

Optimization Techniques for Hybrid Renewable Energy Systems: A Review of Current Developments and Future Research Directions

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Abstract

This literature review provides a comprehensive analysis of optimization techniques applied to hybrid renewable energy systems (HRES) across diverse geographical locations and applications. The review examines multiple optimization methodologies including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Mixed Integer Linear Programming (MILP), hybrid algorithms, and novel bio-inspired metaheuristic approaches. Performance metrics analyzed include Cost of Energy (COE), Net Present Cost (NPC), Life Cycle Cost (LCC), Loss of Power Supply Probability (LPSP), Renewable Fraction (RF), and CO₂ emissions reduction. The review examined relevant studies published between 2014 and 2025, identified through searches of major academic databases using predefined keywords related to HRES optimization, system sizing, energy management, metaheuristic optimization, and technical, economic, reliability, and environmental performance. The reviewed studies encompass various system configurations incorporating photovoltaic panels, wind turbines, battery storage, diesel generators, small hydro power, fuel cells, tidal energy, and hydrogen storage systems. Findings indicate that while traditional GA and PSO methods remain widely used, MILP and hybrid algorithms demonstrate superior performance in achieving optimal solutions with reduced computational time. Simulation-based tools such as HOMER software continue to be valuable for system design and optimization. However, significant research gaps persist, including limited evaluation of system reliability, incomplete consideration of all renewable sources, and insufficient comparative analysis between different optimization techniques. The integration of artificial intelligence and novel bio-inspired algorithms presents promising opportunities for advancing HRES optimization, particularly for microgrid applications and systems operating under dynamic weather conditions.

Keywords: HRES, Optimization Techniques, Genetic Algorithm, Cost of Energy, System Reliability, Renewable Energy Integration.

Introduction

The design and operation of hybrid renewable energy systems (HRES) constitute complex optimization problems involving multiple decision variables, competing objectives, operational constraints, and uncertainties in renewable energy resources and electricity demand. An HRES may combine two or more renewable and conventional energy sources with energy storage to improve the reliability, economic performance, and sustainability of

electricity supply. However, determining the appropriate combination and capacity of system components requires the exploration of a large solution space in which alternative configurations may differ considerably in terms of cost, reliability, renewable energy contribution, and environmental impact. Optimization techniques therefore provide an important means of identifying suitable solutions from numerous feasible alternatives.

Optimization generally seeks to determine the best solution from a set of feasible alternatives while satisfying specified constraints and objectives. In engineering design, this process may involve mathematical models with numerous decision variables and complex objective functions. Conventional mathematical programming techniques can provide exact or highly accurate solutions when an optimization problem possesses suitable mathematical properties. However, many real-world energy-system problems are nonlinear, non-convex, discontinuous, or multi-objective, making them difficult to solve efficiently using conventional deterministic methods. These characteristics have encouraged the development and application of heuristic and metaheuristic optimization techniques.

A major development in metaheuristic optimization was introduced by Kirkpatrick *et al.* (1983), who proposed simulated annealing as a probabilistic approach for solving complex optimization problems. Their work established an important foundation for metaheuristic optimization by drawing inspiration from the physical annealing process and allowing the search to escape local optima through the probabilistic acceptance of inferior solutions. Simulated annealing has subsequently remained an important optimization technique and continues to be applied in large-scale engineering and energy-system optimization problems (Talbi, 2009). The development of metaheuristic methods has since expanded considerably, resulting in a broad range of algorithms designed to obtain optimal or near-optimal solutions for complex problems within reasonable computational time.

Heuristic methods provide practical procedures for obtaining satisfactory solutions when conventional optimization approaches become computationally inefficient. Metaheuristics extend this concept by providing general-purpose search frameworks that can be adapted to different optimization problems with relatively few problem-specific modifications. They are particularly useful for problems involving large and complex solution spaces where exhaustive enumeration is computationally impractical. Recent studies have highlighted the application of metaheuristic algorithms to complex combinatorial and engineering optimization problems, including scheduling, routing, resource allocation, and other large-scale decision-making problems (Maca-Chagüendo & Cobos-Lozada, 2024; Ramadan, 2025; Saber & Zebari, 2025).

Metaheuristic algorithms can broadly be classified according to their underlying search mechanisms and sources of inspiration. Common categories include population-based swarm intelligence algorithms, evolutionary and other non-swarm approaches, and algorithms inspired by physical, chemical, or biological processes. The increasing availability of computational resources and advances in artificial intelligence have further encouraged the application of these approaches to complex engineering optimization

problems. In energy systems, metaheuristic techniques are particularly relevant because optimization problems frequently involve nonlinear relationships, multiple local optima, discrete and continuous decision variables, and conflicting technical, economic, and environmental objectives. Such characteristics can make conventional optimization approaches susceptible to local optima or computational difficulties (Twahaa & Ramli, 2018).

Despite their advantages, metaheuristic algorithms are not universally superior, and their performance depends on the characteristics of the optimization problem, parameter settings, search operators, and the balance between exploration and exploitation. Population-based algorithms, for example, may require substantial computational resources as population size and problem complexity increase. They may also experience premature convergence or stagnation when population diversity is lost, while inappropriate parameter settings can adversely affect convergence, solution quality, and robustness (Eiben & Smith, 2015). Consequently, the selection and evaluation of optimization algorithms remain important considerations in the design and operation of HRES.

The increasing application of optimization techniques to HRES has generated a substantial body of literature addressing system sizing, energy management, component selection, dispatch scheduling, and multi-objective optimization. Different studies have employed genetic algorithms (GA), particle swarm optimization (PSO), simulated annealing (SA), and other evolutionary, swarm-based, physics-inspired, and artificial-intelligence-based algorithms to determine suitable HRES configurations. Singh *et al.* (2022) discussed the limitations of conventional PSO, particularly its susceptibility to premature convergence and local optima, and highlighted the potential of hybridization strategies for improving exploration and exploitation.

More recent research has continued to demonstrate the application of optimization algorithms to increasingly complex HRES configurations.

Several review studies have also attempted to consolidate the development of optimization techniques for HRES. In particular, Ansari *et al.* (2023) provided a comprehensive assessment of optimization techniques applied to HRES, with considerable attention to optimization strategies for isolated microgrids. Their review provided an important foundation for understanding the application of optimization approaches to hybrid renewable energy systems. However, the continued development of metaheuristic and artificial-intelligence-based optimization methods, together with the increasing integration of diverse renewable generation technologies and energy storage systems, has expanded the literature beyond the scope of earlier reviews. In particular, recent studies have introduced new optimization approaches, hybrid algorithms, and broader combinations of generation and storage technologies, while increasingly evaluating HRES using multiple technical, economic, reliability, and environmental criteria. These developments create a need for an updated and more focused assessment of recent advances in HRES optimization.

Unlike Ansari *et al.* (2022), the present review extends the existing literature by examining recent developments in HRES optimization and systematically considering the diversity of optimization algorithms, system configurations, and performance indicators reported in the literature. The review covers studies published between 2014 to 2025 and considers hybrid configurations involving solar photovoltaic, wind energy, conventional diesel generation, and energy storage systems. The reviewed applications include both standalone and grid-connected hybrid renewable energy systems, particularly microgrids, with emphasis on system sizing, energy management, energy-storage configuration, and optimization of generation capacities across different geographical locations. Particular attention is given to optimization approaches based on genetic algorithms, particle swarm optimization, mixed-integer linear programming, hybrid optimization techniques, and emerging bio-inspired metaheuristic algorithms. The reviewed studies are evaluated using economic, technical, reliability, and optimization-performance indicators, including total system cost, levelized cost of energy (LCOE), loss of power supply probability (LPSP), energy-system sizing, convergence, exploration, exploitation, and solution quality. The main contribution of this review is to provide a structured assessment of the development and application of optimization techniques for HRES, identify the strengths and limitations of different algorithmic approaches, examine the technical, economic, reliability, and environmental criteria used to evaluate optimized systems, and identify important research gaps and future directions. By explicitly defining its publication period, technology scope, application boundaries, geographical scope, and evaluation criteria, the review provides an updated perspective that extends and complements

Statement of the Problem

The increasing application of optimization techniques in hybrid renewable energy systems (HRES) has improved the ability to determine suitable system configurations, component capacities, energy-management strategies, and operating conditions. However, the existing literature remains fragmented in terms of optimization approaches, system configurations, objectives, constraints, and performance indicators. Previous reviews have examined HRES optimization from different perspectives, including optimal sizing, modelling approaches, software tools, control strategies, and metaheuristic algorithms (Bouaouda and Sayouti, 2022). Consequently, there remains a need for a structured synthesis that brings these dimensions together and provides a consistent basis for assessing the suitability of different optimization approaches for HRES applications.

One important gap concerns the inconsistent assessment of HRES reliability. Although reliability is a fundamental requirement of hybrid systems, particularly for standalone and microgrid applications, existing optimization studies do not consistently evaluate reliability alongside economic and technical objectives. Bansal (2022) noted that earlier HRES studies did not adequately address social, technical, economic, environmental, and reliability aspects simultaneously, while Gusain *et al.* (2023) examined the use of economic, reliability, and environmental indicators in metaheuristic HRES optimization. This indicates that

optimizing system cost or component size alone may not adequately demonstrate the suitability of an HRES if the reliability of electricity supply is not simultaneously established. A further gap concerns the limited and uneven consideration of different HRES technology configurations. Many studies and reviews have concentrated on particular combinations of renewable sources, especially solar photovoltaic and wind systems, sometimes coupled with batteries or conventional generators. Khan *et al.* (2022) reviewed HRES configurations incorporating different renewable sources together with sizing, control, and energy-management strategies. Although these studies provide valuable information, differences in the renewable sources, conventional generators, storage technologies, and system architectures considered make it difficult to determine how optimization approaches perform across a broader range of HRES configurations.

Another significant problem is the lack of consistent comparative evaluation of optimization methodologies. HRES studies have employed classical mathematical techniques, artificial-intelligence-based approaches, metaheuristic algorithms, hybrid algorithms, and software-based optimization tools. Thirunavukkarasu *et al.* (2023) reviewed classical, artificial-intelligence, hybrid, and software-based optimization techniques for HRES and highlighted differences in the objectives, decision variables, and reliability constraints considered across studies. Similarly, Singh *et al.* (2016) reviewed optimization techniques, power-management strategies, control approaches, and multi-objective optimization methods for hybrid solar-wind systems. These studies demonstrate the wide range of optimization approaches available for HRES; however, differences in objective functions, constraints, system configurations, datasets, and performance criteria make direct comparison of their relative effectiveness difficult.

The development of hybrid and emerging metaheuristic algorithms has further increased the need for systematic comparative assessment. Anoune *et al.* (2018) reviewed sizing methods and optimization techniques for photovoltaic-wind hybrid systems and compared stochastic, deterministic, artificial-intelligence-based, and other optimization approaches, with particular attention to system cost and power reliability. Memon and Patel (2021) similarly reviewed optimization techniques used for HRES sizing and reported the increasing application of genetic algorithms, particle swarm optimization, and hybrid optimization approaches. These studies demonstrate the continued development of optimization methodologies; however, the use of different formulations, system configurations, and evaluation criteria makes it difficult to establish whether an algorithm that performs effectively for one HRES configuration will provide similar advantages under different operating conditions.

The problem is further complicated by the diversity of HRES technologies and applications reported in the literature. Existing studies have considered different combinations of renewable energy sources, energy-storage technologies, conventional generators, and system architectures. Taghizad-Tavana *et al.* (2025) examined a broader range of HRES technologies and optimization approaches, including different renewable-energy

configurations and applications. This diversity demonstrates the flexibility of HRES but also limits the generalization of findings across different applications. Variations in renewable-resource availability, load characteristics, system architecture, reliability requirements, objective functions, and economic assumptions can substantially influence the performance of an optimization method

Consequently, there is a need for a comprehensive and consistent synthesis of HRES optimization research that considers optimization methodology, system configuration, economic performance, technical performance, reliability, environmental indicators, and algorithmic characteristics together. Existing reviews have made important contributions to the understanding of HRES optimization, but they have often focused on particular technology combinations, optimization techniques, or application areas. The present review addresses this gap by synthesizing evidence across classical mathematical, evolutionary, swarm-based, hybrid, and bio-inspired metaheuristic optimization approaches, with emphasis on their applications, strengths, limitations, and reported performance. The review therefore seeks to identify persistent gaps in HRES optimization research and provide a clearer basis for understanding the suitability of different optimization approaches for diverse HRES applications.

Objectives and Research Questions

The main objective of this review is to critically examine and synthesize the optimization techniques applied to hybrid renewable energy systems (HRES), with emphasis on their applications, performance, advantages, limitations, and suitability for different system configurations and operating conditions. Specifically, the review aims to identify and classify the major optimization techniques applied to HRES, including classical mathematical, evolutionary, swarm-based, hybrid, and bio-inspired metaheuristic approaches; examine their applications in system sizing, energy management, dispatch, component selection, and operational optimization; compare their reported economic, technical, reliability, environmental, and computational performance; assess the extent to which reliability is considered alongside economic and technical performance; examine the influence of HRES technology configurations and application contexts on optimization outcomes; identify the major strengths and limitations of the different optimization approaches, including convergence, computational requirements, parameter sensitivity, premature convergence, and exploration-exploitation balance; and identify research gaps and future directions for developing more robust and comprehensive optimization approaches for HRES.

To guide the review, the following research questions are addressed: (i) What optimization techniques have been applied to the design and operation of HRES? (ii) How can the existing optimization techniques be classified according to their underlying principles and search mechanisms? (iii) How have GA, PSO, MILP, hybrid algorithms, and emerging bio-inspired metaheuristic algorithms been applied to HRES sizing, energy management, and operational optimization? (iv) What economic, technical, reliability, environmental, and

computational metrics are commonly used to evaluate optimized HRES? (v) To what extent is reliability considered alongside economic and technical performance in existing HRES optimization studies? (vi) How do different HRES technology configurations and application contexts influence the reported performance of optimization techniques? (vii) What are the major strengths and limitations of different optimization approaches in terms of solution quality, convergence, computational requirements, and robustness? and (viii) What major research gaps remain, and what directions should future research pursue to improve HRES optimization?

Review Organizing and Analytical Framework

As this study is a review rather than an empirical investigation involving primary data collection, a conventional theoretical or conceptual framework is not required. Instead, the review adopts an analytical framework based on optimization technique, HRES configuration, application context, optimization objective, and performance criteria. The literature is first organized according to the class of optimization technique employed, including classical mathematical optimization, evolutionary algorithms, swarm-intelligence algorithms, hybrid optimization techniques, and emerging bio-inspired metaheuristic algorithms. Within each category, the reviewed studies are examined according to their applications in HRES sizing, energy management, dispatch, component selection, and operational optimization. The review then considers the HRES configuration and application context, including the renewable-energy sources, conventional generators, energy-storage technologies, and system architectures employed in each study, with attention to standalone, grid-connected, and microgrid applications. The studies are subsequently evaluated according to the performance criteria used to assess optimization outcomes, including economic indicators such as total system cost and Levelized Cost of Energy (LCOE), technical indicators such as component sizing and energy balance, reliability indicators such as Loss of Power Supply Probability (LPSP), environmental indicators such as carbon emissions, and algorithmic indicators such as convergence, solution quality, computational requirements, and exploration-exploitation characteristics. Accordingly, the analytical structure of the review follows the sequence optimization technique, HRES configuration and application, optimization objective, performance metrics, strengths and limitations and research gaps. This framework provides a consistent basis for comparing studies conducted using different algorithms, system configurations, datasets, objective functions, and performance criteria, while enabling the findings to be synthesized across algorithmic, technical, economic, reliability, and environmental dimensions.

Review Methodology and Search Strategy

This review adopted a narrative literature review approach to examine optimization methods, hybrid renewable energy system (HRES) configurations, economic performance,

reliability, and environmental impacts reported in previous studies. The literature search was conducted using MDPI, Web of Science, ScienceDirect and Google Scholar. The search covered publications from 2014 to 2025. Relevant studies were identified using combinations of keywords including "hybrid renewable energy system," "HRES," "optimal sizing," "optimal design," "HRES optimization," "Genetic Algorithm," "Particle Swarm Optimization," "Mixed Integer Linear Programming," "metaheuristic optimization," "Pufferfish Optimization Algorithm," "LPSP," "LCOE," "NPC," and "CO₂ emissions." Boolean operators such as AND and OR were used to combine the search terms and broaden or refine the search. Studies were considered eligible for inclusion when they addressed (i) the design, sizing, optimization, or operation of an HRES; (ii) the application or evaluation of an optimization technique relevant to HRES design; and (iii) one or more technical, economic, reliability, or environmental performance indicators. Studies were excluded when they were unrelated to HRES optimization, focused solely on individual renewable-energy technologies without an optimization component relevant to this review, were duplicate publications, or did not provide sufficient methodological information for meaningful assessment. The screening process involved an initial examination of titles and abstracts, followed by full-text assessment of potentially relevant studies against the stated inclusion and exclusion criteria. The final studies were selected based on their direct relevance to the objectives of the review. The selected literature covers HRES configurations involving photovoltaic (PV), wind, hydro, battery storage, diesel generation, fuel cells, and other energy technologies. The studies were subsequently organized thematically according to the optimization technique employed, system configuration, and performance indicators reported, with particular attention to Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Mixed Integer Linear Programming (MILP), hybrid optimization techniques, and emerging bio-inspired algorithms. Economic indicators considered include Net Present Cost (NPC), Cost of Energy (COE), Levelized Cost of Energy (LCOE), and Life Cycle Cost (LCC), while technical and environmental indicators include Loss of Power Supply Probability (LPSP), renewable fraction, reliability, and CO₂ emissions. Rather than presenting the studies solely as individual summaries, the review compares their findings to identify areas of agreement, differences in reported results, methodological limitations, and unresolved research gaps. The review is narrative rather than systematic and therefore does not claim to provide an exhaustive representation of the HRES optimization literature. In addition, differences among the reviewed studies in geographical conditions, climatic resources, load profiles, system configurations, component costs, fuel prices, project lifetimes, discount rates, and economic assumptions limit direct quantitative comparison of reported COE, NPC, and LCOE values. The screening and interpretation process was conducted collaboratively by the four authors, involving title and abstract screening followed by full-text assessment of potentially relevant studies. The authors discussed the eligibility and relevance of studies to minimize selection and interpretation bias. Nevertheless, some degree of subjectivity may remain due to the

narrative nature of the review. These limitations were considered when synthesizing the evidence and identifying the research gap addressed by the present study.

Solar, Wind, and Battery-Based Hybrid Energy Systems

Solar and wind resources constitute some of the most frequently investigated combinations in HRES optimization because their variability can be partially balanced through complementary generation and battery storage. Al-Shamma'a and Addoweesh (2014) demonstrated that the optimal selection of wind turbines depends not only on wind speed and rated power but also on the desired renewable fraction, while battery storage reduced diesel-generator requirements, fuel consumption, and operating costs. Similar economic advantages were reported by Ogunjuyigbe *et al.* (2016), who obtained a COE of \$0.13/kWh and substantial reductions in lifecycle cost and CO₂ emissions compared with a diesel-only system. Shezan and Ping (2017) also demonstrated the economic and environmental potential of hybrid generation, reporting an NPC of \$160,626 and COE of \$0.431/kWh for an offshore application. Gokul *et al.* (2017) further showed that increasing diesel prices can make renewable hybrid systems increasingly competitive, while Omar *et al.* (2018) reported a COE of \$0.0942/kWh for an optimized wind/PV/tidal/battery system. These findings collectively indicate that combining complementary renewable resources with storage can reduce dependence on conventional generation and improve economic performance. However, the reported cost values vary considerably among the studies and should not be interpreted as evidence that one configuration or optimization approach is universally superior. The differences arise from variations in system scale, location, resource availability, load demand, component costs, and economic assumptions. Reliability is also inconsistently treated. Several studies focused primarily on economic and environmental objectives without incorporating LPSP, making it difficult to determine whether lower-cost configurations also provide adequate electricity supply. Therefore, although the literature generally supports solar-wind-storage hybridization, the evidence also indicates that economic optimization should be accompanied by explicit reliability assessment.

Hydro-Based and Other Hybrid Renewable Energy Configurations

The inclusion of hydro resources provides another pathway for reducing renewable intermittency, particularly in locations with suitable water resources. Adebajji *et al.* (2017) demonstrated this potential through a small-hydro/PV/battery/diesel system for rural electrification in Nigeria. The optimized configuration achieved an LPSP of 0.0054 and a renewable fraction of 0.62, indicating that hydro and PV can complement each other while storage improves supply adequacy. The study nevertheless retained diesel generation and identified computational time as a limitation of GA. Dianabasi *et al.* (2020), using a solar-diesel hybrid system, similarly demonstrated substantial economic improvement compared with diesel-only generation, with the optimized system reducing the reported

energy-generation cost to \$0.132/kWh. The studies suggest that incorporating additional renewable resources can improve resource diversity and reduce dependence on a single generation source. Nevertheless, the continued use of diesel generation in several configurations indicates that many reported HRES solutions remain only partially renewable. Moreover, the economic benefits are not always accompanied by comprehensive assessments of reliability and environmental performance. This creates a need for HRES designs that can combine renewable resources with cleaner dispatchable technologies while simultaneously evaluating cost, supply adequacy, and emissions.

Comparative Performance of GA, PSO, and MILP

The reviewed studies indicate that GA, PSO, and MILP can all provide viable solutions for HRES optimization, but they differ in their computational characteristics and problem-solving mechanisms. GA has been widely applied because of its flexibility in handling nonlinear and multi-variable design problems. The reviewed GA applications generally achieved competitive economic results, although computational burden and parameter dependence were identified as limitations. PSO provides another population-based search mechanism and has demonstrated effectiveness in PV-wind sizing, but its tendency toward premature convergence and local-optimum solutions has been recognized as a potential weakness. Mellouk *et al.* (2019) demonstrated that hybridizing GA and PSO could improve solution quality compared with the individual algorithms, suggesting that combining search mechanisms may help balance exploration and exploitation. MILP provides a fundamentally different mathematical framework. Haddad *et al.* (2019) demonstrated its ability to optimize the scheduling of renewable generation and storage using hourly system data, while Alberizzi *et al.* (2020) applied MILP to determine PV, wind, and battery capacities for an off-grid system. Naderi *et al.* (2022) further compared MILP with multi-objective PSO and reported a lower total cost using MILP. These findings suggest that MILP can provide strong solutions when HRES relationships can be appropriately represented using linear constraints. However, MILP studies did not consistently include LCOE, LPSP, or environmental indicators, limiting the breadth of their performance evaluation. Overall, the literature does not establish a universally superior optimization method. GA offers flexibility for complex nonlinear problems, PSO provides an effective population-based search strategy but can suffer from local optima, while MILP offers a structured mathematical optimization framework. More importantly, differences in system configuration, objective functions, constraints, and operating assumptions make direct numerical comparison difficult. A meaningful algorithm comparison therefore requires the competing methods to be applied under the same system assumptions and evaluated using the same performance indicators.

Economic, Reliability, and Environmental Performance

Economic performance is the most consistently reported criterion across the reviewed studies. Reported COE values range from \$0.0942/kWh to \$0.45/kWh or higher depending

on the system and methodology. Although these results generally demonstrate that optimized hybrid systems can achieve competitive energy costs, the variation between studies prevents direct ranking. A lower COE in one study may result from differences in solar irradiation, wind availability, load demand, system scale, component prices, fuel costs, discount rate, project lifetime, or other assumptions rather than from superior optimization performance. Reliability is less consistently incorporated. Khatri *et al.* (2023) reported LPSP when comparing GA with HOMER. In contrast, several other investigations concentrated on economic performance without quantifying supply adequacy. This creates an important methodological concern because minimizing cost does not necessarily guarantee reliable electricity supply. Indeed, the comparison reported illustrates this trade-off: GA achieved a lower COE and lower non-renewable energy fraction than HOMER but produced a higher LPSP. Thus, economic superiority alone may conceal deterioration in reliability. Environmental performance is also unevenly addressed. Some studies reported substantial reductions in CO₂ emissions relative to conventional diesel systems, while others did not quantify emissions. The overall evidence nevertheless suggests that greater renewable penetration and battery storage can reduce fossil-fuel consumption and associated emissions. However, the inconsistent treatment of emissions, renewable fraction, and reliability indicates that future HRES studies should adopt a multi-objective or multi-criteria evaluation framework rather than relying primarily on economic indicators.

Emerging Optimization Approaches and Complex HRES Applications

The literature is increasingly extending optimization beyond conventional PV-wind-diesel systems. Emad *et al.* (2020) reviewed optimization approaches for wind, solar, and energy-storage systems and highlighted the increasing application of metaheuristic techniques. Pookpant (2019) demonstrated the application of Particle Swarm Optimization (PSO) to the optimal sizing of renewable energy systems, highlighting the capability of population-based optimization techniques to determine suitable renewable generation capacities under system constraints. The study illustrates the growing application of computational intelligence methods to renewable energy system design. These developments indicate a gradual transition from conventional optimization approaches toward more flexible metaheuristic techniques for HRES design and operation. This development is also reflected in applications involving more complex energy systems. Toughzaoui *et al.* (2024) applied GA to a fuel-cell combined heat and power system incorporating PV, an electrolyzer, fuel cell, boiler, and hydrogen storage. Sobti and Anjaneyulu (2024) demonstrated the flexibility of GA for sizing renewable generation and storage under varying residential and commercial load conditions. These studies show that optimization algorithms can accommodate increasingly complex system architectures. However, they also reveal a continuing methodological problem: more complex systems do not necessarily receive more comprehensive performance evaluation. Cost, LPSP, emissions, and renewable contribution are not consistently assessed together. The synthesis therefore

indicates that the field is progressing toward more complex and intelligent HRES optimization, but there remains a gap between algorithmic development and comprehensive practical validation. New algorithms need to demonstrate not only good computational performance but also improvements in economically, technically, and environmentally meaningful HRES indicators.

Findings and Cross-Study Synthesis

The reviewed studies collectively demonstrate that optimization techniques can significantly improve the design and operation of HRES. Across different configurations, hybridization of renewable resources with battery storage generally improves renewable utilization, reduces dependence on conventional generation, and can lower energy costs and emissions. GA has demonstrated considerable flexibility in complex HRES optimization, while PSO provides an effective population-based alternative but remains vulnerable to premature convergence. Hybrid GA-PSO approaches suggest that combining optimization mechanisms can improve search performance. MILP offers a mathematically structured approach capable of determining component sizes and operating schedules where the problem can be appropriately formulated. Despite these advances, the literature does not establish a universally superior optimization technique. Differences in climate, load demand, renewable resources, component costs, fuel prices, system scale, project lifetime, and optimization objectives make direct comparison of reported COE, NPC, and LCOE values inappropriate unless the algorithms are evaluated under common assumptions. The literature also reveals a recurring imbalance between economic and technical evaluation. Cost is frequently emphasized, whereas reliability and environmental performance are not consistently incorporated. Consequently, a system identified as economically optimal may not necessarily provide the required level of electricity supply or achieve the lowest environmental impact. Another unresolved issue is the limited comparative evaluation of emerging metaheuristic algorithms against both established metaheuristics and mathematical optimization methods within the same HRES framework.

Discussion

The findings of this review demonstrate that the effectiveness of an optimization technique for hybrid renewable energy systems (HRES) cannot be assessed solely on the basis of the lowest reported cost. Different optimization methods may produce different trade-offs between economic performance, reliability, renewable contribution, and computational efficiency. Ukoima *et al.* (2024) compared PSO, NSGA-II, and GA-PSO for HRES sizing, energy balance, and load management, demonstrating the importance of comparing competing algorithms using common system and performance conditions. The synthesis further indicates that the performance of emerging metaheuristic algorithms depends strongly on the characteristics of the optimization problem. Rathod and Balaji (2024) applied a modified Harris Hawks Optimization approach to HRES assessment while considering technical, economic, and environmental criteria. Similarly, Abd El-Sattar *et al.*

(2024) developed a modified firebug swarm optimization algorithm for optimal sizing of a hybrid renewable power system. These studies demonstrate the continued development of specialized metaheuristic methods, but algorithm novelty alone does not establish practical superiority. An important finding is that no single optimization algorithm can be considered universally superior for HRES applications. Differences in renewable resources, load demand, system scale, component costs, objective functions, and operating constraints can substantially influence optimization outcomes. Mquqwana and Krishnamurthy (2024) further demonstrate the importance of considering uncertainty in HRES optimization by applying PSO to hybrid renewable energy microgrid design under uncertain conditions. Therefore, meaningful comparisons should be conducted using consistent datasets, system configurations, constraints, and evaluation criteria. The review also reveals an imbalance between economic optimization and reliability assessment. Although cost indicators such as COE, NPC, and LCOE are commonly emphasized, reliability measures such as LPSP are less consistently incorporated. This is important because a lower-cost configuration may not necessarily provide adequate electricity supply. HRES optimization should therefore evaluate economic performance together with reliability, renewable fraction, and environmental impacts. The environmental dimension is also increasingly important as HRES configurations become more complex. Oyewole *et al.* (2024) demonstrated the importance of incorporating economic and environmental uncertainties when optimizing hydrogen-based storage within an HRES. This indicates that the inclusion of hydrogen storage can provide additional flexibility but also introduces economic and environmental considerations that should be incorporated into the optimization framework. Similarly, Yahya *et al.* (2024) investigated an HRES integrating PV, wind, battery, and fuel-cell technologies, demonstrating the increasing application of optimization techniques to more complex multi-source and storage configurations. The technology synthesis further indicates that resource complementarity is an important determinant of HRES performance. Combining complementary renewable resources and storage technologies can improve renewable utilization and reduce dependence on individual intermittent resources. However, increasing the number of components also introduces additional decision variables, operational constraints, and uncertainties. The evidence suggests that HRES research should move beyond simply proposing new optimization algorithms toward standardized and comprehensive performance evaluation. New algorithms should be compared with established methods under identical conditions and evaluated using common indicators such as cost, reliability, renewable fraction, emissions, convergence, and computational requirements. The recent applications of modified Harris Hawks Optimization, firebug swarm optimization, PSO, and other approaches demonstrate continued methodological development, but their practical value should ultimately be established through consistent benchmarking and realistic HRES applications. This approach would improve reproducibility and provide stronger evidence for selecting appropriate optimization techniques for practical HRES deployment.

Recommendations for Future Research

Future studies should standardize the comparison of GA, PSO, MILP, and emerging metaheuristic algorithms using identical HRES conditions and evaluate them using cost, reliability, renewable fraction, emissions, and computational performance. Future research should give greater attention to realistic HRES applications, transparent reporting of algorithm parameters and assumptions, hybrid optimization methods, and standardized benchmark datasets to improve reproducibility and identify genuinely superior optimization approaches.

Conclusion

This review synthesized the development and application of optimization techniques for hybrid renewable energy systems (HRES), with emphasis on optimization methods, system configurations, application contexts, and technical, economic, reliability, environmental, and computational performance. The findings demonstrate that optimization is central to improving HRES design, component sizing, energy management, and operational performance. Across the reviewed studies, hybridization of complementary renewable resources with energy storage generally improves renewable-energy utilization, reduces dependence on conventional generation, and can improve economic and environmental performance. However, these benefits depend strongly on resource availability, load characteristics, system configuration, operating constraints, and the objectives adopted in the optimization model. The synthesis further shows that GA, PSO, MILP, hybrid algorithms, and emerging bio-inspired metaheuristics each offer distinct advantages rather than a universally superior solution. GA provides considerable flexibility for complex HRES optimization, PSO offers an effective population-based search mechanism but may experience premature convergence, while MILP provides a structured mathematical framework for problems that can be appropriately formulated. Hybrid and emerging metaheuristic approaches demonstrate potential for improving search performance and addressing increasingly complex HRES problems; however, algorithmic novelty alone cannot establish practical superiority. The reported performance of an optimization technique is strongly influenced by the characteristics of the HRES problem and by the assumptions under which it is evaluated. A major finding of the review is the persistent imbalance between economic optimization and comprehensive system evaluation. Although COE, NPC, and LCOE are frequently used to demonstrate optimization effectiveness, reliability indicators such as LPSP and environmental measures are less consistently incorporated. Consequently, the lowest-cost configuration should not automatically be regarded as the best HRES solution if it compromises electricity-supply reliability, renewable contribution, or environmental performance. The review therefore establishes that HRES optimization should be treated as a multi-dimensional decision problem in which economic performance is evaluated simultaneously with reliability, renewable fraction, emissions, and computational performance. The review also indicates that increasing resource and storage diversity creates both opportunities and challenges.

Complementary renewable resources and storage technologies can enhance system flexibility and reduce dependence on individual intermittent resources, but additional components introduce more decision variables, operational constraints, uncertainties, and computational complexity. The growing application of hydrogen storage, fuel cells, and other multi-source configurations consequently requires optimization frameworks capable of addressing technological interactions and uncertainty rather than focusing exclusively on component sizing or cost minimization. Overall, the evidence indicates that the principal research challenge is no longer simply the development of new optimization algorithms, but the demonstration of their practical and reproducible superiority under comparable conditions. The limited use of common datasets, system configurations, constraints, and performance indicators make direct comparison of reported results difficult and prevents reliable conclusions about which algorithms perform best across HRES applications. Future studies should therefore benchmark emerging methods against established approaches such as GA, PSO, and MILP using identical conditions and a common set of economic, technical, reliability, environmental, convergence, and computational indicators. Such standardized and comprehensive evaluation would strengthen reproducibility, reduce claims based solely on algorithmic novelty, and provide more reliable evidence for selecting optimization techniques for practical HRES deployment.

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References

- Abd El-Sattar, H., Kamel, S., Hashim, F. A., & Sabbeh, S. F. (2024). Optihybrid: A modified firebug swarm optimization algorithm for optimal sizing of hybrid renewable power system. *Neural Computing and Applications*, 36, 21517–21543. <https://doi.org/10.1007/s00521-024-10196-0>
- Adebanji, B., Adepoju, G. A., Oni, J. O., & Olulope, P. K. (2017). Optimal sizing of an off-grid small hydro-photovoltaic-diesel generator hybrid power system for a distant village. *International Journal of Scientific and Technology Research*, 6(8), 208–213.
- Alberizzi, J. C., Buratti, C., & Moretti, E. (2020). Optimal sizing of an off-grid hybrid renewable energy system for a remote mountain hut using mixed integer linear programming. *Energy*, 196, 117082. <https://doi.org/10.1016/j.energy.2020.117082>
- Al-Shamma'a, A. A., & Addoweesh, K. E. (2014). Techno-economic optimization of hybrid power system using genetic algorithm. *International Journal of Energy Research*, 38, 1608–1623. <https://doi.org/10.1002/er.3191>
- Anoune, K., Bouya, M., Astito, A., & Ben Abdellah, A. (2018). Sizing methods and optimization techniques for PV-wind based hybrid renewable energy system: A review. *Renewable and Sustainable Energy Reviews*, 93, 652–673. <https://doi.org/10.1016/j.rser.2018.05.032>
- Ansari, M. S., Jalil, M. F., & Bansal, R. C. (2023). A review of optimization techniques for hybrid renewable energy systems. *International Journal of Modelling and Simulation*, 43(5), 722–735. <https://doi.org/10.1080/02286203.2022.2119524>

- Bansal, A. K. (2022). Sizing and forecasting techniques in photovoltaic-wind based hybrid renewable energy system: A review. *Journal of Cleaner Production*, 369, 133376. <https://doi.org/10.1016/j.jclepro.2022.133376>
- Bouaouda, A., & Sayouti, Y. (2022). Hybrid meta-heuristic algorithms for optimal sizing of hybrid renewable energy system: A review of the state-of-the-art. *Archives of Computational Methods in Engineering*, 29(6), 4049–4083, <https://doi.org/10.1007/s11831-022-09730-x>.
- Dianabasi, E., Udofia, K., & Okpura, N. (2020). Modelling and optimization of cost function for hybrid power generation system using genetic algorithm. *International Journal of Power Systems*, 5, 40–48.
- Eiben, A. E., & Smith, J. E. (2015). *Introduction to evolutionary computing* (2nd ed.). Springer. <https://doi.org/10.1007/978-3-662-44874-8>
- Emad, D., El-Hameed, M. A., Yousef, M. T., & El-Fergany, A. A. (2020). Computational methods for optimal planning of hybrid renewable micro grids: A comprehensive review and challenges. *Archives of Computational Methods in Engineering*, 27(4), 1297–1319. <https://doi.org/10.1007/s11831-019-09353-9>
- Gokul, B., Suresh, M., & Meenakumari, R. (2017). Optimal sizing of hybrid system for stand-alone application using genetic algorithm. *World Journal of Engineering Research and Technology*, 3(2), 45–56.
- Gusain, C., Tripathi, M. M., & Nangia, U. (2023). Study of meta-heuristic optimization methodologies for design of hybrid renewable energy systems. *Thermal Science and Engineering Progress*, 39, 101711. <https://doi.org/10.1016/j.tsep.2023.101711>
- Haddad, M., Nicod, J., Varnier, C., & Péra, M. (2019). Mixed integer linear programming approach to optimize the hybrid renewable energy system management for supplying a stand-alone data center. *Tenth International Green and Sustainable Computing Conference*, Alexandria, United States. Hal-02867786
- Khan, A. A., Minaei, A. F., Pachauri, R. K., & Malik, H. (2022). Optimal sizing, control, and management strategies for hybrid renewable energy systems: A comprehensive review. *Energies*, 15(17), 6249.
- Khatrī, K. C. A., Shah, K. B., Logeshwaran, J., & Shrestha, A. (2023). Genetic algorithm-based techno-economic optimization of an isolated hybrid energy system. *ICTACT Journal on Microelectronics*, 8(4), 1447–1450. <https://doi.org/10.21917/ijme.2023.0249>
- Kirkpatrick, S., Gelatt, C. D., Jr., & Vecchi, M. P. (1983). Optimization by simulated annealing. *Science*, 220(4598), 671–680. <https://doi.org/10.1126/science.220.4598.671>
- Maca-Chagüendo, M., and Cobos-Lozada, C.-A. (2024). A Systematic Review of Machine Learning-Enhanced Metaheuristics for Solving Capacitated Vehicle Routing Problems. *Revista Facultad de Ingeniería*, 33(68): 18379.
- Mellouk, L., Ghazi, M., Aaroud, A., Boulmalf, M., Benhaddou, D., & Zine-Dine, K. (2019). Design and energy management optimization for hybrid renewable energy system—Case study: Laayoune region. *Renewable Energy*, 139, 621–634. <https://doi.org/10.1016/j.renene.2019.02.066>
- Memon, S. A., & Patel, R. N. (2021). An overview of optimization techniques used for sizing of hybrid renewable energy systems. *Renewable Energy Focus*, 39, 1–26. <https://doi.org/10.1016/j.ref.2021.07.007>
- Mquqwana, M. A., & Krishnamurthy, S. (2024). Particle swarm optimization for an optimal hybrid renewable energy microgrid system under uncertainty. *Energies*, 17(2), 422. <https://doi.org/10.3390/en17020422>
- Naderi, E., Dejamkhoo, A., Seyedshenava, S. J., & Shayeghi, H. (2022). MILP based optimal design of hybrid microgrid by considering statistical wind estimation and demand response. *Journal of Operation and Automation in Power Engineering*, 10(1), 54–65.

- Ogunjuyigbe, A. S. O., Ayodele, T. R., & Akinola, O. A. (2016). Optimal allocation and sizing of PV/wind/split-diesel/battery energy system for minimizing life cycle cost, carbon emissions and dump energy of remote residential building. *Applied Energy*, 171, 153–171.
- Omar, J., Aglzim, S., Chikh, A., & Ahmed, A. B. (2018). Economical evaluation and optimal energy management of a stand-alone hybrid energy system wind/PV/tidal/storage battery based on genetic algorithm. *Electronics*, 7(10), Article 233 <https://doi.org/10.3390/electronics7100233>
- Oyewole, O. L., Nwulu, N. I., & Okampo, E. J. (2024). Optimal design of hydrogen-based storage with a hybrid renewable energy system considering economic and environmental uncertainties. *Energy Conversion and Management*, 300, 117991. <https://doi.org/10.1016/j.enconman.2023.117991>
- Pookpant, S. (2019). Optimal design for hybrid renewable energy system using particle swarm optimization. *International Journal of Renewable Energy Research*, 9(4), 1616–1625.
- Ramadan, R. (2025). A Comprehensive Review of Metaheuristic Algorithms: Classification, Applications, and Future Directions. *International Journal of Computers and Informatics*, 6: 64–69
- Rathod, A. A., & Balaji, S. (2024). Modified Harris Hawks optimization for the 3E feasibility assessment of a hybrid renewable energy system. *Scientific Reports*, 14, 20127. <https://doi.org/10.1038/s41598-024-70663-5>
- Saber Rashid, N., and Zebari, I. M. I. (2025). A Comprehensive Review of Metaheuristic Algorithms for Combinatorial Optimization Problems. *International Journal of Scientific World*, 11(1): 83–92. <https://doi.org/10.14419/d5pxkg39>
- Shezan, S. K. A., & Ping, H. W. (2017). Techno-economic and feasibility analysis of a hybrid PV-wind-biomass-diesel energy system for sustainable development at offshore areas in Bangladesh. *Current Alternative Energy*, 1(1), 20–32. <https://doi.org/10.2174/2405463101666160531145048>
- Singh, A., Sharma, A., Rajput, S., Bose, A., & Hu, X. (2022). An investigation on hybrid particle swarm optimization algorithms for parameter optimization of PV cells. *Electronics*, 11(6), Article 909. <https://doi.org/10.3390/electronics11060909>
- Singh, S., Singh, M., & Kaushik, S. C. (2016). A review on optimization techniques for sizing of solar-wind hybrid energy systems. *International Journal of Green Energy*, 13(15), 1564–1578. <https://doi.org/10.1080/15435075.2016.1207079>
- Sobti, R., & Anjaneyulu, M. (2024). Hybrid renewable energy microgrids: A genetic algorithm approach to system design. *MATEC Web of Conferences*, 392, 01182. <https://doi.org/10.1051/matecconf/202439201182>
- Taghizad-Tavana, K., Esmaeel Nezhad, A., Hagh, M. T., Canani, A., & Safari, A. (2025). Hybrid renewable energy systems for off-grid electrification: A comprehensive review of storage technologies, metaheuristic optimization approaches and key challenges. *Eng.*, 6(11), 309. <https://doi.org/10.3390/eng6110309>
- Talbi, E.-G. (2009). *Metaheuristics: From design to implementation*. Wiley.
- Thirunavukkarasu, M., Sawle, Y., & Lala, H. (2023). A comprehensive review on optimization of hybrid renewable energy systems using various optimization techniques. *Renewable and Sustainable Energy Reviews*, 176, 113192. <https://doi.org/10.1016/j.rser.2023.113192>
- Toughzaoui, Y., Elkhatab, R., Kaoutari, T., Louahia, H., Chaoui, H., & Gualous, H. (2024). Advances in hospital energy systems: Genetic algorithm optimization of a hybrid solar and hydrogen fuel cell combined heat and power. *International Journal of Hydrogen Energy*, 83, 1319–1325.
- Twahaa, S., and Ramlib, M. A. M. (2018). Metaheuristic Optimization Techniques for Renewable Energy Systems: A Review. *Renewable and Sustainable Energy Reviews*, 93: 274–289. <https://doi.org/10.1016/j.rser.2018.05.020>
- Ukoima, K. N., Okoro, O. I., Obi, P. I., Akuru, U. B., & Davidson, I. E. (2024). Optimal sizing, energy balance, load management and performance analysis of a hybrid renewable energy system. *Energies*, 17(21), 5275. <https://doi.org/10.3390/en17215275>

Yahya, W., Saied, K. M., Nassar, A., Qader, M. R., Al-Nehari, M., Zarabia, J., & Jian, Z. (2024). Optimization of a hybrid renewable energy system consisting of PV/wind turbine/battery/fuel cell integration and component design. *International Journal of Hydrogen Energy*, 94, 1406–1418. <https://doi.org/10.1016/j.ijhydene.2024.11.187>