Metaheuristic Optimization Review

♦ ISSN: 2692-4048 Vol: 03, No. 02, 2024 ♦ PP. 11–15

Article DOI: https://doi.org/10.54216/MOR.030203

REVIEW ARTICLE

A Review on Designing Hybrid Energy Systems for Renewable Integration

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Received: November 09, 2024 Revised: December 18, 2024 Accepted: January 10, 2025 ⋆ Corresponding author

ABSTRACT

This paper reviews the design and integration of hybrid energy systems (HES) as a solution to solve the challenges of renewable energy integration. It emphasizes the role of optimization algorithms in improving system performance, reducing costs, and enhancing environmental sustainability by effectively managing energy supply and demand. Recent advances in energy estimating, machine learning, and accurate resource forecasting demonstrate significant system flexibility and efficiency increases. Furthermore, it identifies existing challenges, such as scalability, high initial costs, and integration complexities, while proposing future research and innovation pathways. The study argues that HES can revolutionize energy systems and contribute to global sustainability goals by addressing key gaps.

Keywords: Renewable Integration ▪ Optimization Algorithms ▪ Sustainability Energy Storage ▪ Artificial Intelligence ▪ Energy-efficient hybrid systems

1. INTRODUCTION

Solar energy has proved to be strategic for meeting the world's energy needs while offering less harm to the planet. Renewable energy sources, the common ones being solar, wind, biomass, and hydro, are cheap and renewable compared to traditional fossils. However, their sources are inconsistent and random and thus present a major challenge when integrating into the existing energy systems. Such complications require new energy supply strategies to enhance stability, reliability, and efficiency [1].

Stable energy systems involve improving financial performance, environmental conservation, and the health and welfare of their users. These systems are expected to address present energy demands without affecting future generations' energy supply. HES remains one of the best strategies for addressing this challenge as it incorporates several forms of renewable energy with storage or other conventional energy systems. Such integration has been proven to improve system performance, lessen reliance on a single energy type, and provide a more stable energy supply [2].

Optimization algorithms serve an essential function in the design, operation, and management of hybrid energy systems. They intend to optimize energy utility and minimize the cost and emissions of greenhouse gases. A close examination of the area reveals that optimization techniques help to formulate flexible and effective energy systems that suit complex demand and resource constraints [3].

Hybrid energy systems comprise renewable energy systems, energy storage systems, and energy distribution systems. These components should be coordinated to produce the desired results effectively. Resource availability, energy requirement, system costs, and environmental limitations should also be considered at the design level. Factors such as these give optimization algorithms foundational components to tackle the mentioned challenges methodologically [4].

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Many optimization algorithms are used in the design of hybrid energy systems. Standard approaches include linear programming and mixed-integer programming, which deal with optimum problem resolutions. In contrast, heuristic and metaheuristic algorithms such as genetic algorithms, particle swarm optimization, and simulated annealing allow flexible solutions for complex and nonlinear problems. These methods allow researchers to search large solution spaces and find near-optimal solutions [5].

The deep integration of renewable energies in the energy system showcases the relevance of combined power systems and efficiency algorithms. Sophisticated control approaches derived from online optimization enable these systems to adapt to fluctuations in the energy supply and consumer demand. Machine learning and artificial intelligence add more flexibility and smartness to hybrid energy systems by forecasting resource availabilities and controlling energy flows [6].

However, hybrid energy systems have disadvantages, such as problems associated with increased scale, interface complexity, and stability issues due to technological limitations. Mitigating these challenges requires collaborative work across energy science, engineering, economics, and computation. In addition, multi-stakeholder cooperation involving policymakers, executives, and academics is needed to extend the use of these systems [7].

This review highlights the design and integration of hybrid energy systems for re-establishing renewable energy. Specifically, it overviews the application of optimization algorithms in reaching sustainable energy supply and presents recent developments in this domain. This study seeks to offer a prescription into the current state of the research and look for more possibilities in the future.

2. LITERATURE REVIEW

Global challenges such as climate change, rising energy demands, and depletion of fossil fuels have accelerated interest in hybrid renewable energy systems. Recent research emphasizes techno-economic feasibility, environmental performance, and optimal design of integrated systems that combine renewable resources, storage devices, and conventional backup units.

A techno-economic study of hybrid energy systems for a remote Australian community compared PV, battery energy storage systems, fuel cells, electrolyzers, and hydrogen tanks. The PV/BESS system achieved the lowest net present cost and levelized cost of energy, while PV/FC/EL/HT was optimal for hydrogen integration [8]. Microgrid design studies integrating renewable and diesel generation similarly show that optimized solar PV, wind turbine, battery energy storage, and diesel generator configurations can improve reliability while reducing environmental impacts [9].

For critical loads such as medical facilities, solar–wind–battery microgrids have been optimized using particle swarm optimization and transit search algorithms. Such approaches demonstrate the potential of hybrid systems to provide reliable energy to essential services under both on-grid and off-grid conditions [10]. Studies on remote regions also indicate that PV, wind turbine, and battery combinations can meet demand in areas with limited grid access when optimized through metaheuristic approaches [11].

Wind energy assessment and hybrid microgrid optimization in Saudi Arabia showed that PV/WT/BS configurations are suitable for regions with low wind potential and can guide scalable hybrid microgrid designs [12]. Hybrid electric vehicle studies further demonstrate that renewable integration, advanced control strategies, and new materials can improve propulsion performance and sustainability [13]. Energy storage research on electrochemical capacitors, including EDLCs, pseudocapacitors, and hybrid systems, highlights their adaptability to renewable energy systems, transportation, and grid storage [14].

Multilevel inverter studies show that hybrid three-level and five-level inverters can extend linear modulation range without introducing lower-order harmonics. These inverters offer fault-tolerant capabilities, inherent capacitor balancing, and suitability for electric vehicles and industrial motor drives [15]. Other work integrates response surface methodology, multi-objective bat algorithms, and VIKOR decision-making to optimize photovoltaic thermal systems, demonstrating highly accurate predictive models and diverse Pareto-optimal solutions [16].

Industrial energy applications include optimization of integrated energy systems in chlor-alkali processes, where wasted hydrogen utilization and grid scheduling reduce cost, emissions, and hydrogen curtailment [17]. Hybrid energy systems for EV charging combine photovoltaic and wind power with high-gain bidirectional converters, fuzzy controllers, and social spider optimization to improve maximum power point tracking and grid interaction [18]. Residential zero-energy building studies integrate wind power, gas turbines, hydrogen production, and neural-network-based multi-objective optimization to provide electricity, heating, cooling, and hydrogen [19].

Renewable-energy-powered automation for transformer coil winding machines integrates solar and wind power with energy storage and advanced automation. Machine learning and computational simulations improve winding precision, torque, speed, energy consumption, downtime, and reliability [20]. Biogas integration studies in Aras de los Olmos, Spain, optimize biomass inflow into a biogas reactor supported by solar, wind, and hydro-based storage, demonstrating reliable rural energy availability and cost-effective sustainability [21].

Table 1 presents a comprehensive summary of the reviewed literature on hybrid energy systems, highlighting design optimization and applications across diverse contexts.

The studies examined demonstrate remarkable progress in integrating renewable energy technologies and optimizing system performance. From hybrid microgrids and fault-tolerant inverters to renewable automation and biomass-based energy production, these advancements showcase the potential to revolutionize energy systems across residential and industrial sectors. While significant strides have been made, the literature suggests areas for further exploration, such as enhanced scalability, improved energy storage solutions, and refined control systems.

Table 1. Summary of Literature Review

Ref.	Study Focus	Key Findings	Optimization Methods Used	Application/Impact
[8]	Techno-economic feasibility of hybrid energy systems	PV/BESS had the lowest NPC and LCOE; PV/FC/EL/HT was optimal for hydrogen integration.	Cuckoo Search Algorithm	Remote Australian community energy supply, cost reduction, and resource optimization.
[9]	Microgrid design with renewable and diesel integration	Solar PV/WT/BES/DG configuration optimized cost and reliability.	Hybrid Particle Whale Optimization Algorithm	Rural and remote microgrid systems with improved environmental outcomes.
[10]	Solar–wind–battery microgrid for medical load	PSO achieved the lowest LCOE; transit search was effective for on-grid setups.	Particle Swarm Optimization; Transit Search	Optimized energy supply for critical loads in Ain Al-Sokhna, Egypt.
[11]	Renewable hybrid microgrid for remote regions	PV/WT/B1 achieved the lowest total annual cost with high reliability.	Particle Swarm Optimization	Addresses power demands in remote areas with limited grid access.
[12]	Wind energy integration in hybrid microgrids	PV/WT/BS configuration was optimal for low-wind-potential regions.	Not specified	Framework for scalable hybrid microgrid designs in Saudi Arabia.
[13]	Electric propulsion systems for hybrid vehicles	Advanced control strategies and materials enhanced performance.	Finite element analysis; AI-driven methods	Renewable energy integration into electric vehicle technologies.
[14]	Electrochemical capacitors for energy storage	Focused on EDLCs, pseudocapacitors, and hybrid systems.	Electrochemical impedance spectroscopy	Renewable energy systems, transportation, and grid storage.
[15]	Multilevel inverters for high-voltage applications	Hybrid MLIs offered fault tolerance and reduced harmonics.	DSP and FPGA-based simulations	Electric vehicles and industrial motor drives.
[16]	Optimization of photovoltaic thermal systems	Hybrid RSM–MOBA framework achieved high efficiency.	RSM, MOBA, VIKOR	Enhanced hybrid solar system performance.
[17]	Energy systems for chlor-alkali processes	Optimized hydrogen utilization reduced costs and emissions.	Non-dominated genetic algorithm	Low-carbon industrial energy systems.
[18]	Hybrid energy systems for EV charging	HGBMZ converter enhanced efficiency and fuzzy control optimized MPPT.	Social Spider Optimization Algorithm	Sustainable EV charging with grid integration.
[19]	Hybrid systems for zero-energy residential buildings	Optimized integration of wind power and hydrogen.	Neural-network-based multi-objective optimization	Scalable zero-energy urban living.
[20]	Renewable automation for manufacturing	Solar and wind energy reduced costs and improved reliability.	Machine learning and computational simulations	Renewable-energy-powered industrial automation.
[21]	Biogas integration in hybrid energy systems	Optimized biomass flow improved rural energy reliability.	Robust optimization tools	Rural sustainability through renewable energy and biomass integration.

3. DISCUSSION

Hybrid energy systems present a promising pathway toward integrating renewable energy sources in contemporary energy networks. Their capacity for cross-technology operation counterbalances the intermittency and variability of renewables. However, designing efficient and cost-effective HES presents unique problems that require sophisticated optimization techniques and complex system architectures [22].

One major issue is handling the fluctuating nature of systems that depend on renewable resources such as solar and wind power. These are location- and time-specific and therefore require daily balancing of supply and demand. Energy storage systems such as batteries, hydrogen storage, and pumped hydro storage are important for accomplishing this variability. Nevertheless, economic and environmental costs remain involved with integrating storage into HES.

Optimization approaches can be summarized by the general multi-objective formulation

$$\min F(x) = \left[f_{\text{cost}}(x),\ f_{\text{emission}}(x),\ -f_{\text{reliability}}(x) \right], \qquad (1)$$

subject to energy-balance and capacity constraints:

$$P_{\text{RES}}(t) + P_{\text{storage}}(t) + P_{\text{grid}}(t) = P_{\text{load}}(t), \quad t = 1, 2, \ldots, T. \qquad (2)$$

The levelized cost of energy is commonly expressed as

$$\text{LCOE} = \frac{\sum_{t=1}^{T} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}}, \qquad (3)$$

where I_t, M_t, F_t, E_t, and r denote investment cost, operation and maintenance cost, fuel cost, generated energy, and discount rate, respectively.

Advanced optimization algorithms play a pivotal role in solving these problems. Classical linear and mixed-integer programming provide exact solutions for deterministic formulations, while heuristic and metaheuristic methods offer flexibility in nonlinear and uncertain settings. Cuckoo search, particle swarm optimization, genetic algorithms, social spider optimization, and hybrid whale-based approaches are common examples in recent HES studies.

Artificial intelligence and machine learning improve HES design through forecasting, energy management, and adaptive control. Accurate prediction of solar irradiance, wind speed, demand, and storage availability allows operators to implement real-time policies that reflect current conditions. Reinforcement learning algorithms are increasingly applied to learn dynamic control strategies in large, complex, and multi-agent energy systems [25].

Despite these improvements, important obstacles remain. Scalability remains problematic in large urban and industrial settings. Investment costs for renewable technologies and energy storage are high at early stages of adoption. Integration of different components also lacks standard interfaces, creating interoperability challenges between power technologies. Mitigating these risks requires business model innovation, monetary incentives, and research partnerships [26].

Policy frameworks and regulations strongly influence HES implementation. Feed-in tariffs, tax credits, and research grants can support renewable electricity generation. International cooperation in technical standards and best-practice exchange can significantly promote global advancement. Stakeholders across the energy sector must ensure that proposed solutions are feasible, affordable, and socially acceptable [27].

Environmental aspects continue to drive HES advancement. Although these systems decrease greenhouse gas emissions, they still have environmental effects based on technology choice, materials, manufacturing, and disposal. Life-cycle assessment helps decision-makers understand long-term sustainability and identify paths for reducing ecological impact [28].

Further studies should design durable and flexible optimization models that account for real-world constraints. These frameworks should include advanced storage, renewable energy sources, and socio-economic and environmental aspects. Cooperation between energy engineering, computer science, and economics is crucial to continuing progress in this research area [29].

Hybrid energy systems are a revolutionary solution to the issue of integrating renewable energy sources. Their success depends on removing technical, economic, and policy constraints while using state-of-the-art optimization methodologies. The application of these systems demonstrates their potential to reform future global energy systems and highlights the need for ongoing research efforts [30].

4. CONCLUSION

Hybrid energy systems are essential for incorporating renewable energy into the general energy mix. Associating renewables with energy storage and conventional technologies helps address intermittency and variability. Because of their ability to deliver fair, continuous, reliable, and clean energy, HES will be indispensable in achieving decarbonization objectives worldwide.

Optimization algorithms are necessary in the design, management, and operation of HES. Classical techniques such as linear and mixed-integer programming provide exact solutions to well-defined deterministic problems. However, modern energy systems are highly complex and multi-objective and usually require advanced techniques. Heuristic and metaheuristic methods, including genetic algorithms, particle swarm optimization, and simulated annealing, provide general solutions for nonlinear and uncertain systems.

Artificial intelligence and machine learning have brought HES capabilities to a higher level. Machine-learning models accurately predict renewable generation and demand patterns, which is fundamental for real-time optimization. Reinforcement learning techniques can optimize storage and distribution networks under real-time conditions, enabling dynamic energy management and more resilient adaptive systems.

Although HES has excellent potential, it is still associated with challenges that require continuous effort. High initial cost can prevent wide adoption, and the integration of solar panels, wind turbines, battery systems, hydrogen systems, and control units is often hampered by limited standardization and interoperability. These challenges require combined actions from policymakers, researchers, and industry stakeholders.

Environmental considerations should remain attached to HES development. Even as these systems reduce greenhouse gas emissions and fossil-fuel consumption, their material choices, manufacturing processes, and disposal strategies can still create impacts. Life-cycle assessment is informative for evaluating long-term sustainability and guiding future system design.

Future research should focus on scalable architectures, advanced energy storage, interoperable control systems, and integrated optimization frameworks that balance cost, reliability, and environmental performance. By addressing these gaps, HES can support a sustainable, resilient, and energy-efficient future.

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