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Review

Review of Optimal Design and Enhanced Hybrid Energy Systems Using Energy Management Strategies

Fadhil Khadoum Alhousni [1,*], Paul C. Okonkwo [1] and El Manaa Barhoumi [2]

[1] Mechanical & Mechatronics Engineering Department, College of Engineering, Dhofar University, Salalah 211, Oman; pokonkwo@du.edu.om
[2] College of Engineering, Dhofar University, Salalah 211, Oman; ebarhoumi@du.edu.om
* Correspondence: falhousni@du.edu.om; Tel.: +968-99674453

Abstract

Hybrid energy systems (HESs) have garnered significant interest in recent years because they combine many energy sources to enhance efficiency and dependability. This review article thoroughly examines the most effective design approaches and tactics for improving performance in hybrid energy systems through efficient energy management. The problem encompasses multiple aspects of HES design optimization, such as identifying the most efficient component sizes, choosing the most appropriate technology, and setting up the system. Furthermore, it involves implementing an energy management system (EMS) to optimize the system's overall efficiency. Moreover, this article examines difficulties, current progress, and potential research prospects. A hybrid system, which integrates renewable sources with backup units, provides a cost-efficient, eco-friendly, and dependable energy supply and outperforms single-source systems in satisfying diverse load requirements. An essential factor in these hybrid systems is the precise evaluation of the ideal dimensions of the components to ensure that they sufficiently meet all the load requirements while minimizing both the initial investment and ongoing operating expenses. This study extensively examines suitable methods for determining the proper sizes, as the current body of literature describes. These methods can significantly enhance renewable energy systems' economic feasibility and practicality, promoting their wider adoption.

Keywords: hybrid energy systems (HESs); energy management strategies (EMSs); renewable energy integration; optimal system design; sustainable power systems

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1. Introduction

Hybrid energy systems (HESs) are gaining increasing recognition as a viable approach to addressing the challenges of energy sustainability, security, and reliability. To mitigate the inherent inconsistencies and instability of individual energy sources, it is recommended to construct a hybrid energy system that integrates various renewable and conventional sources, such as solar, wind, hydro, and biomass, and storage technologies [1,2]. Optimizing the building and operation of HESs is essential for attaining optimal energy efficiency, lowering expenses, and mitigating environmental effects [3]. Energy management systems (EMSs) play a pivotal role by coordinating energy flow between different sources, storage, and loads to enhance efficiency and prolong the lifetime of system components. Advanced optimization techniques—such as mathematical programming, evolutionary algorithms, and machine learning—have been widely applied to identify the most effective system configurations [4]. This study evaluates the efficacy of optimization methodologies,

including mathematical programming, evolutionary algorithms, and machine learning, in establishing the ideal size and arrangement of HES components [5]. Precise modeling and simulation are crucial for assessing the performance of HESs in different operational scenarios and exploring several modeling approaches for renewable energy sources, energy storage systems, and other components of hybrid systems [6]. These strategies encompass physics-based models, data-driven models, and hybrid modeling approaches. These methodologies aim to comprehend the dynamic interactions among system components and evaluate their influence on overall performance. In addition, this study utilizes simulation tools, such as system-level simulations and dynamic modeling, to assess system performance and enhance design parameters [7]. This includes addressing transient occurrences and unpredictability. Internationally, countries are implementing legislation to encourage the adoption of sustainable energy technology, enhance energy efficiency, and establish initiatives for resource preservation, recognizing the importance of the energy industry. Hybrid systems, which integrate renewable and conventional sources, provide a consistent energy supply, particularly in remote areas, thus diminishing reliance on fossil fuels and advancing sustainability. Energy management systems are essential for improving health, safety, and environmental performance and increasing efficiency [8,9]. These systems efficiently regulate and oversee the movement of energy between various sources, storage systems, and loads to maximize the system's performance in real time. An effective strategy for managing energy in an HES involves integrating different control systems, such as rule-based control, model predictive control, and artificial intelligence-based control [10]. These algorithms employ real-time data, weather forecasts, and demand estimations to optimize energy distribution, minimize energy losses, and prolong the lifespan of system components. A comprehensive control mechanism is crucial for effectively managing power distribution in a multi-source energy system. Figure 1 illustrates the conceptual framework of this review, delineating the interconnections between hybrid system design, modeling and simulation, EMS methodologies, control strategies, and prospective research avenues.

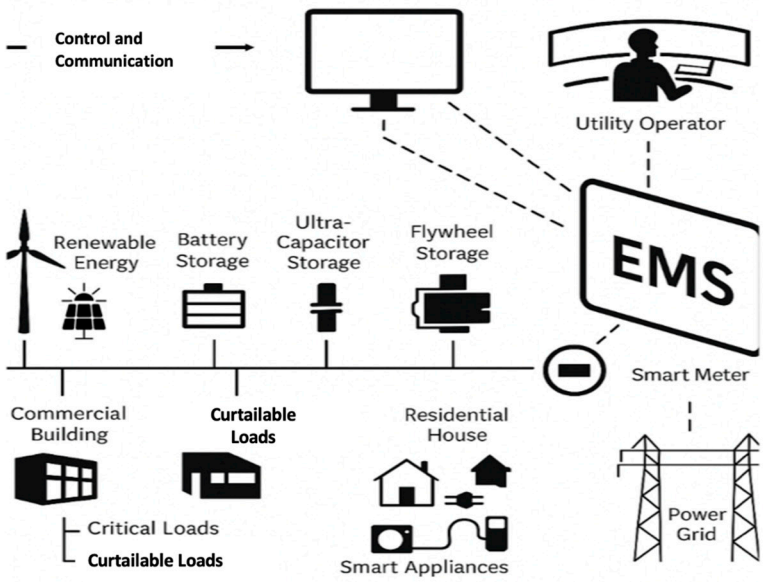


Figure 1. General architecture of a hybrid energy system with energy management.

Although numerous research studies have examined optimization techniques and EMSs in hybrid systems, the current literature is frequently disjointed and lacks a cohesive viewpoint that links optimal design, modeling, and management. This review consolidates existing knowledge into a structured framework and offers a comparative examination

of strategies to solve this gap. This method underscores current obstacles and delineates avenues for subsequent investigation. This study employs advanced energy management techniques to identify the optimal arrangement and enhance the efficiency of hybrid energy systems. The project aims to improve the understanding of achieving optimal efficiency and reliability in HESs by analyzing various optimization and modeling methodologies and applying fundamental energy management strategies. Despite extensive research, current studies often remain fragmented, focusing on either optimization, modeling, or EMSs, without providing an integrated perspective. This review seeks to bridge that gap by consolidating knowledge into a structured framework that highlights interconnections across design, control, and management strategies. Unlike earlier reviews, which focus on either sizing, optimization, or control in isolation, this paper integrates optimal design, modeling and simulation, energy management strategies, and control methodologies into a unified framework. The novelty of this review lies in (i) systematically comparing strengths and weaknesses of approaches across all dimensions of HESs, (ii) proposing a classification framework linking design, modeling, EMSs, and control strategies, and (iii) outlining a future research agenda that addresses critical gaps in life cycle assessment, scalability, and socio-economic integration.

2. Optimal Design and Enhancement of Hybrid Energy Systems

Procedures using novel optimization techniques to prove the superiority of new HESs have been revised within the literature using mathematical and mechanical engineering tests. Essentially, the goal is to fulfill energy requirements in the most efficient way possible at the minimum cost. The techno-economic model and multi-objective optimization are used to address capital cost, operating cost, reliability, and environmental harm [11]. Figure 2 illustrates the key components of a hybrid energy system architecture, including renewable sources, energy storage, backup power, inverters, and an EMS.

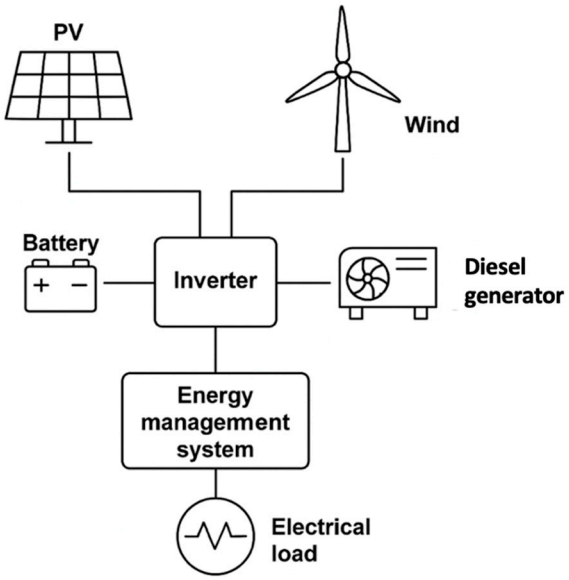


Figure 2. The key components of a hybrid energy system.

A major aspect of hybrid renewable systems is accurate estimation of component sizes so that initial investment and continuous operational costs are minimal [11]. A lot of research has been performed to optimize hybrid renewable energy system configurations. A comprehensive study conducted by Khan et al. [12] examined various models that analyzed load profiles, resources, and optimal sizing for a hybrid system comprising wind power, solar PV, and fuel cells. To enhance the efficiency and reliability of the system,

several studies were conducted. Various control strategies have been proposed to manage system components. Rafique et al. [13] conducted a survey. These techniques allow for efficient energy sharing, minimize energy waste, and extend component life. They perform this by taking into account data, weather forecasts, and demand predictions. The study by Manas et al. [14] of an off-grid PV–wind hybrid system aimed to study the various interactions in the system between renewable sources, storage systems, and load to enhance system efficiency and also reduce dependency on the grid. Intelligent grids have explored multiple-objective optimization procedures, including a new load-prioritizing algorithm, to enhance their versatility and robustness [15]. Research was conducted by Shi et al. [16], who studied different methods utilizing a preference-driven coevolutionary algorithm to optimize HES designs with several competing objectives, including cost, power supply reliability, and pollution. This method persistently adjusts system configurations to achieve Pareto-optimal solutions. For assessing HESs' performance under different operational conditions, precise modeling and simulation techniques are critical [17]. They facilitate insight into the dynamic interactions of system components through various modeling methods, ranging from physics-based models to data-driven models, and utilizing algorithms. Governments across the world are implementing policies that boost the use of renewable energy, etc. [18,19]. Hybrid systems mix renewable energy and conventional energy sources to ensure a reliable supply of electricity, especially in off-grid places. HES optimization consists of appropriately selecting and tuning components to satisfy energy demands while minimizing costs and environmental impacts. By using modern models and optimizing and controlling energy usage, HESs can become better, more reliable, and greener. Ongoing research to enhance the performance of HESs, in light of changing energy needs, is crucial.

2.1. Modeling and Simulation of Hybrid Energy Systems Sizing

Modeling and simulation must be accurate to evaluate HESs under different operational conditions. This section discusses various modeling methods related to renewable energy sources, energy storage systems, and hybrid system components. The authors will discuss physics-based models, data-driven models, and hybrid modeling techniques to understand how different components of systems interact with each other and overall system behavior. Furthermore, a variety of simulation methods are analyzed, including system-level simulation and dynamic modeling, to study system behavior and optimize design parameters while considering transient phenomena and uncertainties. Many expert researchers have performed design optimization of hybrid renewable energy systems in the literature. The main goal is to find the most effective arrangement of power systems, which includes the best siting, type, and sizing of generation units at appropriate nodes to cater to load demands with a minimum cost and minimal environmental impacts. A thorough evaluation of a design requires considering the total lifetime costs and emissions of a system, including capital, operational, and maintenance costs. The goal of optimal hybrid system design is to select the most cost-effective combination of generator configurations, types, and sizes, resulting in minimum lifetime costs and emissions. The ideal configuration is a hybrid system configuration with the lowest net present value of all the viable choices available. There are many optimization techniques and much software for integrating and optimizing real-time systems. Researchers have employed various optimization techniques to determine the optimal dimensions of hybrid systems. Table 1 below provides a comparative analysis of the above optimization methods.

Table 1. A comparative analysis of optimization approaches.

Optimization Methodology	Description	Strengths	Limitations	Ref.
Mathematical Programming	Uses linear and nonlinear programming to optimize system size and configuration.	Provides precise solutions and handles well-defined constraints.	Computationally expensive for large-scale aerospace systems.	[20]
Evolutionary Algorithms (EAs)	Utilizes GAs, PSO, and DE to find optimal solutions in design, control, and routing.	Effective for complex, multi-objective problems and large search spaces in aerospace applications.	Convergence time may be long and results depend heavily on initial population settings.	[21]
Machine Learning (ML)	Applies supervised and reinforcement learning for optimization and control.	Adaptive to dynamic conditions, supports real-time optimization and fault detection.	Requires large, high-quality datasets and extensive computational resources.	[22]
Hybrid Modeling Approaches	Combines physics-based and data-driven models to improve system performance.	Balances accuracy with efficiency; integrates simulation and empirical data for better prediction.	Increased model complexity and challenges in integrating different modeling approaches.	[23]
Simulation-Based Optimization	Uses Monte Carlo, system dynamics, or stochastic models to simulate system behavior.	Accounts for uncertainty and transient phenomena in flight dynamics and thermal systems.	Requires extensive simulation time, especially for high-fidelity or large-scale problems.	[24]

The comparison reveals that each optimization technique has unique merits and drawbacks. Mathematical programming provides precise solutions but struggles with large-scale or highly nonlinear problems. Evolutionary algorithms are more flexible and practical for complex, multi-objective optimization but often require long convergence times and are sensitive to initial parameter settings. Machine learning approaches adapt well to dynamic and uncertain conditions, offering real-time optimization potential, but depend heavily on high-quality datasets and computing resources. Hybrid modeling balances accuracy and efficiency by combining physics-based and data-driven models, though integration complexity remains a barrier. This suggests that no single approach is universally optimal; instead, hybrid or multi-method strategies appear most promising for practical HES design. Research shows that optimization approaches are used to find the right dimensions of hybrid renewable energy systems. The efficiency of the methods depends on the application, system size, data, and computational requirements. In the future, research can study the combination of optimization techniques that can generate robust solutions to aid hybrid energy systems that offer solutions to costs, efficacy, and sustainability. By employing these methodologies, we can enhance the design and operational efficiency of hybrid energy systems, thereby contributing to more effective global energy solutions.

2.2. Commercially Available Software Tools for Hybrid System Sizing

This investigation study focuses on designing hybrid renewable energy systems (HRESs) optimally. This has been extensively studied and has a substantial body of literature. The main aim of this design problem is to identify the superior configuration of power generation units in terms of location, type, and size for a specific number of nodes

of a system [25]. It should suffice to meet energy demand at minimum total system costs. Typically, other HRESs are evaluated based on lifetime cost and emissions. Lifetime cost consists of three important costs, namely capital cost, operation cost, and maintenance cost [26]. Furthermore, lifetime costs are adjusted over time. Optimal configuration aims to find the cheapest and cleanest mix of generation technologies. The optimum design or optimum configuration for a system refers to the configuration that has the lowest NPV for all feasible and dispatchable configurations. Renewable energy systems using different sources of energy can be analyzed and simulated, specifically using particular software. We can access more renewable energy software from various academic and research institutions. Simulation software tools allow comparing the efficiency of systems and the energy cost of multiple designs to find a suitable, efficient design [27,28]. A widely used tool is HOMER v3.14.2, created by the US National Renewable Energy Laboratory (NREL). HOMER has models of various devices like PV systems, wind turbines, hydroelectric generators, batteries, diesel generators, fuel-based generators, electrolysis systems, and fuel cells [28]. Programs like HOMER allow system designers to evaluate some or a combination of the following options. First, the system uses available energy resources and their costs. Second, if the grid is connected, for these simulations, the software needs to be given a very detailed set of input parameters with energy resource profiles, techno-economic constraints, storage needs, and management strategies. The specific inputs include the type and characteristics of each component, capital and replacement costs, operation and maintenance expenses, efficiency rates, and expected operational lifetime. Figure 3 indicates the general architecture of this software tool.

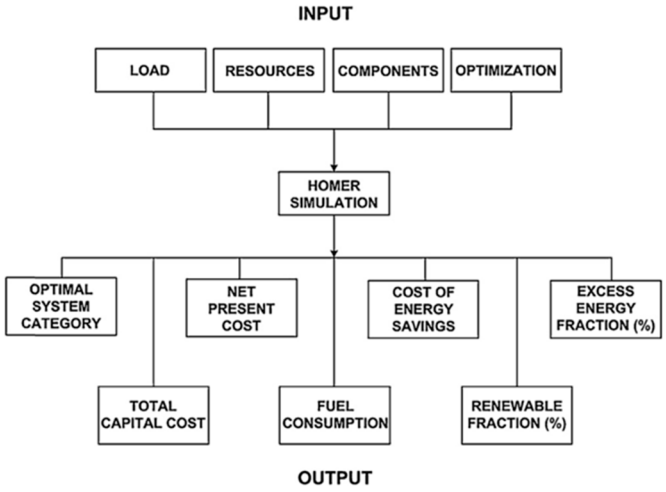


Figure 3. The general architecture of the HOMER software tool.

According to previous studies, the HOMER software is widely used in renewable energy systems, as noted in the literature. Both grid-connected and standalone systems have been studied. Additionally, many researchers have examined the simultaneous integration of conventional systems, such as diesel, with renewable energy systems using HOMER. The study by Bahramara, S. et al. employed HOMER to analyze the technical and economic feasibility of standalone renewable energy systems, especially in remote and off-grid areas. For example, researchers have used HOMER to optimize configurations involving PV systems, wind turbines, and battery storage to provide reliable electricity to isolated communities with minimal dependence on fossil fuels. These studies show HOMER's ability to handle complex simulations involving fluctuating renewable energy supply and varying load demands. Besides off-grid solutions, HOMER has also been widely applied in evaluating grid-connected renewable systems. These studies usually focus on identifying the optimal renewable energy share that can be integrated into the

grid while maintaining system reliability and lowering costs. For a detailed review of the commercial software tools used for the performance evaluation and optimization of hybrid renewable energy systems, see Table 2.

Table 2. Brief comparison of the main approaches applied for the sizing of hybrid renewable energy systems in the literature.

Energy Management Approach	Advantages	Disadvantages	Remarks/Literature Insights	Ref.
Simplex algorithm	Easy to understand	Relatively lower performance for finding the global optimum compared to GAs, etc.	Used in early-stage feasibility studies	[29]
Linear programming	Structured and fast; well-established	Not suitable for nonlinear systems; inflexible	Common in economic dispatch models	[30]
Evolutionary algorithm	Capable of global optimization; suitable for complex, nonlinear systems	Requires significant computational resources and parameter tuning	Widely applied in HRES optimization	[31,32]
HOMER	Makes it easy to understand the main concepts of a sizing procedure with efficient output figures; it can be downloaded freely	"Black box" code utilization; first-degree linear equation-based models for hybrid system components that do not represent the source characteristics exactly	Most cited tool in hybrid system research	[33]
Other software tools (HYBRID2 v1.3, etc.)	The advantage changes from approach to approach	Harder to find examples in the literature	Used in advanced and research-grade simulations	[34]
Neural networks	Efficient performance in most types of applications; easy to find examples in the literature	Needs a training procedure	Emerging in energy demand prediction and smart grid control	[35]
Design-space-based approach	Easy to implement and understand	Computational time inefficiency	Useful in sensitivity analysis and educational contexts	[36]

The surveyed software tools and sizing approaches illustrate trade-offs between usability, accuracy, and computational demand. Rule-based or simplex/linear programming methods are structured and fast but limited in handling nonlinearities and dynamic system behavior. Evolutionary algorithms offer global optimization and effectively handle complex systems, yet they require substantial computational resources and meticulous parameter tuning. Widely used tools such as HOMER are highly accessible and user-friendly, but their "black box" nature and simplified component models reduce transparency and accuracy. Neural networks and other intelligent techniques show strong potential for prediction and control but depend on large datasets and training processes. Ultimately, hybrid approaches that combine the accessibility of commercial tools with the precision of advanced optimization techniques are most promising for practical HES planning and deployment. In summary, HOMER has been widely recognized as a powerful tool for modeling and optimizing renewable energy systems in various configurations, including standalone,

grid-connected, and hybrid systems. The literature consistently highlights its strengths in scenario analysis, cost estimation, and environmental assessment, making it a valuable resource for both academic researchers and energy planners.

3. Energy Management Strategies in Hybrid Renewable Energy Systems

Governments of the world are adopting policies that favor renewable energy technologies, as this sector is increasingly seen as strategic. Many countries promote renewables, increase energy efficiency, and formulate conservation plans and legislation. Efforts are being made to ensure a definite supply of power in incredibly remote areas through the use of hybrid systems. By utilizing more than one source, these systems reduce fossil fuel dependence. There is a lot of research being conducted on hybrid systems and their uses, which is primarily for rural electrification. To deliver all the load with the use of renewable energy, to minimize expenditure on diesel, to protect the components, and to finally feed back to the grid, it is important to use an efficient EMS. Centralized controllers, often integrated with a SCADA-like monitoring environment, enable EMS implementation. There are various comprehensive review papers on renewable energy systems detailing hybrid system configurations, sizing methods, storage options, and control methods. Notably, Chauhan and Saini review standalone systems, Bajpai and Dash review standalone hybrid systems, and Gu et al. [37] review combined cooling, heating, and power microgrid systems, and Nehrir et al. [38] performed a study. Industry review articles explore a range of subjects, including, but not limited to, Huang et al.'s work on energy management strategies for microgrids, Ahtisham Urooj and Ali Nasi [39], and research on the role of energy storage in hybrid microgrid systems. Different mathematical programs and optimization methods are used for designing and planning energy management strategies, as shown in Figure 4.

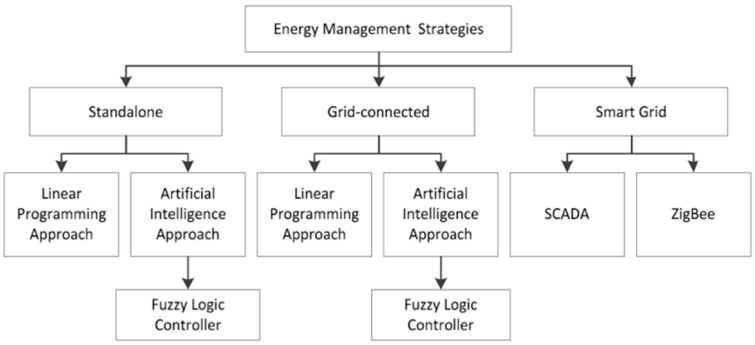


Figure 4. Commonly used approaches for energy management strategies.

This article thoroughly evaluates the approaches that various authors adopt in their studies on energy management systems. Renewable energies are key resources for power production to meet large-scale electrical energy demands by accessing HRESs. The techniques mostly applied by the researchers in this field are standalone hybrid renewable energy systems and grid-connected hybrid renewable systems, as shown in Figure 4. This research study summarizes the various methodologies applied for energy management in renewable hybrid systems. The study examines multiple standalone and grid-connected hybrid system setups to determine whether mapping an efficient energy management technique for one type of renewable energy system can be applied effectively to other configurations. Various reviewed studies that evaluate multiple strategies have explored the most effective energy management approaches. This paper extends the above work by zeroing in on important forms of energy management in hybrid renewable energy systems. We first analyze articles that discuss energy management strategies in standalone hybrid renewable energy systems, focusing on the specific plan for each setup. The discussion

then revolves around energy management strategies in smart grids, specifically those that incorporate renewable energy sources. The last portion shows research that uses fuzzy logic to devise control strategies that optimize energy flow in hybrid systems.

3.1. Energy Management Utilizing Intelligent Approaches for Standalone Applications

Recent studies analyzed the management of energy of hybrid systems using advanced techniques like genetic algorithms, differential evolution, neural networks, fuzzy logic, and neuro-fuzzy systems. The objective of these strategies is to optimize the efficiency of renewable resources like PV and wind energy to fulfill the required energy demand. Using sizing algorithms, researchers minimize the costs associated with a system, since unmet demand and fuel consumption depend on the uncertain characteristics of the renewable energy source. The most feasible solution for a hybrid power system is to consider the design parameters of system components and the features of an EMS. This involves finding out the monthly percentages of the charge and discharge of storage units, restricting the start-up and shutting down of generators, and determining the state of charge (SOC) of energy storage. The effectiveness and efficiency of the presented method for a hybrid power system were demonstrated through a comparative analysis with established methods. The system primarily consists of PV as well as wind power sources and also an EMS, which control the distribution of energy between sources, load, and energy storage devices for stable and secure operation. Two control loops are implemented: a fast loop for energy conversion and a longer loop for energy management. The hybrid system for the introduced EMS integrates power sources from wind, solar, and bioethanol reformers controlled through the useful energy. The EMS achieved efficiency in the system by taking into account load demand, battery state of charge, and environmental variables, stabilizing and balancing energy within limits. Wind energy was designated as the priority for electricity generation, and solar power was utilized to supplement it. A lot of research was conducted to develop energy management strategies for standalone hybrid systems employing multiple energy sources through the application of theoretical analyses and experimental investigations. Bursir Khan et al. introduced a framework of distributed energy management systems that utilizes several agents to control microgrid systems with diversified energy resources and loads. Simulation results in MATLAB/Simulink SimPowerSystems (vR2023b) showed the system's high performance. Bruni et al. proposed a power management strategy using neural networks to forecast and manage a hybrid energy system at the laboratory scale. Through analyzing the above three energy management strategies, Upadhyay and Sharma [40] evaluated the most efficient capacity of a hybrid energy system comprising renewable sources, a diesel engine, and a battery bank [40]. The optimization techniques used for determining the size of the system were particle swarm optimization, genetic algorithms, and biogeography-based optimization. The cycle charging method proved to be the most effective. Neural networks (NNs) are often used to control and regulate hybrid systems, resulting in systems with computational intelligence similar to human intelligence in different domains. These systems can quickly adapt to changing environments and learn to make informed decisions. NN systems are created to mimic human thought processes, such as the processing of information, voice perception, forecasting, classification, and regulation. An NN incorporating solar wind, diesel, and battery was integrated by Palma Behnk et al. [41] in an energy manager of a microgrid. The method was to allot the generating units each an online set point and a shortage consumer signal via demand-side management for minimizing and satisfying the electric load demand. The implementation and testing of precise data demonstrated the cost-effectiveness and power equilibrium of the established management systems. Azmy and Erlich [42] proposed an artificial neural network methodology to enhance the efficacy

of proton exchange membrane fuel cells in residences. Hatti and Tioursi proposed a method that utilizes quasi-Newton-based neural networks, which efficiently adjust settings without the need for a new optimization after every modification of operation conditions. Their research article documents the implementation and testing of this new control algorithm and system, which validates both the cost-efficiency and power balance of the existing control systems. Basir Khan et al. [43] suggested a distributed energy management approach using multiple agents instead of using a centralized controller. This system enables precise management of single energy sources and loads within a microgrid. The proposed model employs non-cooperative game theory to facilitate multi-agent cooperation in energy systems. Simulation results showed great performance under various conditions, as proven via the MATLAB/Simulink SimPowerSystems environment. Brka et al. [44] proposed a predictive power management strategy for a laboratory energy system on a small scale. The system consisted of a simulated renewable source, a battery, and a fuel cell. Neural networks are often used for the control and management of hybrid systems due to their computational intelligence and human-like capabilities. Because of their capability to learn information on their own from examples and provide accurate and timely responses to new input, their popularity in engineering applications has significantly increased. Neural networks are already being used in industry for management and control of hybrid systems due to their computational intelligence and knowledge of particular fields, just like that of a human being. The inherent capability of neural networks to learn information by themselves from examples and respond with exactness and promptly to inputs has led to their use in all branches of engineering. These systems aim to maximize operation and meet the demand of electric load. Azmy and Erlich [45] suggested that an artificial neural network technique could be applied to enhance the performance of proton exchange membrane fuel cells suitable for use in HOMER. The findings revealed that the suggested algorithm efficiently allows for the rapid and straightforward adjustment of FC parameters, resulting in a reduction in all costs of the system and approximation of ideal values. Lin et al. [46] present a technique that uses a quasi-Newton-algorithm-based NN to control a PEMFC energy system. The proposed approach results in a dynamic neural network control model capable of effectively managing, stabilizing, and identifying tracking errors thereby proving model efficacy.

3.1.1. Energy Management Based on Linear Programming—Standalone Applications

Optimizing energy management is essential in autonomous hybrid power systems to achieve optimal performance and guarantee a dependable energy supply. This section explores many strategies and approaches to regulate energy in systems, such as PV panels, wind turbines, fuel cells, and other energy storage technologies. Ahmad and Shameem et al. [47] investigated three power management techniques for a self-contained hybrid power system comprising PV panels, wind turbines, and a proton exchange membrane fuel cell. The study's objective was to improve the efficiency of the fuel cell membrane and provide a steady energy flow in the hybrid system. The third strategy, which utilized excess electricity to power the electrolyzer and replenish the battery, had the most favorable results, with an efficiency of around 85% [47,48]. Ipsakis et al. [49] evaluated the efficacy of two power management strategies that employed hysteresis bands in a hybrid wind, PV, and hydrogen storage system. The evaluation spanned four months and focused on the impact of modifying the hysteresis band gap on the system's overall performance. Kanouni and Badreddine et al. [50] proposed a power management control method for a self-sufficient PV/battery system. The technique aims to achieve maximum efficiency and dynamic performance by coordinating unidirectional and bidirectional DC-DC converters while considering the battery's state of charge and meteorological conditions [50,51]. Ismail

et al. [52] conducted a techno-economic assessment of a hybrid system configuration, including PV panels, a battery system, and a microturbine for a small isolated village in Palestine. Their energy management system integrated co-generation, which involved utilizing the microturbine's heat for direct heating applications, decreasing the power production cost [53,54]. Rekioua et al. [55] developed a very effective power management algorithm for an autonomous hybrid system that integrates PV panels, wind turbines, a diesel generator, and battery storage. Research on a wind/diesel/battery hybrid system that supplies power to rural households and schools in a distant region of North Cameroon was conducted by M. Pendieu Kwaye [56]. HOMER has been extensively employed in many global research endeavors to optimize hybrid systems and analyze hybrid systems of PV panels, batteries, and fuel cells [57,58]. TRNSYS software (v18.04) has been used to assess the system's performance and find the most efficient size. Dash and Bajpai [59] utilized a similar approach to study a photovoltaic/fuel cell/battery system, using an energy management strategy for an autonomous hybrid system that integrates renewable energy sources with storage [60]. Their simulations and calculations demonstrated the reliable and consistent supply of electricity for the hybrid system. This section presents a range of energy management strategies for independent hybrid power systems. The critical studies analyzed solutions that involved PV systems, wind power, fuel cells, and battery storage. The main focus was on maximizing the efficiency and dependability of these systems. Various approaches, such as hysteresis bands and co-generation, have substantially enhanced system performance. The extensive utilization of HOMER for system optimization highlights its significance in hybrid energy management. In summary, the solutions studied underline the need for efficient energy management to improve the performance of freestanding hybrid power systems.

3.1.2. Energy Management Based on Intelligent Techniques—Standalone Applications

In recent times, numerous research studies have examined the utilization of intelligent techniques for managing energy in hybrid systems. Several strategies include genetic algorithms (GAs), differential evolution (DE), neural networks, fuzzy logic, and neuro-fuzzy systems [61,62]. This subsection presents a summary of various research studies, with a more detailed analysis of the use of fuzzy logic in energy management systems, which will be provided later. Abedi et al. [63] introduced a novel method to determine the most influential power management methodology for hybrid power systems comprising multiple energy sources and storage devices. The dispatch strategy aims to optimize the utilization of renewable energy sources, such as PV and wind power, to meet electricity demand [6]. It also prioritizes other sources based on a power management optimization process. The excess energy produced by renewable sources is harnessed to charge energy storage devices, such as electrolyzers and batteries, using a system of collective charging [64]. Power management optimization is integrated with sizing algorithms to minimize overall costs, unfulfilled loads, and fuel consumption, considering the unpredictable nature of renewable energy sources. A differential evolution approach using fuzzy logic was employed to address the nonlinear multi-objective optimization problem of a hybrid system [65]. The optimal solution included the design parameters of system components and EMS parameters, including the allocation of monthly charges among storage devices, the distribution of monthly discharges among hybrid generators, the constraints on generator start-up and shutdown, and the state of charge of energy storage [66,67]. The numerical data for the recommended monthly tilt angle of PV panels and the optimal tower height of wind turbines were compared with the optimal sizing values acquired using pre-defined EMSs without employing the developed EMS optimization method [68]. The results demonstrated the efficacy and capability of the proposed technique for the hybrid

power system. Shayeghi, H. et al. [69] developed a theoretical energy management method that forecasts and controls energy use in a wind/diesel/battery hybrid power system based on anticipated future load and resource conditions. This advanced EMS establishes a benchmark for assessing fundamental, practical, non-predictive dispatch methods. The tactics encompass cost-effective discharge, load following, SOC set-points, and complete power/minimum runtime strategies [70]. A comprehensive assessment of the total cost of ownership for fuel and batteries determined that the proposed EMS is more economically advantageous than other available methods. This analysis highlights the significant potential of intelligent solutions in optimizing energy management for standalone hybrid power systems, ensuring efficient, economical, and reliable energy delivery.

3.1.3. Energy Management by Fuzzy Logic Controllers in Standalone Hybrid Energy Systems

This subsection presents a review of the literature on the fuzzy logic-based energy management of standalone hybrid energy systems. One goal is to develop and implement a fuzzy controlled strategy to design and build an EMS for DC microgrid systems [71,72]. One researcher performed simulation and control of energy resources and storage with MATLAB/Simulink tools for a hybrid energy resource study. LabVIEW was used to develop an EMS with monitoring. The fuzzy logic controller is designed to maximize longevity by optimizing the SOC and improving the overall performance of the system while reducing costs [73]. The controller uses two input variables, ΔSOC, which is the battery state of charge, and ΔP, which is the difference between the power demand and the power generated by the microgrid. The output variable is the delta (Δ) of the charging and discharging current of the battery (ΔI) [74]. The functions utilize five membership variables (NB, NS, ZO, PS, and PB) (negative big, negative small, zero, positive small, and positive big). If ΔP is negative, it indicates that the microgrid produces adequately sufficient power for the load demand. Here, the battery is moved to the charging mode if ΔSOC is negative [75,76]. On the other hand, if ΔP is positive, the battery operates in the discharge mode. The implementation of the proposed model in MATLAB/Simulink consisted of a PV system of a power rating of 5 kW, wind turbine of a power rating of 1.5 kW, lithium-ion battery of power rating 1.5 kW, and load of 6.5 kW [77]. The simulation results proved that the proposed system works correctly. It utilizes a fuzzy controller to ensure that the battery SOC does not exceed capable level irrespective of power supplied by the microgrid system [78]. The frequency of the main inverter is varied to attain control. If the microgrid system lacks energy and the battery has a low SOC, the inverter frequency will drop below 50 Hz. On the other hand, if the supply is abundant and the battery is highly charged, the frequency will rise above 50 Hz when the battery's SOC is almost full. Consequently, energy will stop being supplied to avoid overcharging [79,80]. Researchers emphasized that a proposed FLEMS (Flexible Energy Management System) would utilize more of the microgrid's available energy capacity than a conventional on/off EMS. The performance of every component in the operation of the hybrid system was demonstrated [81]. Further using optimization techniques, the size was reduced significantly and hence the complete hybrid system earned back the cost in a very short time. A complementary study focused on increasing the heat output and energy distribution of a combined heat and power (CHP) system. The EMS forms the basis to increase the capacity of CHP and boiler efficiently [82]. The system uses a fuzzy logic controller to manage the uncertainties surrounding electrical and heat demand as well as uncertainties connected to fossil fuel price and COE. Therefore, the EMS helps to optimally choose system components in such a way as to minimize the net present value of the whole hybrid system. Dursun et al. [83] studied an EMS of a standalone hybrid power system comprising wind, PV, fuel cell (FC), and battery elements. The EMS operates on the principles of fuzzy logic The main power sources consist of the

PV and wind energy systems while the FC plays the role of a secondary power source if the primary sources are not available. The battery unit is used to store excess energy generated and feed transient loads. The main purpose of the fuzzy logic-based EMS utilized in this work is to effectively manage the allocation of power throughout the entire system while simultaneously maintaining the stability of the state of charge (SOC) of the battery. The fuzzy logic controller's input is taken as the difference between load demand, power generation by renewable sources (PV, W wind), and the state of charge of the battery. The EMS determines how much power is needed to extract from the backup source FC for support to overcome the increased power requirement from the renewable energy sources. When the SOC falls below the desired level, the FC provides additional power to replenish the battery. In contrast, when the SOC reaches or exceeds the intended level, the energy management strategy effectively controls the battery dynamics in respect to existing renewable electricity supply for load demand. Justification of the superiority of fuzzy logic-based EMSs in study over already-published works has been provided by Maghfiroh et al. [84]. The benefits of these schemes include a fast response time and operating without dependence on systems' mathematical models, as well as convenient adaptability to the changing situation during operation, etc. [85]. Berrazouane and Mohammedi [86] devised a cuckoo search algorithm employing a fuzzy logic controller to manage a standalone hybrid power system. The system consists of PV panels, a diesel generator, and batteries. The battery SOC and net power flow are fed to the fuzzy logic controller [87]. The fuzzy logic controller has three outputs as a result of its processing: the power rating of the PV system, the rated power of the diesel generator, and the battery capacity The outcomes showed that the proposed method outperformed particle swarm optimization based on the fitness performance of the other algorithm. Hosseinzadeh et al. [88] developed a supervised control system for managing and operating autonomous AC/DC microgrids. The controller has the major duties of maximizing the use of renewable energy sources, keeping an appropriate level of charge, and controlling the power of the DC and AC microgrids. The supervisory controller was formalized using the state machine approach. The proposed controller's efficiency was explicitly demonstrated by the results from numerical simulations.

3.2. Energy Management Systems in Grid-Connected Hybrid Renewable Energy Systems

This section provides a comprehensive assessment of several articles that have examined grid-connected hybrid renewable energy systems. Each study strongly advocated for an energy management strategy that enables the regulation of energy flow between different energy generation and storage technologies across the grid [89]. The subsequent section provides a review of studies that have examined the combination of renewable energy sources with a smart grid. Additionally, a separate section reviews publications that propose the use of a fuzzy system for energy control. Several of the studies employed linear programming to execute energy management, while others utilized intelligent methodologies for the same objective. The subsequent sections encompass the research that employed these two methodologies to execute energy management for grid-connected applications. The research that utilized fuzzy logic systems for energy management is reviewed separately, as much of it employed these effective techniques for this goal, as noted earlier.

3.2.1. Energy Management Based on Linear Programming—Grid-Connected Applications

Grid-connected applications and linear programming for energy management have become potential approaches to optimizing resource consumption and improving system efficiency. A demand-side management model was created and pioneered, specifically designed for the Brazilian context [90]. This inventive strategy was integrated with current metering systems, utilizing a prepaid model with advanced control features to shape user

behavior. This model aimed to achieve a fairer distribution of electricity usage among consumers by aligning consumption patterns with the monthly availability of renewable energy [91,92]. It also aimed to address energy scarcity and excessive reliance on diesel generators when renewable energy potential is limited. Several studies employed grid-connected applications and linear programming for energy management. Rani and her colleagues [93] suggested a method to smoothly incorporate PV systems into the power grid to consistently and uninterruptedly supply DC loads with electricity. Their suggested energy flow management method aimed to maximize the use of surplus energy by injecting it into the grid at a high-quality level [94]. This technique achieved adequate energy supply and demand balancing by monitoring battery voltage and adjusting operational modes accordingly. Mojumder et al. [95] proposed a pragmatic model to evaluate the impact of vehicle-to-grid systems on enhancing the energy management of small electric power networks. Their thorough assessment prioritized enhancing power generation efficiency across different units and synchronizing input/output power dynamics to reduce operational expenses [96]. Mayoral et al. [97] proposed a hybrid system that combines PV panels, batteries, super-capacitors, and fuel cells, all coupled with the primary grid. Equipped with an advanced controller, this system ensures continuous power supply, maintains steady functioning of various energy sources, and efficiently exports excess energy to the grid [97,98]. The system proved its ability to satisfy load demands efficiently and seamlessly integrate excess electricity into the grid network through thorough simulations. Finn et al. [99] investigated the capacity of price-based demand response systems to motivate industrial users to synchronize their electricity consumption with wind-generated power on the grid. This method sought to maximize the use of wind energy resources and reduce stress on the power grid during high demand by taking advantage of low-price periods and introduced a complex energy management approach designed explicitly for microgrids that consist of PV systems, wind turbines, and battery storage, all connected to the primary power grid [100,101]. By utilizing predictions of renewable energy production and up-to-date information on the flow of electricity, this method guarantees the most efficient energy distribution while successfully adjusting for any variations in the availability and consumption of power. Comodi et al. [102] proposed a new method for determining the appropriate size of PV plants in the grid. Their solution includes the use of micro-gas turbines to improve reliability and efficiency. Their solutions, which were created to minimize the uncertainty of power provided by photovoltaic systems and decrease the use of primary fuel, emphasized the need for proactive energy management to maximize the system's efficiency. Saadat et al. [103] examined the economic and environmental viability of combining hydrogen systems with pre-existing hydroelectric and wind power plants. Their pioneering energy management method utilized hydrogen as an energy transporter, enabling smooth energy storage and conversion to electricity during moments of high demand [104]. Byun et al. [105] thoroughly assessed hybrid systems that include renewable sources, diesel generators, and the current grid infrastructure. Their strategy emphasized using renewable energy sources and battery storage to meet temporary power needs, highlighting the potential for obtaining the best economic and environmental results [105,106]. Furthermore, various other research studies, such as the ones conducted, have employed advanced optimization techniques to optimize the performance and sustainability of grid-connected hybrid systems.

3.2.2. Energy Management Based on Intelligent Techniques—Grid-Connected Applications

Energy management in grid-connected applications entails incorporating intelligent methodologies to maximize the utilization of renewable energy sources and improve the dependability and effectiveness of power systems [107]. Recent progress has been made

in developing advanced control and optimization techniques to tackle the ever-changing nature of energy supply and demand. This section examines two prominent methodologies that utilize intelligent techniques to optimize energy management in grid-connected systems and reviews the existing research. Gao et al. [108] suggested a dual-layer coordinated control strategy that combines forecasts and real-time data to accomplish efficient and dependable energy operations. This approach was assessed in independent and grid-connected situations, emphasizing its versatility and efficiency in various operational circumstances. A study was conducted by Bahmani-Firouzi and Azizipanah-Abarghooee [109] in which they proposed an enhanced bat algorithm specifically designed to optimize the capacity of battery storage systems in microgrids. This evolutionary technique has the potential to significantly improve the sustainability of microgrid operations by prioritizing cost efficiency and battery system longevity. These methods emphasize the importance of using intelligent strategies to manage energy systems. This is especially important for optimizing the benefits of renewable energy sources and enhancing the overall performance and reliability of grid-connected applications.

3.2.3. Energy Management by Fuzzy Logic Controllers in Standalone Hybrid Energy Systems

Efficient energy management is essential in standalone hybrid energy systems to ensure system stability and optimize operating costs. Intelligent control systems, such as fuzzy logic controllers, are increasingly used to deal with the intricacies of controlling numerous energy sources [71,110]. This section examines a fuzzy logic-based method that seeks to enhance the efficiency of distribution networks by prioritizing cost and stability. Their algorithm regulates the allocation of power from different energy sources to fulfill load requirements, prioritizing renewable sources. This technique involves designing batteries to discharge only when the anticipated load for the next interval is not substantial [111]. This guarantees that batteries are allocated for significant loads, improving system stability and reducing voltage drops. A fuzzy system calculates the required battery energy when renewable sources are insufficient, particularly during off-peak periods [112]. The system utilizes two fuzzy input variables and one fuzzy output variable. The inputs consist of two variables: the time remaining until the next peak and the battery's current charge level, measured as the ratio of available energy to the energy required at the next peak [113,114]. The result is the percentage of the load that the batteries need to fulfill. The first input consists of fuzzy subsets categorized as small, medium, and large. The second input contains small, medium, and large subsets. The output variable consists of six subsets: tiny, small, big, medium, large, massive, and very large [115]. The first input covers six hours, whereas the second covers a range three times as extensive. The output range is 100%; combining these inputs results in twelve distinct fuzzy rules [116]. There is a significant time interval until the next peak, and the battery's charge level is also high; the battery will be able to satisfy a large percentage of the output load. In contrast, when the battery's charge level is shallow, the output will be negligible, regardless of the time until the next peak [117]. The regulations are specified in a table that is cited as a reference. Simulations showcased the effectiveness of this method, emphasizing its capability to enhance the efficiency and dependability of independent hybrid energy systems [63,118].

3.3. Energy Management Strategies in Smart Grids Including Renewable Energy Sources

In past years, there have been significant changes in the way energy is generated, transmitted, and used. For most nations, achieving a reliable and secure source of energy outside fossil fuels is an important goal. To meet this objective, smart grids with renewable energy sources are essential. Smart meters, intelligent sensors, and real-time data exchange of bidirectional energy between energy providers and consumers is needed

for smart grids [91,119]. This design helps to control the efficient distribution of energy, giving consumers the power to choose wisely. Although smart grids have several benefits, they could be more manageable, in particular regarding renewable energy [120]. Excess energy generated during some times at the expense of overcrowding distribution networks causes concern along with the intermittence of renewable energy generation at other times (Phuangpornpitak and Tia) [121]. The researchers Alsayegh et al. [122] also found that extensive penetration of renewables can cause grid stability issues such as voltage surges, reliability and stability issues, voltage swings, and harmonics. These problems can be mitigated by using a supervisory control system to oversee, manage, and direct energy flow among these sources. An effective energy management plan is crucial for leveraging renewable energy in smart grids [123]. A plan is effective if all sources within the innovative grid system are provided with the necessary technology (directly or through power electronics interfaces) for interconnection [124]. The proposed scheme must encompass real-time control and automatic regulation. The objective is to enhance power distribution and spur local consumption of various energy sources [125]. Another goal is to lower customer energy costs and enhance reliability. The plan for managing energy will allow for system expansion to enable the incorporation of additional sources or the higher capacity of existing sources [126]. Smart meters facilitate real-time and cumulative metering of electricity use. They can be set up to operate with any feed-in tariff or pricing plan. Monitoring and supervision systems that regulate electricity flow are another key part of the smart grid. Some examples of such systems are SCADA and ZigBee devices [126,127]. The SCADA system uses a combination of software and hardware for data collection and control communication. It operates as a central controller to manage processes and energy in power grids. The system gathers technical data; if equipment fails, an alarm signal is triggered. It analyzes data and executes required operations to control energy. SCADA systems incorporate essential components such as human–machine interfaces, input/output devices, controllers, networking equipment, and software [128]. Dumitru and Gligor [129] proposed and implemented an energy management system integrated with SCADA for monitoring renewable energy usage by consumers connected to public networks. They demonstrated the effective use of renewable resources through careful management. Batista and colleagues [130] studied ZigBee devices to determine their effectiveness for wireless monitoring and control in smart grids. The findings revealed that these devices can function for long periods without servicing. Aly et al. [131] developed an energy system using renewables that worked with an intelligent house. They used a two-way communication protocol and a GSM modem for effective flow of energy. Their technology effectively managed peak energy consumption periods, generating significant savings on energy bills and thereby proving the strength of renewables in intelligent energy systems [132].

4. Control and Management of Hybrid Renewable Energy Systems

Energy management solutions are important for optimizing hybrid energy systems' HES performance and efficiency. Leveraging these techniques can effectively control and optimize the flow of energy from different sources to storage and load in real time to harness its potential [2,133]. To manage the energy in hybrid energy systems effectively, many control techniques have been proposed, such as rule-based control, model predictive control, and artificial intelligence-based control [134]. The utilization of real-time information, along with weather predictions and demand estimates, is harnessed by these algorithms to optimize energy dispatch, minimize losses, and prolong the lifespan of system components [135]. Effective power dispatching in a multisource energy system necessitates the implementation of an overall controlling technique. The main objectives are to follow load

variations and maintain the state of charge of battery banks so that power interruption is avoided and battery life is increased [136]. To achieve these goals, the controller must find the suitable online operating modes for every generation subsystem and switch from power control to maximum power conversion. A comprehensive supervisor control was developed for a hybrid system of wind and PV generation subsystems, a battery bank, and AC load, as outlined in Reference [137]. The control objectives of the wind and solar subsystems was achieved using robust sliding-mode control principles. In another study, the authors presented a comprehensive control approach for a hybrid renewable energy system [138]. A controller for pitch angle regulates the wind generation system and the PV unit is controlled by a maximum-power point tracking (MPPT) controller. Everything was modeled dynamically. Excess electricity from wind and PV is sent to an electrolyzer for hydrogen production and storage [139,140]. When there is a power shortage, the fuel cell stack uses the stored hydrogen to give power for the electrical demand. An energy management and control subsystem of a grid-connected wind/solar hybrid power system has been realized in hardware. The overall system comprises various components, including a programmable logic controller (FBs-40MAT from FATEK), AC multifunction electric power meters, a grid-connection control module, a human–machine interface (HMI), DC electric power meters, and an RS485/TCP converter for controlling and managing multi-source operation [141]. For proper operation of hybrid renewable energy systems, effective communication is essential. Modbus RTU is utilized inside and between subsystems, while computer communication is enabled by RS485/TCP converters [142]. Table 3 is a synopsis of the control and management of hybrid renewable energy systems.

Table 3. Summary of system control and hybrid renewable energy systems.

Control Paradigm	Energy Sources Considered	Outcome	Ref.
Load following (LF) and Maximum-Efficiency Point Tracking (MEPT)	PV, wind, FC	Four energy control strategies are proposed and analyzed for the standalone Renewable/Fuel Cell Hybrid Power Source (RES/FC HPS). The concept of load following (LF) and Maximum-Efficiency Point Tracking (MEPT) are used to control the fueling rates.	[137]
Rule-based hierarchical control strategy	PV, FC, electrolyzer, battery bank, SC	An advanced energy management strategy for a standalone hybrid energy system is proposed. The control strategy is designed to ensure the optimal energy management of the hybrid system. This strategy aims to satisfy the load demands throughout the different operation conditions and to reduce the stress on the hybrid system.	[47]
Master–slave concept with droop control	PV, wind, battery	The control strategy based on a communication link increases the control complexity and affects the expandability of the HRES. The master–slave control with the droop concept does not require a communication link and provides good load sharing. In addition, the master–slave concept adds features, such as the flexibility, expandability, and modularity of the HRES.	[91]

Table 3. *Cont.*

Control Paradigm	Energy Sources Considered	Outcome	Ref.
Threshold-based energy diversion strategy	PV, battery, FC	The energy management strategy is based on diverting any excess PV energy into the electrolyzer when the battery is charged to 99.5%. This protects the battery from overcharging. In this developed strategy, there is no need for a dump load as the generated energy is matched with the load demand.	[48]
Priority-based sequential control	PV, FC, UC	The purpose of the energy management strategy is to satisfy the load requirement continuously. The priority is to utilize the PV energy and any excess energy is used to generate hydrogen. The excess energy is directed to the ultra-capacitor when the hydrogen storage system is full. The solar system will be shut down if the capacitor is fully charged.	[78]
Forecast-based optimization strategy	PV, battery, FC	The strategy is based on weather forecasts and the objective of the control strategy is to optimize the use of renewable sources to ensure their use while improving the comfort conditions of the house.	[46]
Multi-agent distributed control	PV, wind, micro-hydropower, diesel, battery	A distributed energy management system architecture based on multi-agents is proposed. The purpose is to provide control for each of the energy sources and loads in the microgrid system.	[43]
Forecast-based predictive control with real-time updates	PV, wind, battery, FC	Forecasting of both the renewable sources and loads is carried out prior to implementing the proposed strategy. The power management system is continuously updated by updating both the decision time interval and any time lags resulting from hardware sensors.	[44]
Comparative strategy analysis: cycle charging, peak shaving, load following	PV, wind, diesel, battery	Three energy management strategies were checked: the cycle charging strategy, peak shaving strategy, and load following strategy. The cycle charging strategy was found to be the most effective in comparison with the other strategies.	[40]

A comparative analysis of the surveyed control paradigms shows clear trade-offs between simplicity, adaptability, and scalability. Rule-based and threshold-based methods are straightforward to implement, yet they lack flexibility under rapidly changing operating conditions. Forecast-based and predictive control strategies provide higher efficiency and stability by integrating weather and demand forecasts, but they depend on accurate data and significant computational capacity. Distributed multi-agent control offers robustness, modularity, and resilience for microgrids, but at the cost of higher coordination complexity and communication overhead. Overall, no single strategy can be considered universally optimal; instead, hybrid approaches that combine predictive accuracy with decentralized robustness are most promising for achieving reliable and cost-effective control of HESs in real-world applications. Implementing complete control and management systems in HRESs improves energy efficiency, dependability, and economic feasibility. Through the integration of sophisticated control methodologies and resilient energy management

systems, these systems can adjust to fluctuating situations, enhance energy allocation, and facilitate sustainable energy objectives.

5. Challenges and Recent Advancements

Hybrid renewable energy systems combine more than one method of energy generation or storage to give more reliable, renewable energy. Even if they have a lot of abilities, many challenges hinder their effective use and efficiency. We need advanced technology solutions to solve these challenges. Combining HRESs with current power grids is not possible and poses significant challenges. To effectively manage the flow of energy and information in both directions, standardized communication and control protocols need to be developed. HRES coordination with the grid is a key requirement to achieve stability and dependability in the grid.

- The intermittency of solar and wind energy requires an efficient energy storage system (ESS). But such a system cannot be overused. Most of the time, single ESS technologies cannot achieve a balance between energy density, power density, lifetime, and cost. Hybrid energy storage systems (HESSs) are considered a good solution for this problem due to the weight of benefits. Challenges exist in the optimization of HESS configuration and ensuring the compatibility of diverse storage technologies.
- HRES deployment is costly because of high initial capital, including the cost of renewable energy generators, storage systems, and all other required supportive systems. The high initial costs of HRESs are a significant barrier to adoption.
- System Sizing and Optimization: Determining the optimal size and configuration of HRES components is complex, involving trade-offs between cost, performance, and reliability. Efficiencies and added costs can arise from either oversizing or undersizing. To solve these challenges, advanced optimization algorithms are being developed, which use AI and ML techniques.
- For the proper functioning of HRESs, effective control strategies need to be established for proper operation and energy management. Recent advancements include the integration of AI for predictive, real-time, and fast decision-making. The systems need complex controls and strong energy management systems.
- The safety and reliability of HRESs, especially with the integration of different energy storage technologies, is a key issue. We need to manage degrading batteries, prevent failures, and ensure consistently functioning under harsh conditions with hybrid renewable energy.
- The creation, operation, and disposal of HRES components must not harm the environment and must be sustainable. The materials developed should be recyclable and the process of manufacturing should have a low environmental footprint. And system disposal should be performed responsibly during the HRES life cycle.

Several advances have been developed in response to these recent issues.

- AI techniques are used in these systems to enhance decision-making for smart energy management and predicting system behavior.
- Scientists are investigating new materials and technologies to develop new energy storage, such as solid-state batteries that make these systems more efficient, safe, and longer-lasting.
- Efforts are underway to develop standard protocols related to system integration, communication, and control for reducing interoperability issues and for facilitating the deployment of HRESs.

- Nations' governments are launching policies and supplying incentives that reduce the financial hurdles of taking up HRESs to promote clean energy transition and strengthen the resilience of nations' energy grids.

To solve issues with HRESs, there should be a strategy that includes technology enhancement, planning, and legislation support. Continuous R&D should enable HRESs to unlock their full potential and pave the way for a sustainable future. This review emphasizes numerous significant insights. Initially, optimization-based design methodologies such as mathematical programming, evolutionary algorithms, and AI-driven techniques yield considerable enhancements in cost-efficiency and dependability; nevertheless, they are heavily reliant on data accessibility and processing resources. Secondly, EMS methodologies, including rule-based control, model predictive control, and intelligent procedures, provide complementary benefits but are not universally applicable to all system configurations. Third, hybrid storage technologies that integrate batteries and supercapacitors provide promising potential but necessitate further empirical validation. Potential applications encompass rural electrification, smart grids, and transportation systems, wherein HESs might enhance resilience and sustainability. Nonetheless, existing constraints—such as elevated capital expenditures, the sporadic nature of renewable resources, interoperability issues, and the absence of established protocols—require resolution. Future research should prioritize AI-driven predictive emergency management systems, interdisciplinary optimization strategies, and regulatory frameworks that mitigate financial and technical obstacles.

6. Discussion

The present status of research on renewable energy systems and energy management systems indicates substantial advancement toward sustainable energy solutions. Key characteristics encompass the interdisciplinary character of contemporary endeavors, varied application contexts, and the implementation of sophisticated optimization methodologies [143,144]. These developments demonstrate significant potential for decreasing fuel use, alleviating greenhouse gas emissions, and minimizing environmental consequences. Nonetheless, some significant restrictions must be resolved for research findings to achieve greater effect and practical applicability. Recent research has primarily concentrated on renewable energy system-based microgrids, especially those including solar systems and battery storage. Venturing into creative sectors, such as DC microgrids, has provided improved efficiency and adaptability. Although numerous optimization strategies have been employed to enhance the cost and energy efficiency of these systems, many studies still depend on single-objective formulations. Multi-objective optimization, while gaining attention, encounters difficulties in reconciling opposing objectives such as cost minimization, CO_2 emission reduction, and storage optimization. Moreover, optimization is frequently confined to operational phases, neglecting broader considerations such as system life cycle and long-term scalability.

Comprehensive control systems for coordinating various renewable energy sources within microgrids are still inadequately developed. While numerous studies advocate for optimization-driven EMS solutions, they often neglect the practicalities of real-time implementation in dynamic contexts characterized by fluctuating demand and supply [145]. Precise load forecasting, including meteorological projections, market information, and real-time demand indicators, is crucial for enhancing system reliability. Nevertheless, forecasting models that integrate accuracy with flexibility across various operational settings continue to pose a problem [146].

Environmental sustainability is an additional aspect necessitating further focus. Although the operational advantages of renewable energy systems are extensively documented, the embodied emissions and life cycle effects of technologies like photovoltaic

panels, wind turbines, and batteries are frequently overlooked. Incorporating Life Cycle Assessment (LCA) into system evaluations would provide a more thorough assessment of sustainability.

Subsequent research must also tackle concerns like scalability and empirical validation. Solutions must be flexible to varying grid conditions and regulatory frameworks. Comparative analyses across locations with differing policy frameworks may yield significant insights into optimal practices and obstacles to the extensive implementation of HESs. Moreover, nascent technologies like artificial intelligence and blockchain have prospects for enhancing resilience, decision-making, and decentralized energy management; nevertheless, their integration necessitates further investigation. Enhanced engagement with industry is essential to corroborate theoretical models with long-term operational data. The economic feasibility could be enhanced by integrating cost–benefit analysis and payback evaluations, which can inform decision-making for governments and investors. Ultimately, sociological and behavioral factors—such as user acceptance and community involvement—must be taken into account to guarantee the successful deployment and expansion of HES solutions. Although the progress in RE systems and EMSs is praiseworthy, overcoming the limitations identified in this section will be essential for realizing sustainable energy transitions. Future research can facilitate the development of robust, efficient, and ecologically sustainable hybrid energy systems by concentrating on integrated control strategies, precise forecasting, life cycle sustainability, scalability, and practical implementation.

7. Conclusions and Recommendations

The growing trend of global energy demand for sustainable energy generation in various locations, such as remote and off-grid regions, has mobilized HRESs. Global implementation of HRESs is underway to improve energy mixes in off-grid sites. They fulfill energy needs and provide sustainable energy in inaccessible areas. There will be an optimum system of HRESs based on a balance between maximum technical performance and maximum economic feasibility. The efficiency of the development of a system must be consistent with demand and must produce the system with minimal overall cost of power production. Here are some recommendations to further enhance HRES effectiveness.

I. Design Protocols
   - Autonomous rural systems: Prioritize multi-objective evolutionary algorithms (e.g., PSO, GA) integrated with HOMER simulations, which have proven to be cost-effective and reliable in isolated communities.
   - Grid-integrated microgrids: Highlight the combination of AI-driven predictive energy management systems with hybrid storage solutions (batteries and supercapacitors) to address intermittency and alleviate grid stress.
   - Developing versus developed regions: In developing countries, low-cost rule-based or fuzzy controllers are practical due to constrained computer resources, but established grids can leverage advanced model predictive and AI-driven control.

II. Implications for Policy and Regulation
   - Governments ought to implement region-specific feed-in tariffs, tax incentives, and subsidies that correspond to local resource availability (e.g., solar prevalence in MENA versus wind in Northern Europe).
   - The standardization of communication protocols and grid integration norms is crucial for facilitating interoperability among renewable sources, storage systems, and national grids.

- Policies ought to promote public–private collaborations to mitigate substantial initial capital expenditures via collaborative finance frameworks.

III. Insights on Practical Deployment

- Life Cycle Assessment (LCA) should be integrated into project design to evaluate environmental and social implications, in addition to economic viability.
- Pilot projects should be utilized as standards for expansion, particularly in rural electrification and smart grid integration.
- Capacity-building activities, including local training programs for technicians and operators, must follow deployment to guarantee long-term sustainability.

Through the integration of sophisticated optimization techniques, locally tailored EMSs, and supportive legislation, HRESs can evolve from theoretical study to extensive practical use. This comprehensive strategy provides a means to achieve sustainable, resilient, and equitable energy systems.

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