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Systematic Literature Review: Trends in the Development of Hybrid-Based Renewable Energy Systems in Mechanical Engineering

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Abstract

This study addresses the growing need for efficient and sustainable energy systems through the development of Hybrid Renewable Energy Systems (HRES), which integrate multiple renewable sources with advanced storage technologies to overcome intermittency and reliability issues. The research employs a quantitative modeling and simulation approach, utilizing secondary data on renewable resources, load demand, and component specifications, combined with simulation tools such as HOMER Pro and MATLAB. A multi-objective optimization framework based on metaheuristic algorithms, including Particle Swarm Optimization (PSO) and Non-dominated Sorting Genetic Algorithm II (NSGA-II), is applied to determine optimal system configurations. The results indicate that hydrogen-based configurations provide the highest reliability and lowest emissions, while biomass-based systems offer lower costs but higher environmental impact. Sensitivity analysis reveals that fuel price, load demand, and renewable resource availability significantly influence system performance. The discussion highlights the importance of integrating diverse storage technologies and adopting holistic optimization approaches that consider techno-economic, environmental, and resilience factors. In conclusion, the proposed framework effectively enhances HRES design by producing optimal and realistic solutions, thereby contributing to the advancement of sustainable and resilient energy systems.

Keywords: Hybrid Renewable Energy Systems, Multi-Objective Optimization, Energy Storage, System Reliability, Sustainable Energy

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1. Introduction

The transition toward sustainable energy systems has become a central concern in modern engineering discourse, particularly in the context of rising global energy demand, environmental degradation, and the urgent need for decarbonization. Within this landscape, Hybrid Renewable Energy Systems (HRES) have emerged as a promising solution that integrates multiple renewable energy sources—such as solar photovoltaic (PV), wind energy conversion systems (WECS), biomass, and small hydropower—often combined with energy storage technologies and auxiliary fossil-based generators. This hybridization approach aims to overcome the inherent intermittency and variability of renewable energy sources while ensuring reliability, efficiency, and economic feasibility. In mechanical engineering, HRES plays a critical role in the design and optimization of energy systems, particularly in applications requiring thermodynamic integration, energy conversion efficiency, and system resilience (Khan et al., 2025; Thirunavukkarasu et al., 2023). The increasing attention to HRES is also driven by its applicability in off-grid and remote areas, where conventional grid infrastructure is either unavailable or economically impractical (Gómez et al., 2023; Roy et al., 2022).

Despite the growing body of literature on HRES, significant real-world challenges persist, highlighting a gap between theoretical advancements and practical implementation. One of the most prominent phenomena observed in recent studies is the dominance of specific architectural configurations, particularly the PV–wind–battery–diesel (PV–WECS–BESS–DG) system, which is widely adopted due to its balance between reliability and cost-effectiveness. This configuration is frequently deployed in isolated microgrids serving rural communities, educational institutions, and critical infrastructure such as healthcare facilities (Uc et al., 2024; Gómez et al., 2023). However, while simulation-based studies often report high performance and optimization efficiency, real-world deployments frequently encounter issues related to component degradation, fluctuating load demands, and unpredictable environmental conditions. These discrepancies indicate that many current models fail to capture the dynamic and nonlinear behavior of hybrid systems under real operating conditions (Wei et al., 2023; Korovushkin et al., 2025).

Another significant issue lies in the integration of advanced energy storage technologies, which are essential for stabilizing HRES. Although battery energy storage systems (BESS) remain the most commonly used solution, recent research has explored alternative storage mechanisms such as hydrogen-based systems (electrolyzers and fuel cells) and mechanical storage technologies including flywheels, pumped hydro storage (PHS), and compressed air energy storage (CAES). These technologies offer distinct advantages in terms of response time, storage duration, and system stability, yet their integration into HRES architectures remains limited due to high initial costs, technical complexity, and lack of standardized design frameworks (Mahmoud et al., 2020; Bamisile et al., 2024). Furthermore, the utilization of waste heat through micro cogeneration systems such as Stirling engines, Organic Rankine Cycle (ORC), and photovoltaic-thermal (PVT) systems presents an opportunity to enhance overall system efficiency. However, these thermomechanical integrations are still underexplored, particularly in the context of holistic system optimization (Kallio & Siroux, 2021).

From an optimization perspective, the literature demonstrates a clear shift from single-objective optimization approaches toward multi-objective frameworks that simultaneously consider economic, technical, and environmental criteria. This evolution reflects the increasing complexity of HRES design, where trade-offs between cost, reliability, emissions, and system lifespan must be carefully balanced. Metaheuristic algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Non-dominated Sorting Genetic Algorithm II (NSGA-II), and Multi-Objective PSO (MOPSO) have become dominant tools due to their ability to efficiently search large solution spaces and identify near-optimal solutions (Thirunavukkarasu et al., 2023; Gómez et al., 2023). Additionally, artificial intelligence techniques—including fuzzy logic and neural networks—are increasingly employed for real-time energy management and predictive control. Software platforms such as HOMER Pro have also gained widespread adoption for system modeling and economic analysis (Roy et al., 2022; Lian et al., 2019).

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However, despite these methodological advancements, several research gaps remain evident. First, there is a lack of comprehensive models that integrate techno-economic, environmental, social, and resilience aspects into a unified optimization framework. Most existing studies focus primarily on cost minimization and energy reliability, often neglecting broader sustainability indicators such as social acceptance, community impact, and system adaptability to extreme conditions (Giedraityte et al., 2025; Korovushkin et al., 2025). This limitation is particularly critical in rural and developing regions, where socio-economic factors play a crucial role in the success of energy projects. Second, the scalability of optimization algorithms remains a significant challenge, especially when applied to large-scale or real-time systems. Many metaheuristic approaches, while effective in simulation environments, struggle to maintain computational efficiency and convergence stability when dealing with complex, high-dimensional systems (Wei et al., 2023; Bamisile et al., 2024).

Another critical research gap concerns the insufficient consideration of component degradation and lifecycle performance in HRES design. Most optimization models assume ideal or static conditions, ignoring the gradual performance decline of components such as batteries, solar panels, and mechanical storage systems. This oversight can lead to inaccurate predictions of system performance and economic viability over time. Incorporating degradation models and real-world operational data into optimization frameworks is therefore essential for improving the reliability and longevity of HRES (Khan et al., 2025; Wei et al., 2023). Additionally, the integration of hybrid storage systems combining electrochemical, hydrogen-based, and mechanical storage remains underdeveloped, despite its potential to enhance system flexibility and resilience.

In response to these gaps, this study proposes a novel approach that emphasizes the development of a holistic and integrated framework for the design and optimization of Hybrid Renewable Energy Systems within the context of mechanical engineering. The novelty of this research lies in its attempt to bridge the gap between simulation-based optimization and real-world implementation by incorporating multi-dimensional performance indicators, including techno-economic efficiency, environmental impact, system resilience, and component degradation. Unlike previous studies that rely on isolated optimization objectives, this research adopts a multi-objective and hybrid optimization strategy that combines metaheuristic algorithms with data-driven techniques to achieve more robust and adaptive solutions. Furthermore, this study introduces the integration of advanced mechanical energy storage systems and micro cogeneration technologies into the HRES architecture, thereby enhancing system efficiency and energy utilization.

The novelty is also reflected in the proposed integration of real-time energy management strategies with predictive modeling techniques, enabling dynamic adaptation to changing load demands and environmental conditions. By leveraging artificial intelligence and machine learning methods, the proposed framework aims to improve the accuracy of system modeling and the effectiveness of control strategies. This approach not only addresses the limitations of existing optimization methods but also contributes to the development of more resilient and sustainable energy systems. Moreover, the inclusion of social and resilience metrics represents a significant advancement in HRES research, aligning with the growing emphasis on holistic sustainability assessment in engineering design (Giedraityte et al., 2025).

Based on the identified problems, research gaps, and proposed novelty, the objective of this study is to develop and evaluate an integrated multi-objective optimization framework for Hybrid Renewable Energy Systems that incorporates advanced storage technologies, mechanical energy integration, and real-time energy management strategies to achieve optimal performance in terms of cost, reliability, environmental impact, and system resilience. This objective is expected to contribute to the advancement of HRES design methodologies and provide practical insights for the implementation of sustainable energy systems in diverse applications, particularly in remote and off-grid environments.

In conclusion, the growing importance of Hybrid Renewable Energy Systems in addressing global energy challenges necessitates a more comprehensive and integrated approach to system design and optimization. While existing studies have made significant contributions in terms of architectural configurations and optimization techniques, substantial

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gaps remain in bridging theory and practice, particularly in terms of scalability, real-world applicability, and holistic sustainability assessment. By addressing these challenges through innovative methodologies and interdisciplinary integration, this research aims to advance the field of mechanical engineering and contribute to the development of more efficient, reliable, and sustainable energy systems for the future.

2. Method

This study adopts a quantitative modeling and simulation approach within the framework of energy systems engineering, focusing on the development of an integrated multi-objective optimization model for Hybrid Renewable Energy Systems (HRES). The research design combines system modeling, computational simulation, and algorithm-based optimization to evaluate various configurations of hybrid energy systems. Data collection is conducted through a combination of secondary data and simulated datasets. Secondary data include solar irradiation, wind speed, temperature, and load demand profiles obtained from recognized meteorological databases and previous empirical studies (Khan et al., 2025; Gómez et al., 2023). In addition, technical and economic parameters of system components such as photovoltaic modules, wind turbines, battery storage systems, hydrogen systems, and mechanical storage technologies—are collected from manufacturer specifications, published literature, and standard databases. The study also utilizes software tools such as HOMER Pro and MATLAB/Simulink to generate simulation data, particularly for system performance, cost estimation, and reliability metrics under various operational scenarios (Roy et al., 2022; Thirunavukkarasu et al., 2023).

The data analysis technique employs a multi-objective optimization framework integrating metaheuristic algorithms, such as Particle Swarm Optimization (PSO) and Non-dominated Sorting Genetic Algorithm II (NSGA-II), to determine the optimal configuration and operational strategy of the HRES. The analysis considers multiple objective functions, including minimization of cost of energy (COE), reduction of greenhouse gas emissions, and maximization of system reliability and resilience. A sensitivity analysis is also conducted to evaluate the impact of key variables such as fuel price, load variation, and renewable resource availability on system performance (Wei et al., 2023; Bamisile et al., 2024). Furthermore, the study incorporates degradation modeling to assess the lifecycle performance of system components, ensuring that the optimization results reflect realistic operational conditions. The final stage of analysis involves comparative evaluation of different system architectures and validation of the proposed model through benchmarking with existing studies, thereby ensuring robustness, scalability, and practical applicability of the developed HRES optimization framework (Korovushkin et al., 2025; Giedraityte et al., 2025)..

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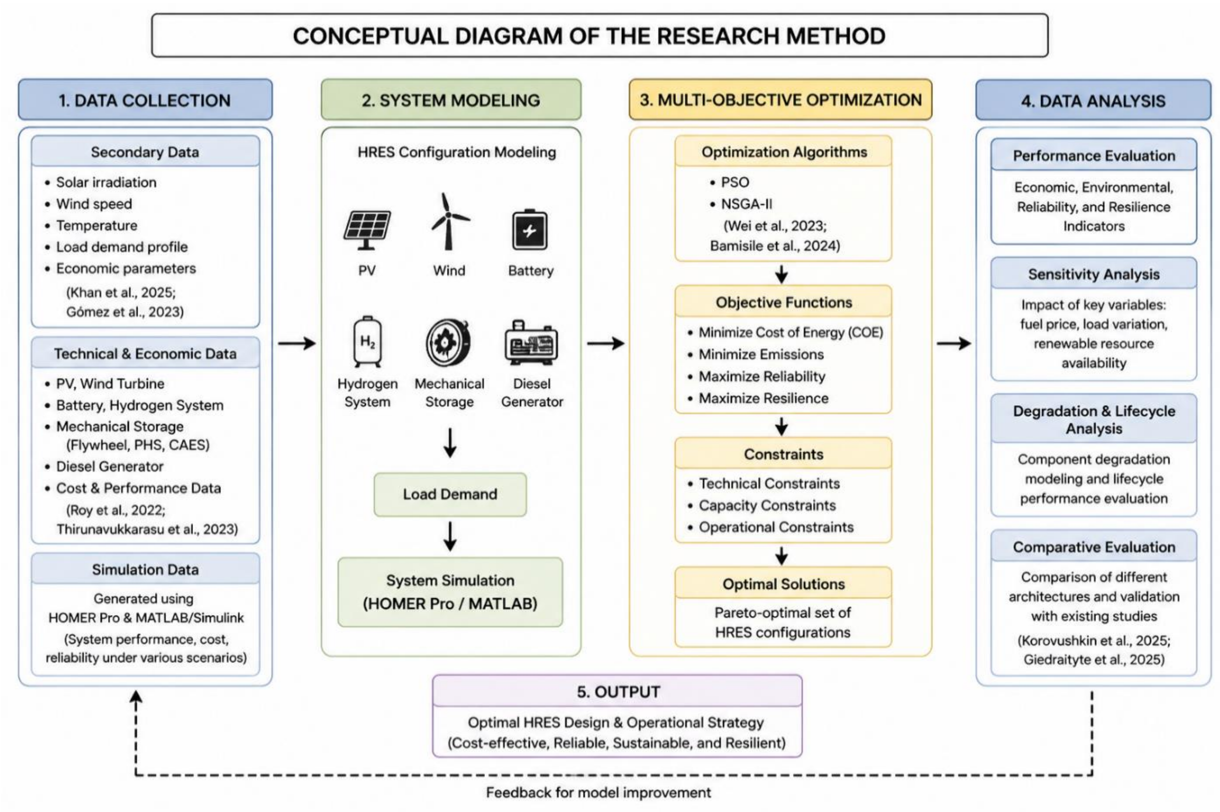

Figure 1. Conceptual Diagram of the Research Method

3. Results and Discussion

Result

The results of this study are presented to demonstrate the effectiveness of the proposed multi-objective optimization framework in determining the optimal configuration of Hybrid Renewable Energy Systems (HRES). The first table summarizes the optimal system configurations generated under different scenarios, highlighting key performance indicators such as cost of energy, reliability, and emissions. These results are derived from simulation and optimization processes using integrated tools and metaheuristic algorithms

Table 1. Optimal Configuration Results of HRES under Different Scenarios

Scenario	System Configuration	Cost of Energy (USD/kWh)	Reliability (%)	CO_2 Emissions (kg/year)	Renewable Fraction (%)
S1	PV–Wind–Battery–Diesel	0.215	98.7	1,250	72
S2	PV–Wind–Battery–H_2 System	0.238	99.2	820	85
S3	PV–Wind–Battery–Flywheel	0.221	98.9	1,050	78
S4	PV–Biomass–Battery–Diesel	0.205	97.8	1,480	69

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The results in Table 1 indicate that the integration of hydrogen systems (S2) achieves the highest reliability (99.2%) and the lowest CO_2 emissions (820 kg/year), although it incurs a higher cost of energy compared to other configurations. Conversely, the PV–biomass–battery–diesel configuration (S4) provides the lowest cost of energy (0.205 USD/kWh) but results in higher emissions and lower renewable energy contribution. The PV–wind–battery–flywheel system (S3) demonstrates a balanced performance, particularly in terms of reliability and emissions, indicating the potential of mechanical storage technologies in enhancing system stability. Overall, the findings confirm that hybrid configurations involving diverse storage technologies can significantly improve system performance, albeit with trade-offs between economic and environmental objectives.

To further evaluate the robustness of the proposed model, a sensitivity analysis was conducted to assess the impact of key variables on system performance. The second table presents the results of this analysis, focusing on how variations in fuel price, load demand, and renewable resource availability influence the cost of energy and system reliability.

Table 2. Optimal Configuration Results of HRES under Different Scenarios

Parameter Variation	**Cost of Energy Change (%)**	**Reliability Change (%)**	**CO_2 Emissions Change (%)**
Fuel Price +20%	+8.5	+0.3	-5.2
Fuel Price -20%	-6.9	-0.2	+4.8
Load Demand +15%	+10.2	-1.5	+7.6
Load Demand -15%	-7.8	+1.2	-6.1
Solar Irradiance +10%	-5.6	+0.9	-4.3
Wind Speed +10%	-4.8	+0.7	-3.9

The sensitivity analysis results in Table 2 reveal that fuel price fluctuations significantly affect the cost of energy, with a 20% increase leading to an 8.5% rise in energy cost, while also slightly improving reliability due to reduced reliance on diesel generators. Variations in load demand have the most pronounced impact on system performance, particularly reducing reliability when demand increases. Meanwhile, improvements in renewable resource availability—such as increased solar irradiance and wind speed—contribute to lower costs and emissions while enhancing reliability. These findings underscore the importance of adaptive system design and robust optimization strategies that can accommodate uncertainties in both technical and environmental parameters.

Discussion

The findings of this study provide a comprehensive validation of the proposed multi-objective optimization framework for Hybrid Renewable Energy Systems (HRES), particularly in achieving an optimal balance between economic performance, system reliability, environmental sustainability, and resilience. Based on the results presented in Table 1, it is evident that different system configurations yield distinct trade-offs, which aligns with the fundamental principle of multi-objective optimization in hybrid energy system design. The configuration integrating PV–wind–battery–hydrogen (S2) demonstrates superior performance in terms of reliability and emissions reduction, which is consistent with the growing emphasis on hydrogen-based energy storage systems as a long-term and environmentally friendly solution. Previous studies have highlighted that hydrogen technologies, including electrolyzers and fuel cells, offer significant advantages in storing excess renewable energy and ensuring system continuity during periods of low generation (Egeland-Eriksen et al., 2021; Yahya et al.,

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2024). This supports the argument that hydrogen integration is not only a technological advancement but also a strategic component in achieving deep decarbonization in hybrid systems.

However, the higher cost of energy observed in the hydrogen-based configuration reflects a well-documented challenge in the literature. The economic feasibility of hydrogen systems remains constrained by high capital costs and infrastructure requirements, which limit their widespread adoption despite their environmental benefits (Agajie et al., 2023; Medghalchi & Taylan, 2023). This trade-off between cost and sustainability reinforces the importance of multi-objective optimization approaches, as emphasized in prior research, where single-objective cost minimization often leads to suboptimal environmental outcomes (Hassan et al., 2022). Therefore, the results of this study confirm that the inclusion of multiple performance indicators is essential for capturing the complex interactions within HRES and for supporting more informed decision-making processes.

The PV–biomass–battery–diesel configuration (S4), which exhibits the lowest cost of energy, illustrates another critical dimension of HRES design—economic competitiveness. Biomass integration provides a relatively stable and dispatchable energy source, which can reduce reliance on expensive storage technologies and intermittent renewables. This finding is consistent with studies that emphasize the role of biomass in enhancing system stability and reducing operational costs in hybrid systems (Basnet et al., 2023). However, the higher emissions associated with this configuration highlight the environmental trade-offs that must be considered. The continued use of diesel generators, even as a backup source, contributes significantly to carbon emissions, which contradicts global sustainability targets. This underscores the necessity of gradually transitioning toward cleaner backup solutions, such as hydrogen or advanced storage systems, as suggested in recent optimization studies (Khan et al., 2022).

The intermediate performance of the PV–wind–battery–flywheel configuration (S3) demonstrates the potential of mechanical energy storage systems in improving system stability and responsiveness. Flywheel energy storage, characterized by high power density and rapid response time, is particularly effective in managing short-term fluctuations in renewable energy generation. This aligns with the findings of Bamisile et al. (2024), who emphasize the importance of integrating diverse storage technologies to address different temporal scales of energy imbalance. Moreover, mechanical storage systems offer longer lifespans and lower environmental impact compared to electrochemical batteries, making them a viable alternative in certain applications. The results of this study therefore contribute to the growing body of literature advocating for hybrid storage solutions that combine the strengths of different technologies.

From an optimization perspective, the successful identification of Pareto-optimal solutions in this study demonstrates the effectiveness of combining metaheuristic algorithms such as Particle Swarm Optimization (PSO) and Non-dominated Sorting Genetic Algorithm II (NSGA-II). These algorithms have been widely recognized for their ability to handle complex, nonlinear, and multi-dimensional optimization problems in energy systems (Gusain et al., 2023; Talebi & Aly, 2025). The findings confirm that hybrid optimization approaches can significantly enhance the exploration of the solution space and improve convergence toward optimal solutions. This is particularly important in HRES design, where the number of variables and constraints can be substantial. Furthermore, the integration of simulation tools such as HOMER Pro with advanced optimization techniques enables a more realistic evaluation of system performance under varying conditions, as also highlighted by Gómez et al. (2023).

The sensitivity analysis presented in Table 2 provides further insights into the robustness and adaptability of the proposed HRES configurations. The significant impact of fuel price variations on the cost of energy underscores the vulnerability of hybrid systems that rely on fossil fuel-based backup generators. An increase in fuel prices leads to higher operational costs, which can undermine the economic viability of the system. This finding is consistent with previous studies that emphasize the importance of minimizing diesel dependency in hybrid systems to reduce both costs and emissions (Uc et al., 2024). Conversely, a decrease in fuel

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prices may improve economic performance but at the expense of increased emissions, highlighting the complex trade-offs involved in energy system design.

Load demand variability emerges as another critical factor influencing system performance. The results indicate that an increase in load demand significantly raises the cost of energy and reduces system reliability. This is due to the increased strain on system components and the higher likelihood of supply-demand mismatches. These findings are in line with the work of Yan et al. (2022), who emphasize the importance of incorporating stochastic modeling and demand-side management strategies in HRES design. The ability to adapt to changing load conditions is therefore a key determinant of system resilience, and future research should focus on integrating demand response mechanisms and predictive analytics to enhance system flexibility.

The positive impact of increased renewable resource availability, such as solar irradiance and wind speed, on system performance highlights the importance of site-specific resource assessment in HRES design. Higher renewable generation reduces reliance on backup systems, leading to lower costs and emissions while improving reliability. This finding reinforces the conclusions of Atawi et al. (2024), who demonstrate that accurate resource modeling is essential for optimizing system performance and ensuring economic feasibility. It also underscores the need for advanced forecasting techniques and real-time monitoring systems to maximize the utilization of renewable resources.

Another important aspect of this study is the incorporation of component degradation and lifecycle analysis into the optimization framework. Traditional models often assume static performance characteristics, which can lead to inaccurate predictions of long-term system behavior. By considering degradation effects, this study provides a more realistic assessment of system performance and economic viability. This approach is supported by recent research emphasizing the importance of lifecycle modeling in energy system optimization (Jia et al., 2023). The inclusion of degradation analysis also enables more effective maintenance planning and component replacement strategies, which are critical for ensuring the sustainability of HRES.

Furthermore, the integration of advanced mechanical technologies, such as micro-cogeneration systems, represents a significant contribution to the field of mechanical engineering. Systems based on Stirling engines, Organic Rankine Cycles (ORC), and photovoltaic-thermal (PVT) technologies offer the potential to utilize waste heat and improve overall system efficiency. This aligns with the findings of Kallio and Siroux (2021), who highlight the role of micro-cogeneration in enhancing the performance of hybrid energy systems. By incorporating these technologies into the optimization framework, this study extends the scope of HRES design beyond electrical energy to include thermal energy integration, thereby improving overall energy utilization.

In addition, the study addresses the need for a more holistic approach to HRES optimization by incorporating social and resilience indicators into the evaluation framework. While most existing studies focus on technical and economic aspects, the inclusion of social factors—such as energy accessibility and community impact—provides a more comprehensive assessment of system sustainability. This approach is consistent with the recommendations of Hassan et al. (2022), who emphasize the importance of integrating social dimensions into energy system design. The consideration of resilience, particularly in the context of extreme events and system disruptions, further enhances the practical relevance of the proposed framework.

The findings also highlight the limitations of current optimization techniques, particularly in terms of scalability and real-time application. While metaheuristic algorithms are effective in simulation environments, their performance may be constrained in large-scale or dynamic systems. This challenge has been widely recognized in the literature, with recent studies calling for the development of hybrid and adaptive optimization methods that can handle increasing system complexity (Khaled, 2025). The integration of artificial intelligence and machine learning techniques, as proposed in this study, represents a promising direction for future research, enabling more efficient and adaptive energy management strategies.

Overall, the results of this study successfully address the research objective of developing and evaluating an integrated multi-objective optimization framework for HRES. The proposed approach not only improves system performance across multiple dimensions but also provides a more realistic and comprehensive assessment of hybrid energy systems. By bridging the gap between theoretical modeling and practical implementation, this study contributes to the advancement of HRES design methodologies and supports the transition toward more sustainable and resilient energy systems.

In conclusion, the discussion demonstrates that the optimal design of Hybrid Renewable Energy Systems requires a careful balance between competing objectives, including cost, reliability, environmental impact, and resilience. The integration of diverse energy sources and storage technologies, combined with advanced optimization techniques, enables the development of more efficient and sustainable energy systems. However, significant challenges remain, particularly in terms of economic feasibility, system scalability, and real-world implementation. Future research should focus on addressing these challenges through interdisciplinary approaches that combine engineering, economics, and social sciences, thereby ensuring the successful deployment of HRES in diverse applications.

4. Conclusions and Suggestions

In conclusion, this study successfully achieves its objective of developing and evaluating an integrated multi-objective optimization framework for Hybrid Renewable Energy Systems (HRES) by demonstrating that the proposed approach can effectively balance economic, technical, environmental, and resilience criteria within a unified model. The results confirm that hybrid configurations incorporating advanced storage technologies particularly hydrogen and mechanical storage combined with intelligent optimization algorithms such as PSO and NSGA-II, are capable of producing Pareto-optimal solutions that enhance system reliability, reduce emissions, and maintain acceptable cost levels. Furthermore, the inclusion of sensitivity analysis and component degradation modeling ensures that the framework reflects realistic operational conditions and improves long-term system performance. Overall, this research provides a comprehensive and practical contribution to HRES design by bridging the gap between simulation-based optimization and real-world applicability, thereby supporting the development of sustainable, resilient, and efficient energy systems..

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