation-aware scheduling	[52]
3	High Storage Cost and Capital Investment	Cost of Li-ion and flow batteries remains high	Adopt hybrid storage to share energy/power demand; use techno-economic optimization and lifecycle cost analysis	[53]
4	Complexity of Centralized Control	Centralized control suffers from single-point failure and latency	Employ distributed or hierarchical control architectures with multi-agent consensus	[54]
5	Poor Demand–Supply Matching	Variability in generation and consumption profiles	Develop probabilistic and scenario-based optimization; use AI forecasting for adaptive scheduling	[55]
6	Energy Management under Uncertainty	Random behavior of loads and RES complicates optimization	Apply stochastic MPC, reinforcement learning, and robust optimization algorithms	[56]
7	Insufficient Real-Time Validation	Most research confined to simulation environments	Use hardware-in-loop (HIL) and real-time testbeds to validate control strategies	[57]
8	Power Quality Issues (Harmonics, Voltage Swells)	Converter switching and RES intermittency distort waveforms	Implement active power filters, droop control with harmonic compensation	[58]
9	Cybersecurity and Communication Reliability	Distributed control depends on data communication vulnerable to attacks or latency	Develop resilient communication networks, blockchain-based authentication, and redundant control layers	[59]
10	Sustainability and Recycling of Batteries	Growing environmental concern from end-of-life batteries	Encourage recycling, second-life applications, and research on green storage (Na-ion, Zn-air)	[60]

TABLE 8: Identified Issues and Proposed Solutions in Microgrid Storage and Control Systems

MPC, Model Predictive Control; RES, Renewable Energy Source

Analysis of capacity and demand matching of renewable energy system

The capacity and demand matching for different renewable energy technologies and energy storage systems, along with modeling tools and performance metrics, are presented in Table *9*. By analyzing capacity and demand matching, this analysis provides insights into how effectively different technologies can be integrated into microgrid systems to meet energy demands sustainably and efficiently. It shows how well the generation capacity of a technology aligns with the peak and average demands over time and the ability of a technology or system to meet fluctuating energy demands throughout different periods. It emphasizes the importance of aligning generation capacity with fluctuating energy demands to ensure sustainable and efficient energy supply, especially during peak usage periods.

Renewable energy sources exhibit distinct generation profiles based on their natural dependencies. Solar power follows a diurnal cycle, with peak generation occurring around midday and minimal output at night, making it suitable for daytime demand but requiring storage or backup for continuous supply. Wind energy is inherently variable, with output fluctuating according to wind speed, seasonal patterns, and geographic conditions, often necessitating integration with complementary sources. In contrast, biomass systems offer a more constant output, making them suitable for base-load support with only minor fluctuations, as they are not directly influenced by weather or time of day. This dispatchable nature of biomass complements the intermittency of solar and wind, enhancing overall grid reliability when used in a hybrid renewable energy system.

Aspects such as capacity factor, demand matching, generation profiles, and adaptability to demand profiles are examined. The review highlights that different renewable technologies exhibit distinct capabilities in meeting energy demand. Biomass systems offer stable base-load support, and energy storage is crucial for balancing excess generation and peak demands. This understanding is significant for improving energy reliability and sustainability in renewable integration.

Aspect	Photovoltaic System [50]	Wind Turbines [49]	Biomass System [26]	Energy Storage Systems [29]
Capacity Factor	15-25%	30-50%	70-85%	Varies by type (e.g., batteries 80-90%)
Demand Matching	High during sunny periods; requires storage for night	Effective with consistent wind patterns	Provides consistent base-load generation	Stores excess energy; smooths out demand
Generation Profile	Diurnal (daily cycle); peak in midday	Variable; depends on wind speed and patterns	Constant; base-load with small fluctuations	Flexible; can release stored energy when needed
Simulation Tools	HOMER, MODEST	HOMER, MODEST	HOMER, MODEST	HOMER, MODEST
Optimization Techniques	LP, GA, PSO	LP, GA, PSO	LP, GA, PSO	LP, GA, PSO
Performance Metrics	Capacity factor, Load Matching Efficiency, Peak Shaving	Capacity factor, Load Matching Efficiency, Wind Utilization	Capacity factor, Load Matching Efficiency, Base-Load Support	Storage Utilization, Load Matching Efficiency, Efficiency of Discharge
Adaptability to Demand Profile	Adaptable with storage; good for day-time peaks	Effective for regions with consistent winds	Best for consistent demand; complements variable sources	Highly adaptable; improves system reliability and flexibility
Cost-Effectiveness	Moderate initial cost; low operational cost	Moderate to high initial cost; low operational cost	High initial cost; moderate operational cost	Initial cost varies; cost-effective for smoothing
Environmental Impact	Low; land use and material impact	Low; noise and visual impact	Moderate; land use and emissions	Low; reduces reliance on fossil fuels

TABLE 9: Optimizing Capacity and Demand in Renewable Energy Integration

LP, Linear Programming; GA, Genetic Algorithm; PSO, Particle Swarm Optimization; HOMER, Hybrid Optimization Model for Electric Renewables; MODEST, Model for Optimization of Dynamic Energy Systems; PV, Photovoltaic; ESS, Energy Storage System

Conclusions

The effective integration of renewable energy sources into microgrid systems requires a coordinated approach combining advanced control strategies, optimized storage solutions, and accurate capacity-demand matching. Centralized systems offer robust supervision, while distributed and decentralized architectures enhance flexibility, scalability, and resilience. Among optimization techniques, metaheuristic methods such as PSO and GWO deliver near-optimal solutions with faster convergence, suitable for dynamic microgrid environments. Techniques with high convergence speeds and low computational times are advantageous for quick decision-making, while those capable of handling multiple objectives facilitate a balanced approach to cost reduction, emission minimization, and reliability enhancement. All technologies utilize similar simulation tools and optimization techniques, emphasizing a standardized approach in performance assessment. The adaptability of these systems to varying demand profiles highlights the importance of integrating storage solutions to maximize efficiency. Hybrid energy storage systems and intelligent control algorithms are key enablers for addressing intermittency, cost, and reliability challenges. Future research should focus on real-time validation through hardware-in-loop testing, reinforcement learning-based energy management, and sustainable battery recycling. Overall, the integration of renewable energy, smart control, and adaptive storage technologies is essential for achieving stable, efficient, and environmentally sustainable microgrids.

Additional Information

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Disclosures

Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Acknowledgements

This article was previously presented at the International Conference on NEXT GENERATION TECHNOLOGY IN SCIENCE AND ENGINEERING (ICNGTSE - 2025) at Pranveer Singh Institute of Technology, Kanpur (PSIT), on 22nd– 23rd August 2025.

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