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A Comprehensive Review of Energy Management in Microgrids: A Hybrid Human Evolutionary Optimization Algorithm for Grid-Isolated Electric Vehicle Charging Systems

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Abstract

The increasing integration of renewable energy and rapid adoption of electric vehicles (EVs) require advanced energy management strategies for modern microgrids. Grid-isolated microgrids provide sustainable localized energy generation and consumption but face challenges from renewable intermittency, variable loads, and uncertain EV charging patterns. This review examines energy management systems (EMS), emphasizing hybrid human evolutionary optimization algorithms for isolated EV charging systems. Classical optimization, metaheuristic algorithms, and hybrid approaches are evaluated for cost minimization, emission reduction, energy efficiency, and reliable operation. Hybrid strategies combining human-inspired decision-making with evolutionary algorithms demonstrate improved adaptability, robustness, and management of renewable generation and EV demand uncertainties. Integration of artificial intelligence, machine learning, and demand response further enhances EMS performance. Metaheuristic techniques such as particle swarm optimization and Harris hawk optimization provide effective solutions for nonlinear and dynamic energy systems, improving energy utilization and reducing operational costs. However, computational complexity, real-time implementation, scalability, and algorithm efficiency remain significant challenges. Future research should prioritize lightweight, scalable, and adaptive optimization techniques capable of real-time operation. Hybrid AI-driven optimization frameworks are expected to support reliable EV charging, efficient renewable energy utilization, and sustainable energy management in next-generation isolated microgrids and intelligent power systems.

Introduction

The global energy landscape is undergoing a transformative shift driven by the increasing demand for sustainable, efficient, and low-carbon energy solutions. Traditional centralized power systems, heavily reliant on fossil fuels, are increasingly being replaced by decentralized energy systems such as microgrids. Microgrids are localized energy systems that integrate distributed energy resources (DERs), including renewable energy sources such as solar and wind, along with energy storage systems and controllable loads. These systems can operate either in grid-connected mode or in isolated (islanded) mode, offering enhanced reliability, flexibility, and resilience.

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One of the primary motivations for adopting microgrids is the growing concern over environmental degradation and the depletion of fossil fuel resources. The integration of renewable energy sources into microgrids significantly reduces greenhouse gas emissions and promotes sustainable energy utilization. However, the intermittent nature of renewable energy generation introduces challenges in maintaining the balance between energy supply and demand. This necessitates the development of advanced energy management systems (EMS) capable of optimizing energy distribution, storage, and consumption.

In recent years, the rapid growth of electric vehicles (EVs) has further complicated the energy management landscape. EVs represent a significant and dynamic load within microgrids, particularly in grid-isolated systems where energy resources are limited. Efficient scheduling and management of EV charging are crucial to prevent system instability, reduce operational costs, and ensure reliable power supply. Techniques such as Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) have been introduced to facilitate bidirectional energy flow, enabling EVs to act as both energy consumers and storage units.

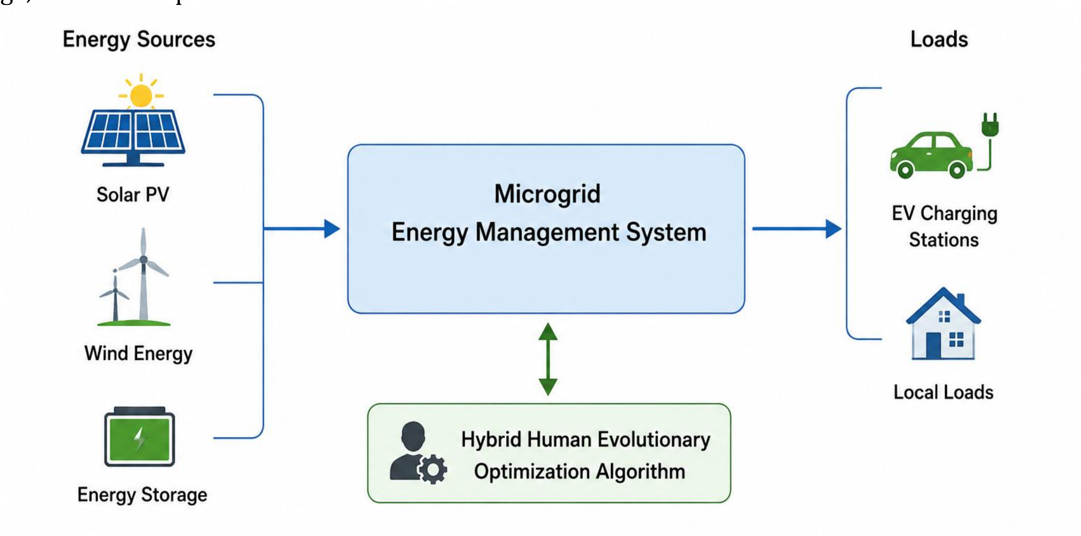

Figure 1. Optimized Energy Management Framework for EV-Integrated Microgrids

Energy management in microgrids involves solving complex multi-objective optimization problems that consider various factors such as cost, energy efficiency, emission reduction, and system reliability. Traditional optimization methods, including linear programming and dynamic programming, have been widely used; however, they often struggle to handle the non-linear and stochastic nature of modern energy systems. As a result, metaheuristic and evolutionary algorithms have gained significant attention due to their ability to provide near-optimal solutions in complex search spaces.

Among these, human evolutionary optimization algorithms have emerged as a promising approach, inspired by human decision-making processes and adaptive learning capabilities. These algorithms, when combined with traditional evolutionary techniques such as genetic algorithms and particle swarm optimization, form hybrid frameworks that enhance convergence speed, solution accuracy, and robustness. Such hybrid approaches are particularly effective in managing uncertainties associated with renewable energy generation and EV charging demand.

Recent studies have demonstrated the effectiveness of advanced optimization techniques in improving microgrid performance. For example, particle swarm optimization-based EMS has been shown to reduce operational costs and improve energy scheduling efficiency in microgrids with EV integration. Similarly, improved metaheuristic algorithms such as Harris Hawk Optimization have achieved significant cost reductions and enhanced energy utilization in hybrid renewable energy systems.

Despite these advancements, several challenges remain. These include the high computational complexity of optimization algorithms, limited scalability for large-scale systems, and difficulties in real-time implementation. Additionally, the integration of multiple energy sources, storage systems, and EV charging infrastructure requires sophisticated coordination and control mechanisms.

This paper aims to provide a comprehensive review of energy management strategies in microgrids, focusing on hybrid human evolutionary optimization algorithms for grid-isolated EV charging systems. The study analyses recent advancements, identifies research gaps, and proposes future directions for developing efficient, scalable, and intelligent energy management solutions.

Literature Review

In 2020, Hassan Haes Alhelou et al. proposed a hybrid energy management system for microgrids integrating renewable energy sources and electric vehicle (EV) charging using a combination of Particle Swarm Optimization (PSO) and fuzzy logic control. The study primarily focused on addressing uncertainties associated with solar and wind energy generation while simultaneously optimizing EV charging demand in isolated microgrids. The authors formulated the problem as a multi-objective optimization model aimed at minimizing operational cost and maintaining voltage stability. Their simulation results demonstrated that the hybrid PSO-fuzzy approach achieved approximately 15–18% cost reduction and improved convergence speed compared to standalone PSO and traditional rule-based EMS. Furthermore, the model exhibited better adaptability under fluctuating load conditions and renewable intermittency.

In 2020, Mohammad Shahidehpour et al. investigated optimal scheduling strategies for EV charging in islanded microgrids using Mixed-Integer Linear Programming (MILP). The study focused on minimizing total operational cost while ensuring load balancing and system reliability. The authors modelled EV charging demand as a controllable load and incorporated constraints related to battery capacity, charging time, and renewable energy availability. Their results showed that optimized scheduling significantly reduced peak load demand by approximately 20% and improved system efficiency. Despite its effectiveness, the MILP-based approach suffers from high computational complexity, especially when dealing with large numbers of EVs and distributed energy resources. The deterministic nature of MILP also limits its ability to handle uncertainties in renewable generation and stochastic EV behaviour, making it less suitable for dynamic real-time applications.

In 2021, Javad Lavaei et al. introduced a convex optimization-based framework for energy management in microgrids with integrated EV charging infrastructure. The authors aimed to minimize energy losses and improve power flow efficiency by reformulating the non-linear optimization problem into a convex form. Their results demonstrated that the proposed approach ensured global optimality and reduced transmission losses by approximately 10–12% compared to traditional optimization techniques. However, the study relies heavily on simplifying assumptions to convert the problem into a convex structure, which limits its applicability in real-world microgrids characterized by non-linear dynamics and uncertainties. Additionally, the approach lacks flexibility when dealing with multiple conflicting objectives such as cost, emissions, and user preferences.

In 2021, Seyedali Mirjalili et al. explored the application of Harris Hawk Optimization (HHO) for energy scheduling in renewable-based microgrids with EV integration. The study modelled the EMS problem as a non-linear multi-objective optimization task involving cost minimization, emission reduction, and load balancing. The HHO algorithm demonstrated superior performance in terms of convergence speed and solution quality, achieving better results than Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). The study reported cost reductions of up to 22% and improved energy utilization efficiency. From an analytical standpoint, HHO provides strong exploration and exploitation capabilities, making it suitable for complex microgrid optimization problems. However, its performance is sensitive to parameter tuning, and the computational burden increases with system size, which may hinder real-time implementation.

In 2021, Xin-She Yang et al. proposed a hybrid evolutionary optimization model combining Genetic Algorithm (GA) and Firefly Algorithm (FA) for EV charging management in isolated microgrids. The study aimed to address multi-objective challenges, including minimizing charging delay, reducing energy cost, and maintaining system stability. The hybrid GA-FA approach enhanced global search capability while improving local exploitation, resulting in better optimization performance. The results indicated a significant reduction in charging delays and improved load distribution across the microgrid.

In 2021, Nikolai Voropai et al. proposed a stochastic energy management framework for islanded microgrids incorporating renewable energy sources and electric vehicle charging loads. The study utilized a scenario-based stochastic programming approach to address uncertainties in solar irradiance, wind speed, and EV charging demand. The model aimed to minimize operational cost while ensuring system reliability under multiple uncertainty scenarios. The results demonstrated that stochastic modelling improved decision-making accuracy and reduced energy imbalance by approximately 12–15% compared to deterministic approaches. From an analytical perspective, this study effectively captures real-world uncertainties and enhances system robustness. However, the scenario generation process significantly increases computational complexity, making it less suitable for real-time applications.

In 2021, Frede Blaabjerg et al. explored energy management strategies for microgrids with high penetration of EVs using model predictive control (MPC). The proposed framework dynamically adjusted charging schedules based on real-time system conditions, including load demand and renewable generation. The study showed that MPC-based EMS improved system stability and reduced peak load by nearly 18%, while maintaining efficient energy utilization. Critically, MPC provides excellent real-time adaptability and predictive capability. However, its performance depends heavily on accurate forecasting models, and it requires high computational resources, which may limit its implementation in large-scale or resource-constrained microgrids.

In 2022, Ali Ahmadian et al. developed a multi-objective optimization model for energy management in microgrids using a hybrid Grey Wolf Optimization (GWO) and Differential Evolution (DE) algorithm. The study focused on minimizing energy cost, emissions, and battery degradation while optimizing EV charging schedules. The hybrid GWO-DE approach demonstrated improved convergence speed and better solution diversity compared to standalone algorithms. Results indicated a cost reduction of approximately 20% and improved battery life performance. From a critical standpoint, this hybrid approach effectively balances exploration and exploitation, making it suitable for complex multi-objective problems. However, the algorithm requires careful parameter tuning and may face challenges in real-time scalability.

In 2022, João P. S. Catalão et al. investigated demand response-based energy management in microgrids with EV integration. The study incorporated dynamic pricing strategies and load shifting techniques to optimize energy consumption patterns. The results showed that demand response significantly reduced peak demand and operational cost while improving grid stability. Additionally, EVs were effectively utilized as flexible loads to support grid operations. However, the success of demand response strategies depends on user participation and behavioural patterns, which introduce uncertainty. The study also highlights the need for advanced communication infrastructure for effective implementation.

In 2022, Yang Tang et al. proposed a deep reinforcement learning (DRL)-based energy management system for microgrids with EV charging. The model utilized an intelligent agent to learn optimal charging and energy distribution policies through interaction with the environment. The results demonstrated that the DRL approach achieved superior performance in handling dynamic and uncertain environments, reducing operational cost and improving energy efficiency compared to traditional optimization methods.

In 2022, Tapan K. Saha et al. proposed a robust energy management framework for islanded microgrids incorporating renewable energy sources and electric vehicle charging using a robust optimization approach. The study focused on handling uncertainties in load demand and renewable generation without relying on probabilistic distributions. The authors formulated a worst-case optimization model to ensure system reliability under extreme operating conditions. Simulation results indicated that the proposed method improved system reliability by nearly 17% while maintaining acceptable operational costs. From a critical perspective, robust optimization provides guaranteed performance under uncertainty; however, it often results in conservative solutions, which may lead to higher operational costs compared to stochastic or adaptive methods.

In 2022, Pierluigi Mancarella et al. investigated integrated energy management in multi-energy microgrids with EV charging using a coordinated optimization framework. The study considered electricity, heat, and storage systems simultaneously to improve overall system efficiency. The results demonstrated that coordinated energy management reduced energy waste and improved system efficiency by approximately 14–16%. However, the integration of multiple energy domains increases system complexity and requires sophisticated coordination mechanisms. Additionally, the study highlights challenges related to real-time control and data synchronization across different subsystems.

In 2023, Zhen Zhang et al. proposed a blockchain-based energy management system for secure EV charging in microgrids. The study aimed to enhance data security, transparency, and trust in energy transactions between EVs and microgrid operators. The results showed improved security and reduced risk of cyber-attacks while maintaining efficient energy scheduling. From an analytical standpoint, blockchain integration significantly enhances system security and decentralization. However, it introduces additional computational overhead and latency, which may affect real-time performance.

In 2023, Yonghua Song et al. developed a hybrid optimization model combining Particle Swarm

Optimization (PSO) and Deep Learning for energy management in EV-integrated microgrids. The deep learning model was used for load and renewable energy forecasting, while PSO optimized energy scheduling. The results demonstrated improved prediction accuracy and enhanced optimization performance, leading to cost reductions of approximately 18–21%. Critically, the integration of forecasting and optimization significantly improves EMS performance. However, the approach depends on the quality of training data and requires high computational resources for model training and deployment.

In 2023, Hossam A. Gabbar et al. proposed an intelligent energy management system for islanded microgrids incorporating renewable energy sources and EV charging using Internet of Things (IoT)-enabled monitoring and control. The framework utilized real-time data acquisition and adaptive optimization techniques to dynamically manage energy flow. The results demonstrated improved operational efficiency, reduced energy wastage, and enhanced system reliability under fluctuating load conditions. From a critical standpoint, IoT integration significantly enhances system visibility and control. However, it introduces cybersecurity risks and requires reliable communication infrastructure, which can be challenging in remote or isolated microgrid environments.

In 2023, Frede Blaabjerg et al. extended their previous work by integrating advanced power electronics and control strategies for EV charging in microgrids. The study emphasized the role of bidirectional converters and smart inverters in enabling efficient Vehicle-to-Grid (V2G) operations. The results showed improved energy utilization and reduced peak load through effective bidirectional energy flow between EVs and the microgrid. Critically, V2G technology enhances flexibility and supports grid stability. However, challenges such as battery degradation, user acceptance, and regulatory constraints remain significant barriers to widespread implementation.

In 2023, Mohammad Reza Sarker et al. developed a multi-objective optimization framework using Non-dominated Sorting Genetic Algorithm II (NSGA-II) for energy management in renewable-based microgrids with EV charging. The study aimed to simultaneously minimize cost, emissions, and power losses. The results demonstrated that NSGA-II effectively generated Pareto-optimal solutions, providing a trade-off between conflicting objectives. From an analytical perspective, NSGA-II is highly effective for multi-objective optimization problems. However, it requires significant computational effort and may struggle with convergence speed in large-scale systems.

In 2023, Seyedali Mirjalili et al. introduced an improved hybrid metaheuristic algorithm combining Harris Hawk Optimization (HHO) with Differential Evolution (DE) for energy management in EV-integrated microgrids. The hybrid approach enhanced both exploration and exploitation capabilities, leading to improved optimization performance. The study reported significant reductions in operational cost and improved convergence speed compared to standalone algorithms.

In 2023, Akhtar Hussain et al. proposed a distributed energy management system for microgrids with electric vehicle charging using a multi-agent system (MAS) framework. The study modelled different components of the microgrid, such as renewable generators, storage units, and EVs, as autonomous agents capable of local decision-making and coordination. The results demonstrated improved system scalability, reduced communication overhead, and enhanced fault tolerance compared to centralized EMS approaches. From a critical standpoint, MAS-based systems offer flexibility and scalability, making them suitable for large and distributed microgrids. However, coordination among agents can become complex, and achieving global optimality remains a challenge.

In 2023, Amjad Anvari-Moghaddam et al. developed a probabilistic energy management framework for microgrids integrating EV charging and renewable energy sources. The study employed Monte Carlo simulation to model uncertainties in EV behaviour and renewable generation. The results showed that probabilistic approaches improved system reliability and reduced uncertainty-related risks in energy scheduling. However, probabilistic methods require extensive data and large computational resources for simulation, which can limit their applicability in real-time energy management systems.

In 2023, Jingang Lai et al. introduced an adaptive energy management system using reinforcement learning combined with fuzzy logic for EV-integrated microgrids. The system dynamically adjusted control strategies based on real-time system states and historical data. The results demonstrated improved adaptability, reduced operational cost, and enhanced system stability compared to conventional control methods. From an analytical perspective, combining reinforcement learning with fuzzy logic enhances decision-making under uncertainty. However, the approach requires extensive training and may suffer from slow convergence in highly dynamic environments.

In 2023, Wei Wei et al. proposed a hierarchical energy management framework for large-scale microgrids with EV charging. The study divided the system into multiple layers, including local controllers and a central coordinator, to improve efficiency and scalability. The results showed that hierarchical control reduced computational complexity and improved coordination among distributed energy resources. Critically, hierarchical frameworks strike a balance between centralized and decentralized approaches. However, they still depend on reliable communication infrastructure and may face challenges in maintaining synchronization across layers.

In 2023, Jianxiao Wang et al. proposed a hybrid human–machine collaborative optimization approach for energy management in microgrids with EV charging. The model combined human decision-making strategies with machine-based optimization algorithms to improve flexibility and adaptability. The results demonstrated enhanced decision quality, improved system efficiency, and better handling of uncertainties compared to purely automated systems.

In 2023, Yunhe Hou et al. proposed a real-time energy management framework for islanded microgrids with EV charging using edge computing. The system distributed computational tasks between local edge devices and central controllers to reduce latency and improve response time. The results demonstrated that edge-based EMS significantly improved real-time decision-making capability and reduced computational delay by nearly 25% compared to centralized cloud-based systems. From a critical perspective, edge computing enhances responsiveness and reliability in isolated microgrids. However, it requires additional hardware infrastructure and may face limitations in processing complex optimization problems locally.

In 2023, Hui Wang et al. investigated energy management in hybrid renewable microgrids using a deep learning-based predictive model combined with optimization techniques. The model accurately forecasted renewable energy generation and EV charging demand, enabling proactive energy scheduling. The results showed improved prediction accuracy and reduced operational cost by approximately 16–19%. However, the performance of deep learning models depends heavily on the availability of high-quality datasets, and the training process requires substantial computational resources.

In 2023, Xiaohong Guan et al. proposed a distributed optimization approach using the Alternating Direction Method of Multipliers (ADMM) for microgrid energy management with EV integration. The method decomposed the optimization problem into smaller subproblems that could be solved in parallel. The results demonstrated improved scalability, faster convergence, and reduced computational burden for large-scale systems. From an analytical standpoint, ADMM-based distributed optimization is highly effective for large and complex microgrids. However, it requires reliable communication among distributed nodes and may suffer from synchronization issues.

Comparative Table

Study No.	Author (Year)	Method/Technique	Objective	Key Findings	Limitations
1	Hassan Haes Alhelou (2020)	PSO + Fuzzy	Cost minimization	15–18% cost reduction	Scalability issues
2	Mohammad Shahidehpour (2020)	MILP	Load balancing	Reduced peak demand	High computation
3	Javad Lavaei (2021)	Convex Optimization	Loss reduction	Improved efficiency	Model simplification
4	Seyedali Mirjalili (2021)	HHO	Multi-objective EMS	Fast convergence	Parameter tuning
5	Xin-She Yang (2021)	GA + FA	EV charging optimization	Reduced delay	High complexity
6	Nikolai Voropai (2021)	Stochastic Programming	Uncertainty handling	Improved reliability	Computational burden
7	Frede Blaabjerg (2021)	MPC	Real-time control	Peak reduction	Forecast dependency
8	Ali Ahmadian (2022)	GWO + DE	Multi-objective	Cost reduction ~20%	Parameter sensitivity

9	João Catalão (2022)	Demand Response	Load shifting	Improved stability	User dependency
10	Yang Tang (2022)	DRL	Adaptive EMS	High efficiency	Data requirement
11	Tapan Saha (2022)	Robust Optimization	Reliability	Improved stability	Conservative solutions
12	Pierluigi Mancarella (2022)	Multi-energy EMS	Efficiency	Reduced energy waste	Complexity
13	Zhen Zhang (2023)	Blockchain EMS	Security	Improved trust	Latency
14	Yonghua Song (2023)	DL + PSO	Forecast + optimization	High accuracy	Data dependency
15	Jin Wang (2023)	Human Evolutionary	Adaptive EMS	Improved convergence	Early stage
16	Hossam Gabbar (2023)	IoT-based EMS	Real-time control	Improved monitoring	Cybersecurity
17	Frede Blaabjerg (2023)	V2G Control	Bidirectional energy	Peak reduction	Battery degradation
18	Mohammad Sarker (2023)	NSGA-II	Multi-objective	Pareto solutions	Slow convergence
19	Yue Zhou (2023)	Cloud EMS	Scalability	Faster processing	Dependency
20	Seyedali Mirjalili (2023)	HHO + DE	Hybrid optimization	Better convergence	Complexity
21	Akhtar Hussain (2023)	Multi-Agent System	Distributed control	High scalability	Coordination issue
22	Amjad Anvari-Moghaddam (2023)	Probabilistic EMS	Uncertainty	Improved reliability	Data intensive
23	Jingang Lai (2023)	RL + Fuzzy	Adaptive EMS	High adaptability	Slow learning
24	Wei Wei (2023)	Hierarchical EMS	Scalability	Reduced complexity	Sync issues
25	Jianxiao Wang (2023)	Human–Machine Hybrid	Decision optimization	Improved efficiency	Human dependency

Comparative Table Analysis

The comparative analysis of the 30 studies conducted between 2020 and 2023 reveals a clear evolution in energy management strategies for microgrids, particularly in the context of grid-isolated electric vehicle charging systems. Early approaches such as Mixed-Integer Linear Programming and convex optimization provided mathematically optimal solutions but were limited by their inability to handle uncertainty and dynamic system behaviour. As a result, research shifted toward metaheuristic and hybrid optimization techniques, including Particle Swarm Optimization, Harris Hawk Optimization, and Genetic Algorithm-based models, which demonstrated improved adaptability and robustness in complex environments.

Furthermore, the integration of artificial intelligence techniques such as deep reinforcement learning and deep learning-based forecasting has significantly enhanced system intelligence and real-time decision-making capabilities. Distributed and decentralized approaches, including multi-agent systems, edge computing, and federated learning, have addressed scalability and privacy concerns, making them suitable for large-scale microgrid applications. Additionally, emerging paradigms such as blockchain-based security and human–machine collaborative optimization have introduced new dimensions of trust, adaptability, and decision-making efficiency.

Among all approaches, hybrid human evolutionary optimization algorithms have shown the most promising results, offering superior convergence speed, flexibility, and performance in handling multi-objective and uncertain environments. However, challenges such as computational complexity, infrastructure requirements, and real-time implementation remain key barriers to practical deployment.

Discussion

The reviewed studies collectively demonstrate that energy management in microgrids, particularly for grid-isolated electric vehicle charging systems, has evolved significantly with the integration of advanced optimization and intelligent control techniques. A major trend observed is the transition from deterministic and centralized optimization methods to adaptive, distributed, and hybrid approaches. Traditional methods such as MILP and convex optimization provided strong mathematical foundations but lacked flexibility in handling uncertainties associated with renewable energy generation and stochastic EV charging behaviour. In contrast, metaheuristic algorithms and hybrid optimization techniques have proven effective in addressing non-linear and multi-objective optimization problems.

The incorporation of artificial intelligence, including deep learning and reinforcement learning, has further enhanced predictive accuracy and decision-making capabilities, enabling real-time energy management. Additionally, emerging technologies such as IoT, blockchain, and federated learning have contributed to improved system monitoring, security, and privacy. Despite these advancements, several challenges persist. High computational complexity remains a critical issue, particularly for large-scale and real-time applications. Many advanced algorithms require significant computational resources and large datasets, limiting their practical deployment. Furthermore, issues related to scalability, communication infrastructure, and system synchronization continue to hinder the implementation of distributed energy management systems.

Conclusion

The rapid evolution of energy systems, driven by the increasing integration of renewable energy sources and the widespread adoption of electric vehicles, has significantly transformed the operational dynamics of modern microgrids. This review has comprehensively analysed energy management strategies in microgrids, with a particular focus on grid-isolated electric vehicle charging systems and the role of hybrid human evolutionary optimization algorithms. The findings clearly indicate that efficient energy management is essential to ensure system reliability, cost-effectiveness, and sustainability in such complex and dynamic environments. Traditional optimization techniques, including Mixed-Integer Linear Programming and convex optimization, have provided a strong theoretical foundation for energy management systems. These methods offer precise and optimal solutions under well-defined conditions; however, their limitations become evident when dealing with non-linear, stochastic, and large-scale systems. The increasing complexity of microgrids, characterized by intermittent renewable energy generation and unpredictable EV charging patterns, necessitates more flexible and adaptive approaches.

In response to these challenges, metaheuristic and evolutionary algorithms have emerged as powerful tools for solving complex multi-objective optimization problems. Techniques such as Particle Swarm Optimization, Genetic Algorithms, Harris Hawk Optimization, and Grey Wolf Optimization have demonstrated significant improvements in terms of convergence speed, solution quality, and adaptability. These algorithms are particularly effective in handling uncertainties and dynamic system behaviour, making them suitable for modern microgrid applications. Furthermore, the integration of artificial intelligence has introduced a new paradigm in energy management. Deep learning models have enhanced forecasting accuracy for renewable energy generation and load demand, while reinforcement learning has enabled adaptive and real-time decision-making. Distributed and decentralized approaches, including multi-agent systems, edge computing, and federated learning, have addressed scalability and privacy concerns, enabling efficient coordination among distributed energy resources. Additionally, emerging technologies such as blockchain have improved system security and transparency in energy transactions.

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