

Review

Scrutiny of Hybrid Renewable Energy Systems for Control, Power Management, Optimization and Sizing: Challenges and Future Possibilities

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Abstract: To fulfill fast-growing energy needs, all energy sources should be utilized. Renewable energy is infinite and clean. However, its main disadvantage is that renewable energy sources are intermittent. A Hybrid Renewable Energy System (HRES) is built by integrating several distinct energy sources to deal with this problem. In regards to energy economy, economics, dependability, and flexibility, these hybrid systems can surpass the limits of individual energy producing technologies. The power capacity of HRESs increased from 700 GW to 3100 GW globally over the period 2000–2021. This study aimed to offer and analyze a comprehensive literature review of recently published works by several researchers in the area of HRESs. The HRES contains different Hybrid Energy Systems (HESs), which are categorized into three parts, namely, PV_Other, Wind_Other and PV_Wind_Other. These systems, based on different optimization techniques/software with techno-economic objective functions and constraints, are reviewed in this paper. The optimal sizing, control, and power management strategies of the HRES are elaborately discussed to harness its potential. It has been determined that Metaheuristic (MH) methods and HOMER software are mostly employed in the fields of HRES sizing, control, power management, and optimization. The review provides a critical analysis of the shortcomings of the existing HRES systems, while choosing optimization parameters, and control and power management schemes. Moreover, the study encapsulates the various challenges/barriers in adopting HRESs. Finally, this review highlights possible future opportunities for PV, Wind, and other HESs in the area of control, power management, optimization, and optimal sizing.

Keywords: control strategies; energy management; hybrid energy system; optimal sizing methods; optimization methods



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1. Introduction

It is well known that fossil fuels, like coal, oils, and natural gases, are the major sources of energy globally. Excessive reliance on fossil fuels in the 20th century severely harmed the natural supply [1,2]. Globally, rising environmental issues and electrical requirements have necessitated the development of alternative sources of energy. Scientists and engineers are constantly working on expanding and using alternate energy sources, which requires researching their finite supply and negative environmental impacts. Solar, biomass, wind, tidal, wave, magneto-hydrodynamic generators, and small hydro technology are some of the alternative energy sources that are now accessible. Among the Renewable Energy Sources (RESs), wind and solar energy appear to be the most encouraging, due to their being limitless, plentiful, and ecological, and having an unrestricted supply in nature. Technological advances in renewable energy systems, enabling them to satisfy the energy needs of remote or off-grid places, where environmental problems are a concern, has resulted in these systems being widely accepted [3]. Photo-Voltaic (PV), wind, and hydropower systems, or a mix of these systems, are examples of important renewable-based energy systems. Along with a renewable-based energy system, backup equipment, such as Diesel Generators (DGs) and Battery Banks might be included to satisfy peak-hour demand. This

Renewable Energy Power System (REPS) is the backbone of modern power systems, but their deployment has both benefits and drawbacks. The benefits of REPS include the utilization of free resources, such as solar and wind, for fuel, minimal cost of operation, minimal maintenance, and no waste of natural resources. Furthermore, these systems do not produce environmental pollution, thereby preserving biodiversity. The disadvantages of REPS include the fact that renewable energy generation is based on natural cycles, and the capital cost of such units is greater than comparably sized nonrenewable generating units. More importantly, renewable systems are unable to meet peak demands well enough without power storage [4,5].

Many researchers have suggested efficient methods and effectively constructed stand-alone PV systems. Stand-alone PV systems are sometimes built with backup and storage. A stand-alone PV system is an appealing way to deliver energy to rural areas, off-grid sites, isolated places, street lights, tourist attraction places, offices of remote communication, and commercial buildings, because of its ease of operation and maintenance. However, the energy conversion efficiency of PV generation is poor, and the price of energy per kilowatt-hour is higher than that of wind power [6]. As a result, the wind energy system has gained considerable importance. Recently, a system based on wind–diesel hybrid power was proposed to satisfy the load requirements of a commercial structure. Generic concepts of a system based on wind–diesel hybrid power systems were reported on so as to gain an understanding of its pros and cons. A highly developed renewable energy system may be cost-efficient, dependable, and enhance standard of living [7].

Renewable resources such as solar energy and wind energy are intermittent and unpredictably variable, due to sudden variations in solar radiation and wind velocity. Furthermore, these sources of energy are unable to adjust to increased demand, rendering the reliability of these systems difficult to maintain. They also necessitate a significant capital commitment, as compared to traditional sources [8]. HRESs, which typically incorporate RESs as the primary sources, with BAs and/or DGs as backup, have been used to conquer the varying nature of renewables. HRESs can ensure power accessibility when one of the generation sources encounters intermittency. These solutions may help to reduce expenses, optimize the size of system components, lower operation costs, and assure access to inexpensive and dependable, as well as sustainable, energy sources [9,10]. The global generation capacity of the HRES is shown in Figure 1 for the years 2000–2021. The development of new mechanisms to study the importance of the HRES is necessary [11,12].

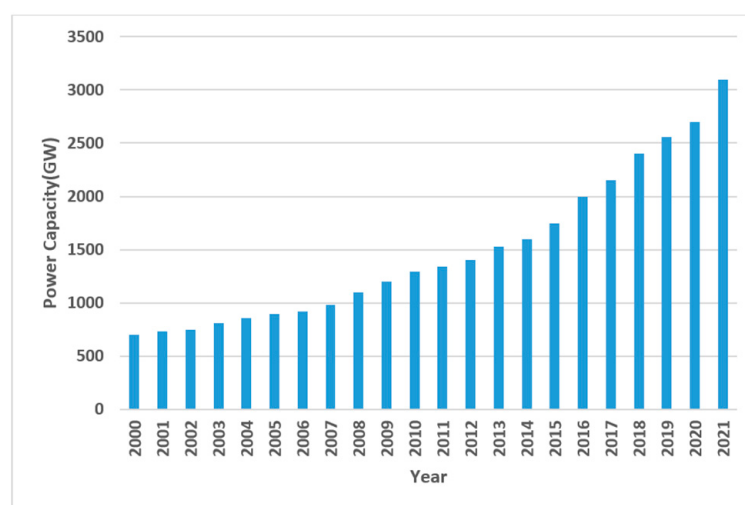


Figure 1. HRES Power Capacity for the years 2000–2021.

The fundamental benefit of HRESs is that the number of generation units may be increased in response to demand, ensuring continuous operation. If there is more generation

than demand, the excess energy can be fed into the grid, resulting in income generation. When electricity generation involves several sources, its stability, dependability, and efficiency are greater. The operating costs of thermal, as well as atomic, power plants are substantial. Most renewable energy-based power generation has low operating costs and is abundant in nature [13]. Furthermore, HES benefits include the following: showcasing electrical system integration approaches, increasing the dependability of RE utilization, offering feasible rural electrification options, encouraging the advancement of modern power electronics interface technology for collecting energy, and resolving RE intermittency [14].

An electric power system classified as a HES comprises HRES and several non-renewable sources of energy, as shown in Figure 2. The scheme can be utilized in the grid, off-grid, or independently, and the sources can be conventional, ecological, or combined [15]. In [5], the first description of a hybrid system based on renewable energy, and quoted as “Typical hybrid systems combine two or more energy technologies”, was proposed. The deployment of such a system was seen as a way to transform the world into “A Renewable World”. The Micro-grid (MG) is an interconnected power system that incorporates sources of energy, consumers, and storage facilities, and is the perfect example of HRES. The necessity for distributed energy resources, incorporating HRESs, like PV with wind generators and battery (BA) storage systems, makes MGs essential in practical applications [16]. MGs can also isolate themselves from the distribution network in the event of upstream disruptions or voltage variations [17,18]. Therefore, hybrid energy sources are becoming more critical, appealing, and cost-efficient choices for electricity in distant or off-grid regions. Gupta, et al. [19] and Patil et al. [20] studied several cases of integrated HRESs in delivering energy to remote regions of Uttarakhand, India. Bhandari et al. installed a novel HES model, combining solar, wind, and hydro power, in rural Nepal. Likewise, several researchers presented various HRES studies in remote locations of the world. The features of an off-grid HRES, with the consequences for the system’s dependability, were investigated by Ahn et al. [21]. Elhadidy and Shaahid advocated for several hybrid renewable energy solutions in energy-saving areas. These hybrid systems were shown to offer consumers reliable and low-cost power, particularly in rural, or off-grid, areas.

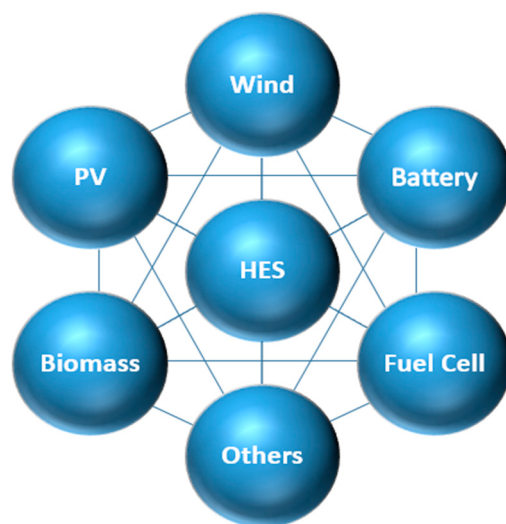


Figure 2. Hybrid Energy Power Supply (HEPS).

A study of several Energy Storage Systems (ESSs) and their abilities to improve dependability with the added stability of wind energy conversion systems was provided in [22]. A survey of current tools and methodologies for determining potential and usable energy in the most significant renewable areas was conducted. Usually, surveys aim to address issues of every renewable resource and tool that aid in analyzing the utilization of a mixture of various sources [23]. Configurations, criterion selection, sizing techniques,

control, and energy management are among the key aspects to consider when developing a HES before its deployment [24,25]. A comprehensive review of these methodologies ensures HRESs offer more reliable and promising techniques. Jose et al. discussed some of the design, modeling, and optimization procedures regarding HRES, created in recent years, in [26]. The performance and reliability of HRES rely heavily on the elements of the system, such as a Wind Turbine (WT), a PV system, a BA storage system, a DG, and a local control center. Thus, the precise modeling of each element gives tools for better understanding the system's performance and dependability. Judging from recent literature, the modeling of the elements is one of the most important tools for optimizing HRESs. Figure 3 shows the percentage of published papers pertaining to deployment of HRES in the recent past.

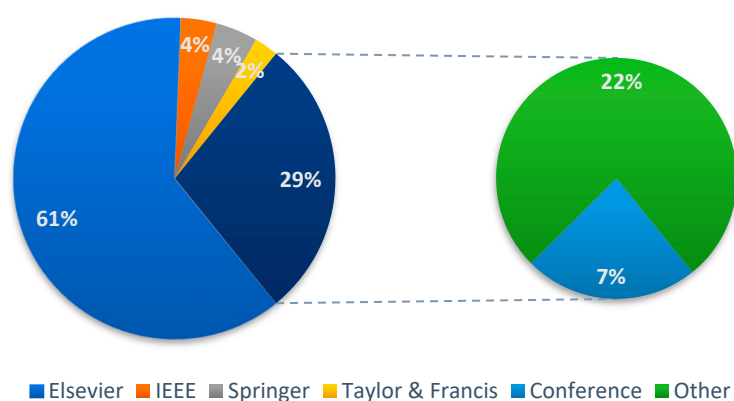


Figure 3. The number of papers, based on the publisher, in terms of percentage.

The main objective of this review was to provide a comprehensive evaluation of modern HRES research in the four key axes of size, optimization, control, and power management. This study also focused on the most recent optimization methodologies employed in HRES, with various combinations of sources, and their objectives and constraints. The main contributions of this review paper are as follows:

- To provide a detailed study of the various sizing methods and optimization approaches.
- To provide in-depth knowledge of the input and output data required for sizing software tools in HRES.
- To provide detailed scrutiny of the optimization techniques/software used in HRES, such as PV_Wind_Other, PV_Other, and Wind_Other, especially in the last two years.
- To present the various control strategies and power management approaches in HRES.
- To compare different control strategies and to discuss the characteristics of power management approaches.
- To present open issues, challenges, confidential analysis, and future prospects of HRES in hybridization with different sources.

The rest of the review paper is structured as follows. HRES sizing methods are described in Section 2. HRES optimization techniques are discussed in Section 3. The comparison of optimization techniques is summarized in Section 4. HRES control and power management approaches are presented in Section 5. Challenges, and future possibilities in HRES, are presented in Section 6. Finally, Section 7 summarizes the review's conclusions.

2. Sizing Methods

The hybrid system's size determines the generator's potential. If the sizing is not done appropriately, the system might be undersized or oversized. The most challenging task is to calculate the actual load and step time to correctly take variations into account. Many researchers use average hours, days, or months as sample data [27]. As shown in

Figure 4, there are two sorts of sizing methods: software and traditional methods. Software methods are known to be economical, easy, and less complex in implementation, compared to traditional methods. Let us first describe the software-based method.

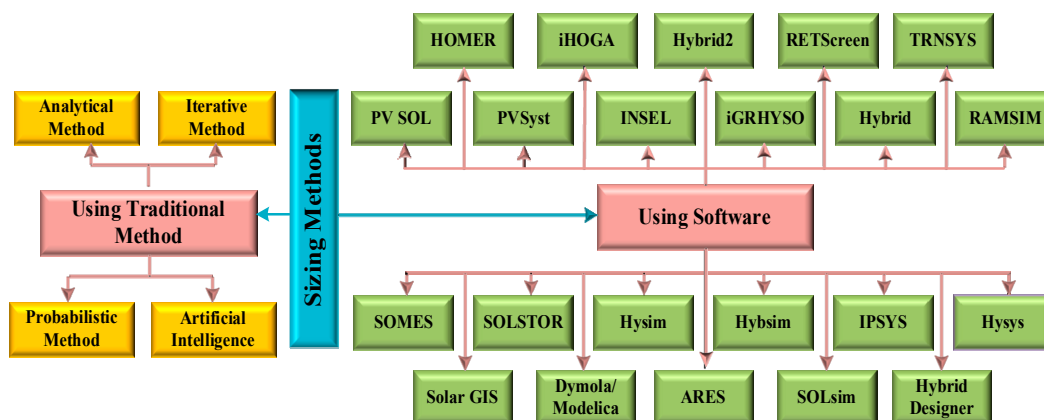


Figure 4. Hybrid system sizing techniques/methods.

Several commercial products to size hybrid systems are available. The majority of such software applications, like RET-Screen, Hybrid Optimization Model for Electric Renewable (HOMER), Integrated Simulation Environment Language (INSEL), Hybrid Optimization by Genetic Algorithm (i-HOGA) and other software, use Windows as a computing platform and Visual C++ as a programming language [28]. For sizing one of a hybrid system, that included a DG, WT, solar generator, and a storage system (BA), in Shiraz, Iran, Baneshi et al., utilized HOMER software. The primary aim of the Baneshi et al. work was to utilize a hybrid scheme that cost the least amount of money and emitted the least amount of carbon dioxide. In one of the examples of modeling, reported for HRES, the optimum economic outcome had a system-levelized cost of 9.3 to 12.6 cents per kWh, with 43.9 percent coming from worldwide output and renewable resources [29]. Rodolfo D Lopez and Jose L Bernal Agustin created iHOGA, a simulation and optimization software, which can build a Multi-Objective (MO) optimization system (Levelized Cost of Energy (LCOE), CO₂ emissions, and unmet load). It gives consumers the option of creating a customized hybrid system. Fadaeenejad et al. utilized the iHOGA program to design a hybrid system composed of two renewable generating units (PV generator, wind generator). Two standard generating units (DG unit, BA) for powering a rural hamlet in Kampung Oparin, Malaysia [30] were also reported by the researchers. Tables 1 and 2 [31] describe the output and input data of every sizing software application.

Mills et al. used this program to size a solar/wind/battery hybrid system in Chicago, USA. The simulation they developed demonstrated that there was enough renewable energy to meet the load profile with the Fuel Cell (FC) [32]. The Canadian Ministry of Natural Resources created RETScreen, a program for assessing and optimizing energy systems, in 1998. It simulates scenarios in various ways, including technological, economic, environmental analysis, power efficiency, and so on [33]. In Shanghai, China, Liqun et al. used the Canadian software to model their solar generator, DG unit, WT, and BA hybrid system. Since the HES was primarily dependent on sustainable energy (over 99 percent), the findings demonstrated a decrease in greenhouse gas (GHG) emissions [34]. The model analysis was implemented in the TRNSYS environment, which is said to be complete and flexible simulation environment for solar and other energy systems. TRNSYS software was created by the University of Wisconsin in Madison, USA, and is mainly used to simulate thermic systems [33].

Table 1. Sizing software for input data.

S. No.	Name of the Software	Input Data									
		Load Requirement	Details of Supplies	Details of Component	Constraints	System Control	Data of Emission	Economic Details	Financial Details	Product Database	Project Database
1.	HOMER	✓	✓	✓	✓	✓	✓	-	-	-	-
2.	iHOGA	-	✓	✓	✓	-	-	✓	-	-	-
3.	Hybrid2	✓	✓	✓	-	-	-	-	✓	-	-
4.	RETScreen	-	✓	-	-	-	-	-	-	✓	✓
5.	TRNSYS	-	✓	-	-	-	-	-	-	-	-
6.	PV SOL	-	✓	✓	✓	-	-	-	✓	-	-
7.	PVSyst	-	✓	-	✓	-	-	✓	-	-	✓
8.	INSEL	-	✓	-	-	-	-	-	-	-	-
9.	iGRHYSO	-	✓	-	-	-	-	✓	-	✓	-
10.	Hybrid	✓	-	-	-	-	✓	-	-	-	-
11.	RAPSIM	✓	✓	-	-	-	-	-	-	-	-
12.	SOMES	✓	✓	-	-	-	-	-	-	-	-
13.	SOLSTOR	-	-	✓	-	-	-	-	-	-	-
14.	Hysim	✓	-	-	-	-	-	-	-	-	-
15.	Hybsim	✓	✓	-	-	-	-	✓	-	-	-
16.	IPSYS	✓	-	-	-	-	-	-	-	-	-
17.	Hsys	✓	-	-	-	-	-	-	-	-	-
18.	Solar GIS	-	✓	✓	-	-	-	-	-	-	-
19.	Dymola/Modelica	✓	-	-	-	-	-	✓	✓	-	-
20.	ARES	✓	-	-	-	-	-	-	-	-	-
21.	SOLsim	-	✓	-	-	-	-	✓	-	-	-
22.	Hybrid Designer	-	✓	-	-	-	-	-	-	-	-

‘✓’ represents input data for sizing software.

Table 2. Sizing software for output data.

S. No.	Name of the Software	Output Data								
		Optimal Sizing	Evaluation of Technological Aspects	Environmental Review	Financial Assessment	Multi-Objective Optimization	Life Span Discharge	Probabilistic Evaluation	Sensitive Assay with Risk Evaluation	Electrical as Well as Thermal Power System Dynamical Modeling Behavior
1.	HOMER	✓	✓	✓	✓	-	-	-	-	-
2.	iHOGA	✓	-	-	✓	✓	✓	✓	-	-
3.	Hybrid2	✓	✓	✓	✓	-	-	-	-	-
4.	RETScreen	-	✓	✓	✓	-	-	-	✓	-
5.	TRNSYS	-	-	-	-	-	-	-	-	✓
6.	PV SOL	-	-	-	✓	-	-	-	-	-
7.	PVSyst	✓	-	-	✓	-	-	-	-	✓
8.	INSEL	-	-	✓	-	-	-	-	-	✓
9.	iGRHYSO	-	✓	-	-	-	-	-	-	✓
10.	Hybrid	-	✓	✓	-	-	-	-	-	-
11.	RAPSIM	-	✓	-	-	-	-	-	-	-
12.	SOMES	-	✓	-	✓	-	-	-	-	-
13.	SOLSTOR	-	-	-	✓	-	-	-	-	-
14.	Hysim	-	-	-	✓	-	-	-	-	-
15.	Hybsim	-	-	-	✓	-	-	-	-	-
16.	IPSYS	-	-	-	-	-	-	-	-	✓
17.	Hysys	✓	-	-	-	-	-	-	-	-
18.	Solar GIS	-	-	✓	✓	-	-	-	✓	-
19.	Dymola/Modelica	-	-	-	✓	-	-	-	-	-
20.	ARES	-	✓	-	-	-	-	-	-	-
21.	SOLsim	-	✓	-	-	-	-	-	-	-
22.	Hybrid Designer	-	✓	-	-	-	-	-	-	-

‘✓’ represents output data for sizing software.

Kamal Anoune et al., utilized this program to model and simulate PV and thermodynamic hybrid systems. The findings demonstrated that the hybrid system was technologically viable and cost effective for a solar PV system [35]. Scientists utilize two fundamental methods, like commercial software and traditional methods. Recent articles quote these as the sizing methods of HRES. Comparison of the software and traditional methods revealed that commercial software is simple to use, versatile in simulation, and quick in optimizing results. However, the software method requires rigorous mathematical analysis in implementation. Traditional approaches can better optimize the sizing field than commercial software. Traditional approaches produce faster results and address MO problems, but they are complicated and limited in flexibility. Traditional sizing procedures are divided into four categories, as given in Figure 4.

In one of the recent works the hybrid system is viewed as a mathematical model for better development and implementation and the hybrid system size is defined as a function of feasibility [23]. In 2015, Amos Madhlopa et al., presented a work in South Africa utilizing an analytical technique for a hybrid system with solar generators in addition to wind turbines as subsystems. The aim was to examine how to increase the hybrid system's water efficiency. Based on the findings, the hybrid central produced 1 GWh of power annually with a cost of 83.84 R/kWh. To obtain such power, the system usually required 75,000 m³ of water per year [24]. Priyanka et al., developed technological–socioeconomic criteria to find the best resource combination. The planning of the design was the reliability evaluation which was carried out utilizing an analytical approach. The suggested formulation was evaluated with various resources and mixture of configurations for an independent power system in Jaisalmer, Rajasthan, India.

This technique was a recursive algorithm program that ended when the optimal system design was achieved [20,25]. This approach was used by Camargo et al., to size a self-contained hybrid system, driven by solar PVs and wind energy, as well as FCs, for delivery to a remote hamlet in Brazil. The reported work aimed to develop a scheme that was both low cost and reliable. After modeling, they found that the best hybrid system design comprised a 500 W solar PV, three wind generators (each having 0.6 kW) plus 5 FCs (each having 1200 Wh). The overall price of this system was 25,672.01 R\$ (the Brazilian real is the country's standard currency) along with a levelized cost of 1.044 R\$ per kWh [26]. The influence of wind speed isolation, along with modifications in the system design, was considered in probabilistic techniques to size an integrated system in [20]. This is among the most often utilized size approaches. However, the results indicated that it might not be the most excellent option for finding the optimal solution [25]. Wen Hui Liu et al. employed the Probability-Power Pinch Analysis (P-PoPA) approach to size solar PVs, wind turbines, biomass, and batteries. The results revealed that the storage system's energy storage capacity, in correspondence with its power rating, increased, while outsourced energy reduced [27].

AI is a broad term that refers to the capacity of a machine or artifact to execute functions comparable to those found in human thought. Subho Upadhyay conducted a review on hybrid power system designs, control, and sizing approaches [20]. Researchers used different algorithms to find the best sizing for hybrid systems.

3. Hybrid Renewable Energy System Optimization Techniques

Algorithms for determining the maximum or minimum of mathematical functions are known as optimization algorithms. When it comes to optimizing a system's design, many objectives might be considered. Two examples of these objectives are improving the efficiency system and lowering the cost of manufacturing. Tuba Tezer et al. [36], E.L.V. Eriksson et al. [37], and Rajanna Siddaiah et al. [38] discussed the different optimization techniques used in HRES. Optimization approaches, and also strategies, can aid in the resolution of complicated issues. When developing an HRES, researchers must examine the performance of its components. The primary objective is to improve performance while lowering expenses. These objectives can be met by optimizing the system's model-

ing [39]. The most important optimization techniques used in HRESs are described in the next section.

3.1. Types of Optimization Techniques

Optimization in HRESs plays a pivotal role in optimizing the functionality of HRESs. Figure 5 shows the three major types of optimization methods, namely, classical, artificial, and hybrid. In addition, the various types and sub-divisions of these optimization techniques are discussed in the following subsections.

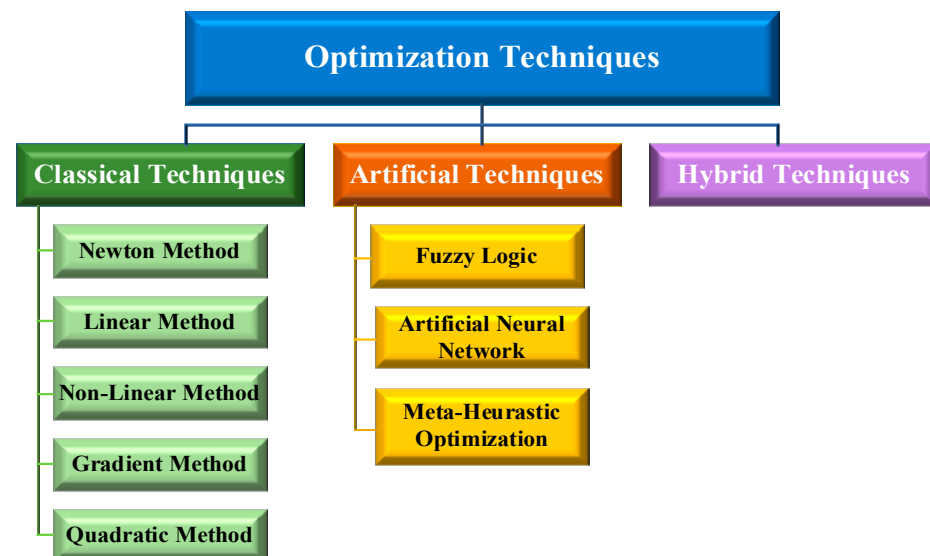


Figure 5. Hybrid system optimization methods.

3.1.1. Classical Techniques

The classical approach or technique is defined as a method of obtaining an optimum solution that uses differential calculation [38]. However, traditional approaches have limitations for applications with non-differentiable and/or continuous objective functions. For HRESs, a variety of conventional optimization approaches have been utilized. Classical techniques for optimizing HRESs include the Linear Programming Model (LPM), Dynamic Programming (DP), Non-Linear Programming (NLP), Newton Method, Gradient Method, and Quadratic Programming (QP), as shown in Figure 5.

LP resolves mathematical and engineering issues involving both continuous and discrete variables [40]. LPM examines scenarios where the design variable space is defined entirely by linear equalities and inequalities, and the objective function is linear. For HRES optimization, this LPM has been applied in various research works [41,42], making use of the LPM's probabilistic abilities to perform durability and economic analyses. Fabian Huneke et al. created a comprehensive model of a hybrid off-grid power system utilizing LPM to optimize the system, financially and sustainably [43]. Shebaz A Memon et al., discussed the application of ordinary LP to enhance hybrid ESSs, for better response times and long-term energy storage [44]. A Sequential LPM was used by M. Vaccari et al. to optimize the economic performance of an HRES. An optimization tool for a standard HRES was created in their research. The developed tools created an operating plan for every instrument over a given time horizon to satisfy all electric and thermal load demands, while potentially incurring the lowest operating expenses [45].

The NLP model investigates generalized circumstances where either the objective functions, the constraints, or both have nonlinear components. NLP is created when either the objective function or the restrictions are nonlinear. Similar to the distinction of handling nonlinear and linear equations, the NLP and LP differ from each other. The methodology used in most NLP methods begins with a primary guess and choosing the direction that

the objective function descends in the event that a minimization problem exists [46,47]. DP investigates situations where the optimization approach subdivides the main problem into smaller sub-problems [48]. With the stages connected to one another, the DP approach can be used to solve sequential or multistage issues. DP has the benefit of allowing for stage-by-stage optimization. It can, therefore, handle the difficulty of more complicated systems, being centered on the concept of optimality. Moreover a sub-policy of an optimal policy must also be an ideal sub-policy [49] in the implementation of DP. Zhi-Hong Zhao created an enhanced fuzzy logic control-based power management method and fuzzy logic control based on DP. The researchers implemented wavelet analysis for the hybrid FC/PV/BA/SC power system on tourist ships [50].

3.1.2. Artificial Techniques

As indicated in the sizing review, most artificial techniques are utilized for optimization. However, this section mainly focuses on methods that academics have recently applied for HRESs.

Fuzzy Logic

The mathematical theory of fuzzy sets is known as fuzzy logic. Suganthi et al., described fuzzy logic as a form of highly valued thinking that integrates with actuality. According to Michael and Warne, who wrote the Electrical Engineering Reference Book, fuzzy logic is a practical approach to defining humanity's experience on a microprocessor. In that book, they stated that it is a method of quickly representing human expert knowledge on a digital processor, where mathematical, or rule-based expert systems, have a problem. Derrouazin, et al., utilized fuzzy logic with multiple inputs and outputs to regulate the energy flux of a hybrid system containing solar PV, WT, and FC. The resulting findings demonstrated that the electronic switch signaled the tracking of the hybrid power systems input power states correctly and immediately. There are numerous fuzzy logic algorithms, such as Adaptive Neuro-Fuzzy Inference System (ANFIS), Fuzzy Analytic Network Process (FANP), Fuzzy Analytic Hierarchy Process (AHP), and fuzzy clustering, which are used to find the best size for a HES. Furthermore, to find the best size for HES, fuzzy GA, fuzzy PSO, fuzzy TOPSIS, fuzzy honey bee optimization, and Quantum behaved Particle Swarm Optimization [31] are also used for faster optimization.

Neelamsetti Kirn Kumar presented fuzzy logic-based load frequency control to perform Artificial Bee Colony (ABC) optimization in an island hybrid power system model. The study's findings demonstrated that the presented Intelligent Fuzzy Control strategy for modeling an independent energy system resulted in minimum variance in frequency and power [51]. A unique approach, dependent on fuzzy logic, was proposed by Sayyed Mostafa Mahmoudi et al. to assess backup and storage systems in evaluating the ideal size of an HRES [52]. Hai-Bo Yuan presented an optimized rule-based EMS, based on GA. The main purpose of the algorithm they developed was to distribute electricity among the FC and the BA systems as efficiently as possible. To maintain BA charge, while taking FC lifespan and performance into account, control variables in real-time rule-based EMS were appropriately adjusted. Hai-Bo Yuan's work also simulated and experimentally tested the optimized rule-based EMS, using a LabVIEW-based experimental rig along with MATLAB/Simulink. The traditional rule-based EMS, fuzzy logic EMS, and DP EMS were also compared. The comparison findings showed that the optimized rule-based EMS achieved a significant performance gain over the traditional rule-based and fuzzy logic EMSs [53].

Neural Network Algorithm

Although Michael and Warne compared the neural network algorithm to the organization of the human mind (brain), several scientists think that the resemblance is superficial when implemented in engineering applications. What is crucial, according to the authors, in engineering applications like HRESs is the training and convergence of ANNs to execute a specified action [31]. ANN in HRESs can be applied to optimize a vast majority

of parameters, like charging, BA, etc., in a variety of ways. Amirtharaj et al., suggested a combination of ANN plus the Adaptive Grasshopper Optimization Algorithm (AGOA), entitled the AGONN approach, to discover optimal use with decreased losses of switching in the system [54]. The findings demonstrated that the suggested approach outperformed the Grasshopper Optimization Algorithm (GOA), the Combined Modified Bat Search Algorithm–Artificial Neural Network (CMBSNN), and the Whale Optimization–Artificial Neural Network (WOANN), while optimizing the current, voltage, and power signals.

Meta-Heuristic Optimization

The study of optimization issues utilizing metaheuristic techniques is known as Meta-heuristic (MH) optimization. The MH optimization techniques are classified as Swarm-based Algorithms, Human-based Algorithms, Physics-based Algorithms, and Evolutionary-based Algorithms. Some MH optimization techniques used in HRESs for reducing LCOE are illustrated below. Researchers have used different types of MH optimization techniques to find the best sizing for hybrid systems, such as Genetic Algorithm (GA), Mine Blast Algorithm (MBA), Non-dominated Sorting Genetic Algorithm (NSGA-II), Particle Swarm Optimization (PSO), MO Self-adaptive Differential Evolution Algorithm (MOSaDE), and Multi-objective Line-Up Competition Algorithm (MLUCA). Additionally, Preference Inspired Co-Evolutionary Algorithm (PICEA), Biogeography Based on Optimization (BBO), Ant Colony Optimization (ACO), Cuckoo Search (CS), Tunicate Swarm Algorithm (TSA), Artificial Electric Field Algorithm (AEFA), Improved Grasshopper Optimization Algorithm (IGOA), Improved Coyote Optimization Algorithm (ICOA), Developed Manta-Ray Foraging Optimization (DMRFO) algorithm, Search Space Reduction (SSR) algorithm are used to find the sizing of the hybrid system.

In addition to the above-said algorithms some other optimization algorithms are also used for sizing HESs, which include Wild Horse Optimizer (WHO), Grey Wolf Optimization (GWO), MO-Artificial Cooperative Search Algorithm (MOACS), Mayfly Optimization Algorithm (MOA), Slime Mold Algorithm (SMA), Runge Kutta Algorithm (RKA), Rule-Based Algorithm (RBA), and Water Cycle Algorithm (WCA). Moreover, Discrete Harmony Search (DHS), Simulated Annealing (SA)–chaotic search, Artificial Neural Network (ANN), Equilibrium Optimizer (EO), Artificial Bee Swarm Optimization (ABSO) algorithm, Improved Fruit Fly Algorithm (IFFA), A-Strong, bacterial food algorithm, fuzzy logic and the others can be used to find the sizing of HRES.

3.1.3. Hybrid Techniques

Combining two or more optimization approaches can conquer the constraints of the specific optimization techniques listed above, resulting in the best performance and dependable HRES solutions. A hybrid technique is an approach that combines two or even more algorithms and provides the benefits of these techniques to compensate for the shortcomings of a single algorithm [37]. SA–Tabu Search (TS), Monte Carlo Simulation (MCS)–PSO, MODO (Multi-Objective Design Optimization)/GA, Artificial Neural Fuzzy Interface System (ANFIS), hybrid iterative/GA, ANN/GA/MCS, Hybrid Firefly–PSO (HF–PSO), Multi-Agent Butterfly–PSO (MA–BFPSO), Hybrid Firefly and Harmony Search optimization technique (HFA/HS), Hybrid Chaotic Maps-based Artificial Bee Colony (HCABC) are hybrid techniques utilized to optimize HRESs. Moreover, Hybrid Bacterial Foraging Optimization Algorithm–PSO (hBFOA–PSO), PSO/DE (Differential Evolution), and evolutionary algorithms have been used to optimize HRESs in several studies [55], for faster computation with less complexity.

Although hybrid approaches improve the optimization's overall performance, they have certain drawbacks in implementation in HRESs. For example, the partially optimistic outcomes of the hybrid MCS–PSO method, and sub-optimal solutions of the hybrid iterative/GA method in [56], and the cost-sizing compromise of the hybrid approaches in [57,58]. The difficulty in the design of the hybrid ANN/GA/MCS method in [59], random adjusting of the inertia weight of the evolutionary algorithm in [60], and complications in the coding

of the optimization Modulation and Coding Schemes (MCS) method are also examples of drawbacks.

4. Comparison of Optimization Techniques

Optimization techniques are distinguished by their high performance, capacity to handle complicated problems, and ability to employ many objective functions. However, the most prevalent disadvantage of all optimization techniques is that they take too long and are complicated. Traditional approaches are the most effective in economic optimization but have a finite number of optimization parameters. Due to the complex procedure and the codes that are employed, the artificial technique needs high hardware performance to function. The benefits of this method are its excellent efficiency, speed, and precision. A combination of classical and artificial techniques demonstrates a strategy that is characterized by great speed and resilience but also requires complicated design and complex code generation.

On the subject of optimization, a study of the literature reveals that researchers have concentrated on the three main types of optimization techniques. Classical techniques are characterized by speed and efficiency in techno-economic assessment, with the downside of constrained optimization space. Artificial techniques are the most commonly used methods in optimization due to their better efficiency, high precision, and rapid convergence. Nevertheless, the disadvantage of this approach is the requirement for sophisticated processing software. Hybrid methods utilize the benefits of each approach to optimize performance and decrease optimization processing time by combining the efficiency and speed of classical approaches with the accuracy and speed of artificial approaches. Despite all of these benefits, the most significant disadvantages of hybrid techniques are complexity of design and the problem of providing code. The critical points observed are the following: (1) When technically optimized (connected to a storage unit, DG, or BA) and commercially optimized (reduced investments or leveled cost), utilizing artificial techniques or commercial software, an HRES may efficiently cover energy demand in remote areas. (2) Most HRES optimization is accomplished using artificial methods or commercial software. Artificial methods include fuzzy logic, GA, and also artificial neural networks. The most often used commercial optimization software is HOMER PRO and RET Screen. The basic diagram for HRES with different input sources is shown in Figure 6. Community A, B, C, and community D are the different types of loads, such as residential load, Electric Vehicles, Industries, and BA storage, as shown in Figure 6. Though HRES communities are classified here as communities A, B, C, and D, the HRES sources cannot be separated from the community if there is to be a continuous supply of energy to inhabitants. The structure of HRES could be disassembled into a variety of configurations, such as PV_Wind_Other, PV_Other, and Wind_Other. Other sources include biomass, BA, FC, Wave, DGs, electrolyzers, pumped storage, etc. Furthermore, other configurations could be possible [61].

The overview of optimization techniques/software used in HES is given in the following subsections. Compared with other optimization techniques/software, the MH optimization technique is primarily used in HESs. The LCOE, NPC, COE and LPSP are the most commonly used objective functions for optimizing HESs. Along with these objective functions, other objectives, which are associated with MO optimization, are also taken into consideration by some authors, such as Annualized Capital Cost (ACC), Internal Rate of Return (IRR), Cost of System Lifespan (CSLS), Loss of Load Expectation (LOLE), Expected Energy Not Supplied (EENS) and so on. Objectives like Loss of Load Probability (LOLP), Annual Cost of Load Loss (ACLL), Forced Outage Rate (FOR), Return on Investment (ROI), Total Annualized Cost (TAC), and Total Life Cycle Cost (TLCC) are interesting to perform in HRESs for technological economic problems. Moreover, Renewable Fraction (RF), Human Development Index (HDI), and Job Creation (JC) MO objectives are factors determining which to employ in the proliferation of hybrid energy systems. MO objectives using objectives like Emission Curtailment (EMC), Operating Costs (OC), Net Present

Value (NPV), Annualized Cost of the System (ACS), Total Energy Transfer (TET), Integral Square Error (ISE), Capital recovery factor (CRF), Salvage Value (SV), Total Net Annual Cost (TNAC), Potential Energy Waste Probability (PEWP), Initial Capital Cost (ICC), Energy Generation (EG), Gross Present Cost (GPC), Annual Energy Production (AEP), and Energy Cost (EC) [62] are really aimed at ensuring the HRES achieves practical implementation in unforeseen circumstances.

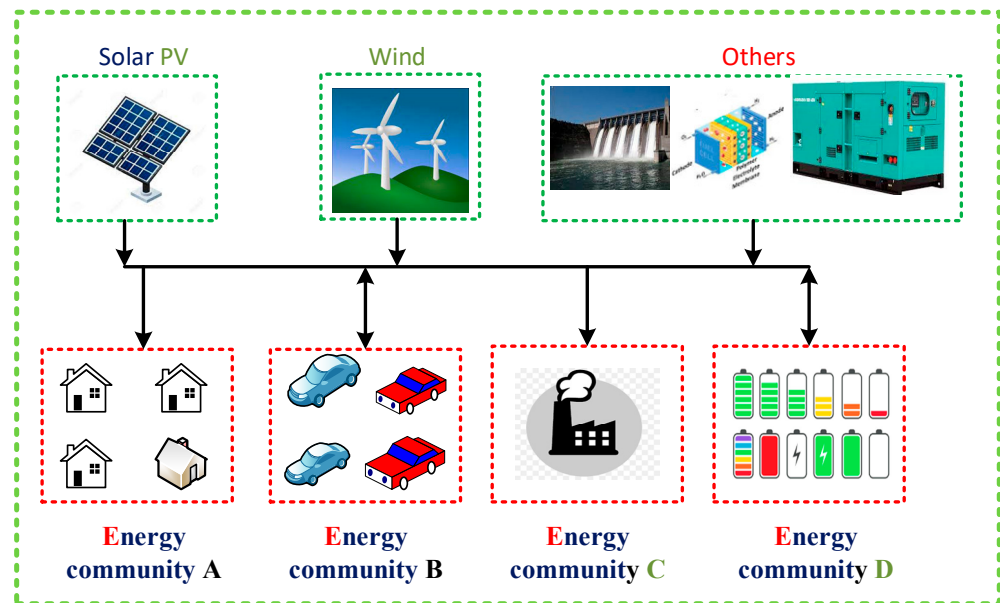


Figure 6. HRES with different sources.

These objectives are subject to constraints, such as the Number of PV (N_{PV}), Number of wind turbines (N_{WT}), Number of batteries (N_{BA}), Number of electrolyzers (N_{EL}), Number of fuel cells (N_{FC}), Area of PV (A_{PV}), Area of WT (A_{WT}), Energy Not Supplied Probability (ENSP), Loss of Energy Probability (LOEP), Interest Rate (IR), Self-Consumption Renewable Fraction (SCRF), LLSP (Loss of Load Supply Probability), Number of biomass gasifier (N_{BG}), and Number of diesel generator (N_{DG}).

4.1. PV_Wind_Others Energy Sources

A detailed overview of HRESs containing PV_Wind_Other sources and a detailed study of various optimization techniques and software applicable to HRESs are discussed in this subsection. From the literature, a detailed analysis of the multiple studies proposed in the last two years, 2021 and 2022, including objective functions, constraints, and references, is presented in Table 3. The MH and hybrid MH optimization techniques have been widely used in the last two years for economic and techno-economic objectives, such as ACC, IRR, LCOE, LPSP, COE, Net Present Cost (NPC), OC, LCA, and TAC. In addition, of the various software used for economic and techno-economic objectives of PV_Wind_Others, HOMER software has been the most commonly used software for the last two years. The pie chart given in Figure 7 shows the percentage of the most frequently used optimization techniques/software, such as MH optimization techniques (66%), Hybrid optimization techniques (11%), HOMER software (12%), and other software (11%) in HES (PV_Wind_Other) in the years 2021 and 2022.

Table 3. Detailed overview of various optimization techniques used in HRESs (PV_Wind_Others).

Ref.	HRES (PV + Wind + Other)	Optimization Technique/Software	Objective Function	Optimization Constraints
[63]	WT_PV_BA_Electrolyzers_FC	PSO, GA	ACC	$N_{PV}, N_{WT}, N_{BA}, N_{EL}, N_{FC}, LPSP$
[64]	PV_Wind_BA	AEFA	CSLS	$ENSP, N_{PV}, N_{WT}, N_{BA}, SOC$
[65]	PV_WT_BA	IGOA	TNPC	LOEP, IR
[66]	PV_WT_ESS	ICOA	COE	SOC, cost of power
[67]	Solar_Wind_FC	HOMERqx	LCOE, GHG emission	Project lifespan, actual yearly discount rate, inflation rate, liters of diesel fuel cost
[68]	PV_Wind_FC	TSA	LOLE, EENS, LOLP, ACLL, FOR	-
[69]	Solar Thermal_Wind_Wave_BESS System	HF-PSO	Pollutant Emission	Equations of balanced power, maximum actual power production, and reactive power of the generator
[70]	Oxy-fuel_PV_Wind_BA	MATLAB/Simulink, Aspen Plus	LCOE	Cut-in, rated, cut-out speed of wind, SOC
[71]	PV_Wind_BA	NSGA-II	LCOE, LPSP	-
[72]	PV_WTs_ BA	HOMER	COE, NPC, SV, IRR, ROI, Simple Payback, TAC, Emissions Reduction	-
[73]	PV/(WT)_DG_lead-acid BA-based Energy Storage	Hybrid two-stage PSO-DE	LCOE, RF, LPSP, HDI, JC, EMC	Instantaneous output power, Power generated by wind, Generator electrical output, Load demand, Power losses, Dump energy
[74]	PV_Wind_generators	HOMER	NPC, LCOE, IRR	-
[75]	Solar_Wind_Pumped storage	SSR	LCOE	SCRF, system power reserve
[76]	PV_WT_ BA storage_ split Stirling engines	NSGA-II	LCOE, LPSP, Dumped power	N_{PV}, N_{WT} , type of WTs, the capacity of the Stirling Engine (ST) + Organic Rankine Cycle (ORC) back-up, N_{BA} and type of BA
[77]	Solar PV_ WTs_ Lithium-ion (Li-ion) batteries_ DGs	Island System LCOEmin Algorithm (ISLA)	NPC	-
[78]	WT_ FC_ PV_Plug-in Hybrid Electric Vehicles (PHEVs)_Liquid Air Energy Storage (LAES) combined with high-temperature Thermal Energy Storage (HTES)	DMRFO	OC, Emissions	System power balance, Power generation constraints
[79]	Solar air collector_ solar chimney_thermoelectric generators_ Savonius WT	GA	Total electrical power	N_{PV}
[80]	Wind_PVs_ FC_ hybrid ESS including BA and supercapacitor	Fuzzy-based MPPT algorithm	Chattering observed in conventional Sliding Mode Control (SMC)	SOC

Table 3. Cont.

Ref.	HRES (PV + Wind + Other)	Optimization Technique/Software	Objective Function	Optimization Constraints
[81]	PV_BA_Wind_CSP	Electric System Cascade Extended Analysis Method	LPSP, LCC, LCOE	-
[82]	PV_Wind_BA	MPSO, GA	Total economic cost	SOC, LPSP
[83]	PV_Wind_FC_DE_BA_hydrogen storage system	MO- Quantum PSO	LPSP, the annual investment cost of equipment, lifetime of HES	N_{WT} , A_{PV} , N_{FC} , N_{BA} , stored energy of the energy storage unit
[84]	Wind_PV_Concentrated Solar Power (CSP) plant_electric heater_BA	NSGA-II	LPSP, LCOE	-
[85]	PV_WT_BA Storage	Roulette algorithm	Total operation and environmental costs	Power for the energy interface, ramp power for the energy interface
[86]	PV_Wind_Diesel_BA	PSO	Component sizes, COE	N_{PV} , N_{DG} , N_{WT} , N_{BA} , LPSP
[87]	PV_Wind_BA	MA-BFPSO	LCOE	SOC, Reliability Index LIR, Component Sizing, Power Balance and Power Flow through BSS
[88]	Wind_PV	GA, TOPSIS	NPC	-
[89]	PV_Wind_BA	NSGA-II	ACS, LPSP, TET	LPSP and cost with Net Zero Energy (NZE) balance
[90]	PV_Wind Generation _distributed Electric Vehicles (EVs)	WHO	ISE	Scaling factors, Proportional gain, integral gain, Integral order of FOPI controller, Tilt gain, Fractional order of tilt integral gain, Derivative gain
[91]	PV_Wind_BA	Solver, Minitab and Statistica	LCOE, diversified energy production density, N_{PV}	-
[92]	PV_Wind_DG	HOMER	LCOE, NPC, COE	-
[93]	PV_Wind_DG_BA_Grid	HOMER	NPC, LCOE	-
[94]	PV_Wind_DG	HOMER	NPC, LCOE	-
[95]	PV_Wind_Biomass	GWO, GA, SA	LCOE, TNPC	A_{PV} , A_{WT} , hourly power of BG, LPSP
[96]	PV_Wind_BA	HOMER	COE	Capacity shortage constraints, operating reserve constraints
[97]	PV_Wind_BA	PSO, GA	LCC	-
[98]	PV_Wind_BA	Adaptive-Local-Attractor-based Quantum-behaved PSO	LCOE, LCA, LPSP	Charging power and energy, Grid, minimum and maximum power and energy
[99]	PV_Wind	PSO	LCOE	Cable rating, A_{PV} , and rotor diameter
[100]	PV_Wind_Biomass_BA	MOACS	Annual LCC, LPSP	SOC, N_{WT} , N_{PV} , and N_{BG} , grid power during the stated period, dump power

Table 3. Cont.

Ref.	HRES (PV + Wind + Other)	Optimization Technique/Software	Objective Function	Optimization Constraints
[101]	PV_Wind_BA	HOMER	LCOE, CRF, NPC, IRR	-
[102]	PV_Wind_BA	NSGA-II	LCOE, LPSP, Equivalent CO ₂ (CO ₂ -eq) life cycle emission	Life Cycle Emission (LCE), the available energy in the BA, charging and discharging capacity of BA
[103]	PV_Wind_Diesel_BA	EO	LCOE, NPC	A _{PV} , A _{WT} , RF
[104]	PV_Wind_CSP_BA_	NSGA-II	LCOE, LPSP	Charging and discharging of BA.
[105]	PV_Wind_BA	GA and ABC	LCOE, LPSP	-
[106]	Solar_Wind_BA	HOMER	NPC, LCOE	SOC
[107]	PV_Wind_FC	HFA/HS	LCOE	Load demand, hydrogen energy storage capacity, LPSP
[108]	PV_Wind_Biomass_BA	Invasive Weed Optimization Backtracking Search Algorithm ((IWO/BSA))	LCOE	A _{PV} , A _{WT} , LPSP, Availability index, Autonomy daily of the BA
[109]	PV_Wind_EV	PSO, ABC	LCOE, LPSP	SOC, charging rate, LPSP, N _{PV} , N _{WT} , grid purchase, sale capacities
[110]	Hybrid Wind Bio BA_Solar PV System	-	COE, NPC	BA bank energy, speed of the wind, LPSP
[111]	PV_WTs_DGs, BESS_Li-ion, Absorbent Glass Mat (AGM) technologies	HOMER, NSGA-II	RF, Cost of potable water, CO ₂ emissions	-

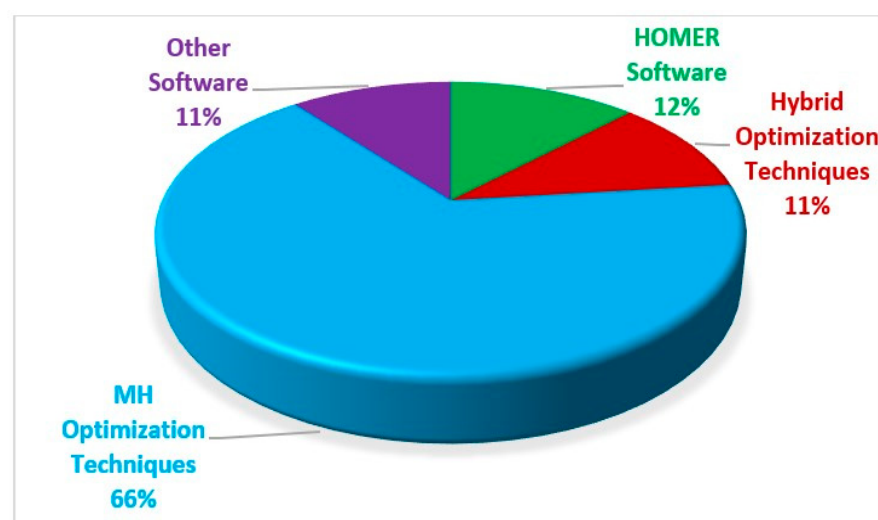


Figure 7. Pie chart for optimization techniques/software used in HES (PV_Wind_Other energy sources) in 2021 and 2022.

4.2. PV_Others Energy Sources

This subsection refers to an extensive analysis of various optimization techniques/software utilized in HRES and a comprehensive overview of HRESs containing PV_Other sources. Table 4 provides a complete evaluation of numerous research works proposed in the past two years, 2021 and 2022, that include objective functions, restrictions, and

references. The last two years have seen a significant increase in the usage of MH and hybrid MH optimization approaches for HES economic and techno-economic goals. Additionally, various software is utilized to achieve the economic and techno-economic goals of PV_Others. However, HOMER software has been the most widely used software for the past two years. Therefore, the percentage of most commonly used optimization techniques/software in HES (PV_Other) for the years 2021 and 2022 is shown in the pie chart given in Figure 8. It can be seen from Figure 7 that the overall occupancy of these software and optimization techniques, such as MH optimization techniques (64%), Hybrid techniques (3%), HOMER software (30%) and other software (3%).

Table 4. Detailed overview of various optimization techniques used in HRESs (PV_Others).

Ref.	HRES (PV+ Other)	Optimization Technique/Software	Objective Function(s)	Optimization Constraints
[112]	Solar PV_Biogas_BA	HOMER	LCOE	Maximum annual capacity shortage, operation reserve (surplus operating capacity)
[113]	PV_BA_hydrogen	NSGA-II	ACS, LPSP, PEWP	SOC, State of Health (SOH), Current hydrogen level, Charging or discharging power of the BESS, output power of FC, Input power of electrolyzer
[114]	PV_energy storage_diesel_reverse osmosis desalination	TS	TNAC, LPS, LPSP	Size of electric diesel power generator, N_{BA}
[115]	PV_Biomass_BA	HOMER	NPC, COE, OC, ICC, EG, RF	BA charging and discharging, energy balance
[116]	PV_BG_Electrolyzer units_Hydrogen Tank units (HT)_FC	MOA	EC, LPSP, Excess energy	Excess energy
[117]	PV_Biomass_Diesel_BA	HOMER	COE, NPC	Return of investment, IRR, payback period, and discounted payback
[118]	PV_FC_Biomass	Hybrid Chaotic PSO and SMA (HC_PSO_SMA), HOMER	Overall system cost	Cost of the solar PV panel, BG, converter, electrolyzer, hydrogen tank, and FC
[119]	PV_Biomass_Li-ion BA	HOMER	BA capacity, NPC, COE, CO_2 emitted	-
[120]	PV_BA Energy Storage _D-STATCOM	MOA	Real power loss	Bus voltage, branch current, active and reactive power balance, radial configuration
[121]	PV_Diesel_BA	PSO	TNAC	LLSP
[122]	PV_BG_BA system	RKA	COE, LPSP	N_{PV} , N_{BA} , N_{DG}
[123]	PV_FC_BA	RBA, DP	Optimal energy management, cost of the system, long-term operation capacity of the system	SOC, output power of FC, and BA energy
[124]	PV_Diesel_BA	HOMER	NPC, LCOE, CO_2 reduction, RF enhancement, increase reliability	PV capacity, DG Capacity, N_{BA} , inverter capacity, SOC

Table 4. Cont.

Ref.	HRES (PV+ Other)	Optimization Technique/Software	Objective Function(s)	Optimization Constraints
[125]	PV_FC	Dynamic Encoding Algorithm	Overall cost function	Power exchange between the solar cell and the FC
[126]	PV_Air-to-Water Heat Pumps (AW-HPs) Water-to-Water HPs (WW-HPs) buffer tank_Borehole Thermal Energy Storage (BTES)	GA	LCOE, and Heat Energy from District Heating, on-site energy production	A_{PV}
[127]	Grid_PV	MATLAB, GA	LCOE	PV modules, strings, component tilt angle, actual length of the southern side of the installation site
[128]	PV_BA_Hydro	PSO, GA	LCOE	-
[129]	PV_Syngas_BA	HOMER	COE, TNPC	-
[130]	PV generator_Pumped Storage System (PSS)_DG	FPA	COE	Power drawn by the electric pump and turbine generated output power
[131]	PV_FC_Boiler units_BA storage	Stochastic p-Robust Optimization (SPRO)	Total cost	Relative regret
[132]	PV_Biomass_BA	HOMER pro	Total NPC	-
[133]	PV_Hydro_FC_Li-ion	Political Optimizer (PO)	LCOE	Active and reactive power generated, Voltage magnitude
[134]	PV_BA_Grid	PSO	LCOE	SOC
[135]	PV_FC	Amended Water Strider Algorithm (AWSA)	LCOE, TAC	LPSP, N_{PV} , Electrolyzer efficiency
[136]	PV	HOMER Pro	LCOE	-
[137]	PV_Biogas	Whale optimization algorithm	LCOE	-

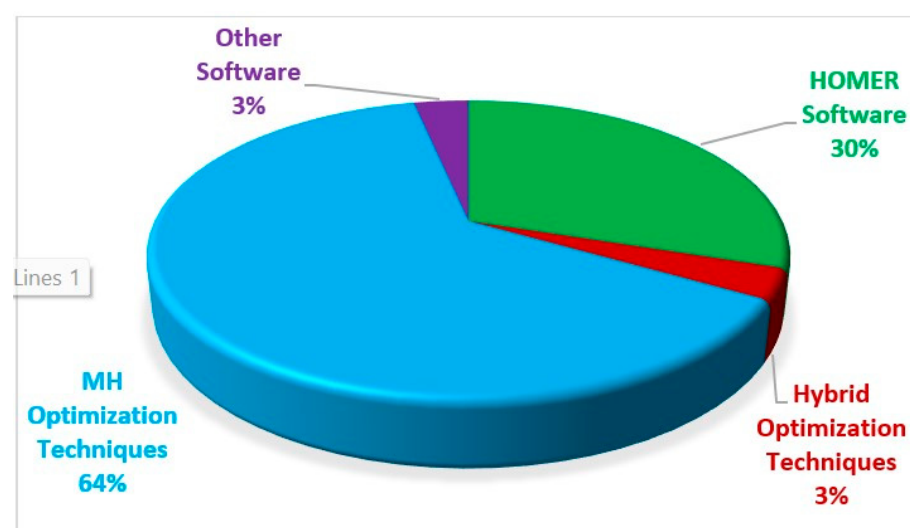


Figure 8. Pie chart for optimization techniques/software used in HES (PV_Other energy sources) in 2021 and 2022.

4.3. Wind_Others Energy Sources

This subsection covers a broad overview of HRESs pertaining to Wind_Other sources and a thorough analysis of the various optimization techniques and tools applicable to wind_other sources. Table 5 illustrates wind_other sources optimization from a review of the literature pertaining to many studies proposed in the previous two years (2021 and 2022). Factors including objective functions, restrictions, and references are incorporated in the table to emphasize its merits. In the past two years, MH and hybrid MH optimization approaches have been widely employed to achieve economic and techno-economic goals, including ACC, IRR, LCOE, LPSP, COE, NPC, OC, LCA, and TAC in the wind_other sources area. In addition, a variety of software is employed by Wind_Others to achieve economic and techno-economic goals. Still, HOMER software has been the most widely used software for the past two years. Figure 9 shows a breakdown of optimization methods and software in terms of percentage for HES (Wind_Other). The detail of optimization techniques/software in percentage for HES (Wind_Other) is presented in Figure 9 as MH optimization techniques (55%), Hybrid Techniques (10%), HOMER software (10%), and other software (25%) in 2021 and 2022.

Table 5. Detailed overview of various optimization techniques used in HRESs (Wind_Others).

Ref.	HRES (Wind_Other)	Optimization Technique/Software	Objective Function(s)	Optimization Constraints
[138]	Wind integrated Hydrothermal System (WHTS)	WCA	FC Emission (FCE)	Load balance, hydraulic continuity, generation limits, reservoir storage capacity, physical ramping capabilities
[139]	Wind_Diesel_BA	HOMER	NPC, COE, Salvage Cost (SC)	Power balance conditions
[140]	Wind_Ocean	AIMMS	LCOE, ACS	Water produced, power demand by RO unit, Swept area of WT
[141]	Wind_Hydro-thermal_power systems	PSO	Energy utilization, wind curtailment, coal costs, CO ₂ emissions	Power of the hydro unit, Total number of working hydro units, Number of hydro units used to replace thermal units
[142]	Wind_ESS_Automatic Generation Control (AGC)	PSO	Overall revenue of the system	Charge and discharge power of ESS, SOC
[143]	Wind_Wave Energy System	Orca3D Software	LCOE	-
[144]	WT_Thermal units	HCABC	Total Production Cost, Emissions	Generation capacity, system loss, Ramp rate limits, and spinning reserve constraints
[145]	Wind_Hydrogen	MCS	LCOE	-
[146]	Geothermal_Wind	EnergPLAN simulation program with EES and Matlab	LCOE, COE, energy and exergy efficiency	-
[147]	Wind	GA	LCOE, AEP	WT rated power, WT rotor diameter and WT hub height
[148]	Wind	Wind Farmer software	LCOE, N _{PV} , IRR	-
[149]	Wind	GA	LCOE	N _{WT} , WT cost, blade diameter, and capacity of the submarine cable
[150]	WT_BA	MPPT algorithms	Load power demand, SOC	-

Table 5. Cont.

Ref.	HRES (Wind_Other)	Optimization Technique/Software	Objective Function(s)	Optimization Constraints
[151]	Wind	MOPSO	LCOE	Radius of the rotor's conductor, current densities in the field and stator windings
[152]	Wind	-	LCOE	-
[153]	WTs_internal combustion engine_adiabatic compressed air ESS	Bi-level optimization strategy	Total cost	-
[154]	Wind_BA	Butterfly PSO	LCOE	-
[155]	Wind	HORIZON 2020 SHIPLYS	LCOE	-
[156]	Wind	Parallel updated PSO	LCOE	Local Buckling, Overall Stability, Load-Carrying Capacity, Geometry Constraint, and Maximum Top Displacement
[157]	Wind_DG_FC_BA_Electrolyzer	HOMER	GPC, LCOE	-

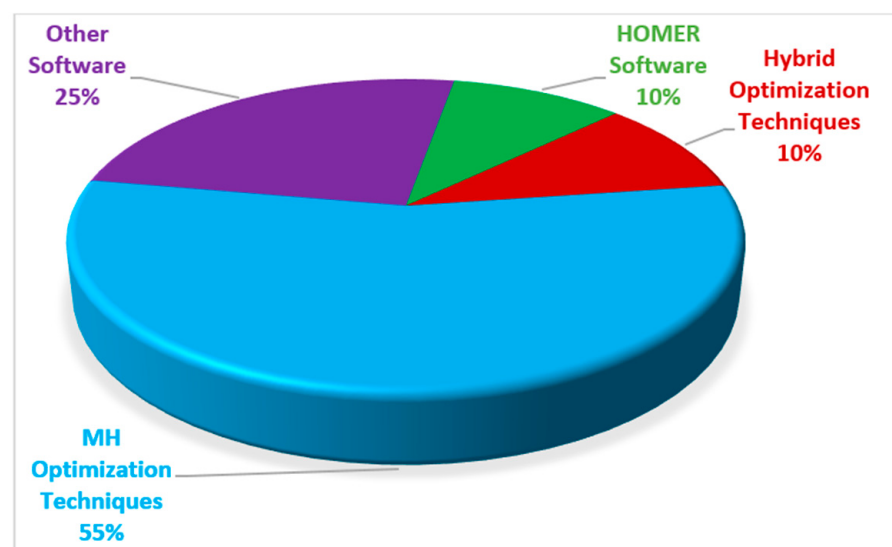


Figure 9. Pie chart for optimization techniques/software for HES (Wind_Other energy sources) in 2021 and 2022.

5. Control and Power Management Approaches in HRES

5.1. Control Mechanisms of HRES

The most challenging aspects of any HES based on renewable energy are effective management and coordination of control to ensure that consumers are not left without electricity. The intermittent nature of solar and wind resources causes electricity instability, irregularity, and quality problems. Various traditional and intelligent techniques have been used to coordinate, control, and conserve energy in hybrid systems [158]. In general, the parameters that should be managed in any hybrid system are system stability (the system's voltage and frequency), protection (power flow monitoring), and power balancing (allocating loads in the most efficient way possible). Secondary control of hybrid systems has been categorized by certain writers, such as Vivas et al., in [159], into three groups: centralized, distributed, and decentralized control. Furthermore, Chong L.W et al., classified control schemes into two categories: traditional control and adaptive control.

Moudud Ahmed et al., provided a critical assessment of power management, along with control research in AC, DC, hybrid AC, or DC MGs. The authors' critical assessment mainly focused on primary, secondary, and hierarchical control with control coordination among the Inter-Linking Converter (ILC) and the ESS [160].

There are many control schemes for WTs in the literature, such as employing MPPT (Maximum power point tracking) on the basis of the PSO [161]. Selecting voltage vectors upon the rotor converter side by Direct Power Control (DPC) [162], pitch control through the robust sliding mode method [163], and so on, are the crucial elements in the application of MPPT for WTs. Many control strategies for solar PV have been used to optimize the operation of solar panels, such as MPPT, based on the General Regression Neural Network (GRNN) [164], and a deep learning neural network for PV power forecasting [165], utilizing MPPT in partially shaded conditions [166], and so on. Voltage control [167], frequency control [168], and control of reactive power [169] have all been studied extensively in DGs.

Other techniques for regulating HRESs include centralized control [170], distributed control [171], hybrid control [172], and classical control methods (Figure 10), like proportional–integral control [173] and Rule-Based Control (RBC) [174]. Intelligent methods, such as MO-PSO [175], fuzzy logic controller [176], Adaptive Neuro-Fuzzy Inference System (ANFIS) [177], and neural network algorithm [178] are examples of classical approaches.

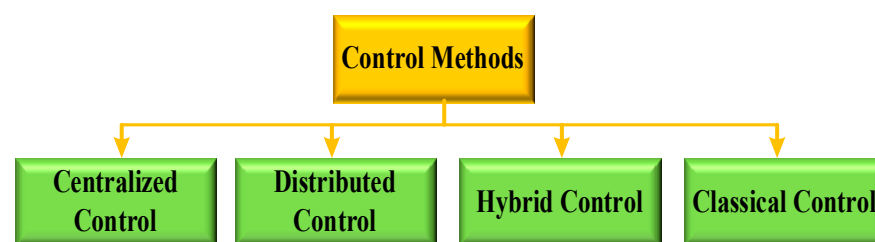


Figure 10. Hybrid system control techniques.

Most hybrid systems utilize distributed or hybrid control since these types of control are efficient in decentralizing control, minimizing system error, and allowing for the use of multiple kinds of control in a single hybrid system. The only limitation of these kinds of control is the ambiguity of the connection, along with processing codes. On the other hand, when a centralizing method of control is utilized in a smaller-scale HRES it shows excellent efficiency and improved performance, along with simplicity in construction. In addition, the cost of centralized control is advantageous when compared to distributed control or hybrid control. Figure 11 compares the most significant control types.

5.2. Management Strategy of HRES

Energy Management Strategies (EMSs) must be utilized to ensure the correct operation of renewable energy-based hybrid systems, to meet demand and improve the system's performance. A robust EMS enables the processes to satisfy demand, extends component lifetimes, and reduces operational costs. In addition, it also maximizes the utilization of RESs, minimizes energy costs output, and protects components from overload damage. As a result of these operations, the power system's reliability is improved, and the performance of the system is optimized [31].

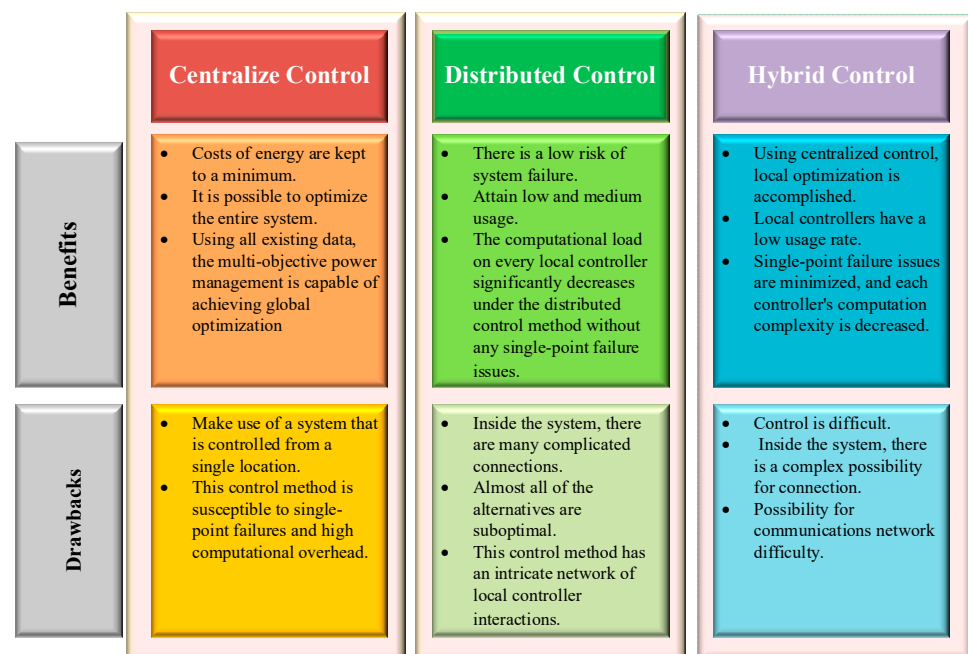


Figure 11. Comparison of the various control techniques.

Hybrid system management enables excellent system performance and accuracy at the lowest cost to provide year-round system supply [159]. Hybridization in energy management of HRESs produces a rise in element lifespan, a decrease in economic parameters (global, leveled costs, etc.), and, as a consequence, maximizes system reliability (Figure 12) [179]. The main characteristics of the management techniques of the HRESs are described in Table 6 [180]. Due to objective strategy (Figure 13) [179], management approaches are divided into three types, shown in Figure 13.

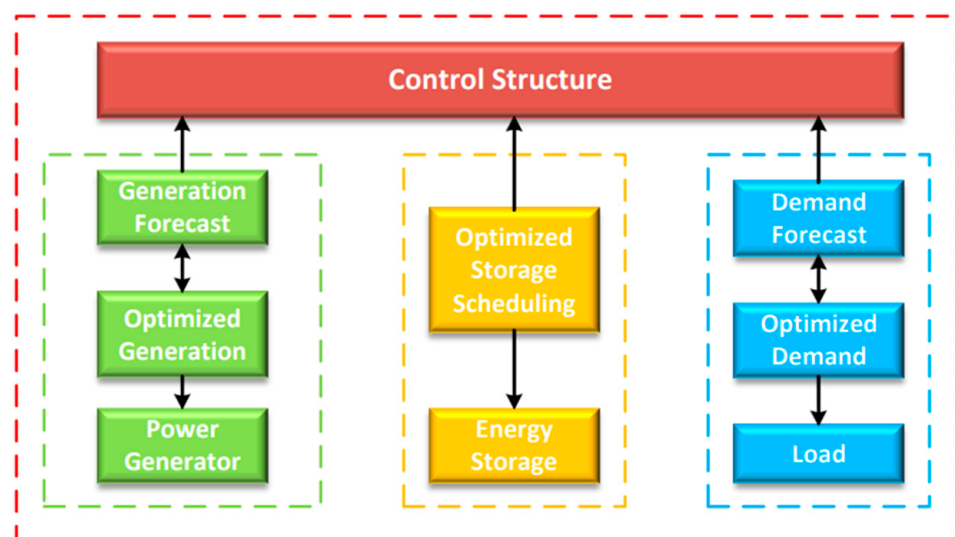


Figure 12. Intelligent energy flow management.

Table 6. Main characteristics of management methods.

Management Methods	Main Characteristics		
	Design Constraints	Main Features	Advantage and Drawback
Technical objective strategy	BA SOC, power balance, and storage system deterioration	BA short time, Flow chart algorithm, Algorithm to regulate power balance	Increased longevity and performance with a medium level of complexity, running and servicing costs are not optimized.
Economic objective strategy	The cost function, BA SOC, and Power balance	Power reference plus precedence, an algorithm to reduce cost	A complicated algorithm, higher operation and maintenance costs, and an un-optimized lifespan.
Techno-economic strategy objective	The cost function, BA SOC, and Power balance	Power reference plus precedence, an algorithm to reduce cost	A complicated algorithm, higher operation and maintenance costs, and an un-optimized lifespan.

**Figure 13.** Hybrid system management methods.

Figure 14 depicts the energy management techniques used in hybrid renewable systems. Energy management is implemented using Linear Programming (LP) in the majority of HRES studies, although other studies made use of intelligent methods for standalone and grid-connected HRESs. Abu Shufiana and Nur Mohammad presented a study on modeling and assessment of economic energy management for integrated MGs. In order to create an MG energy management system, the study employed optimization techniques for LP. The entire cost of electricity usage was minimized via constrained LP optimization. In order to demonstrate the effectiveness of the suggested optimization, it was compared with the heuristic technique, and case studies were discussed. The approach efficiently stored and sold power from a grid-scale battery system while forecasting pricing and loading conditions. In comparison to the heuristic method, the cost of electricity usage in the optimization technique was almost 19% cheaper [181]. Marcin Rabe et al., studied the design of a mathematical model for distributed energy optimization. This study assured energy security in the context of regional energy that was creative, environmentally friendly, and competitively open in employing local energy resources. As a result, it led to the belief that distributed energy could be a successful solution for the issue concerning functioning of traditional energy [182]. Marvin Barivure Sigalo et al. presented an Energy Management System for the Control of Battery Storage in a Grid-Connected MG with Mixed Integer LP. The study's findings demonstrated that the suggested real-time technique worked better than the offline optimization strategy and lowered operational costs by 3.3% [183].

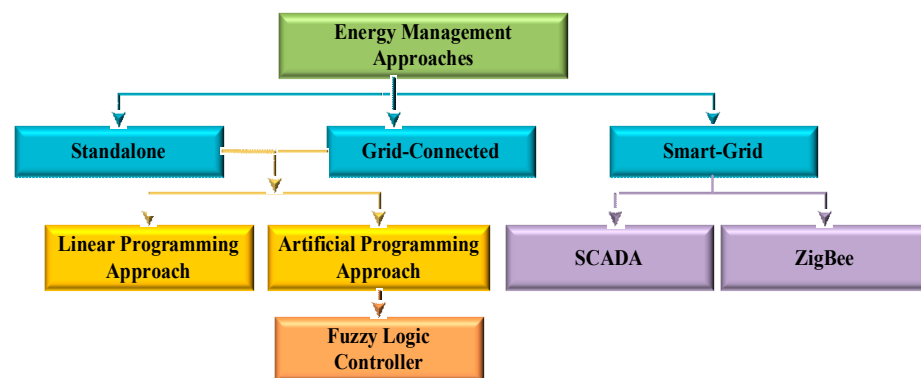


Figure 14. Energy Management Approaches used in HRES.

To regulate the transfer of energy between the many elements (sources of energy, storage systems, loads) that make up the HES, a specific EMS must be used. By adhering to a certain EMS, it is possible to achieve one or more of the purposes, seen in Figure 15.

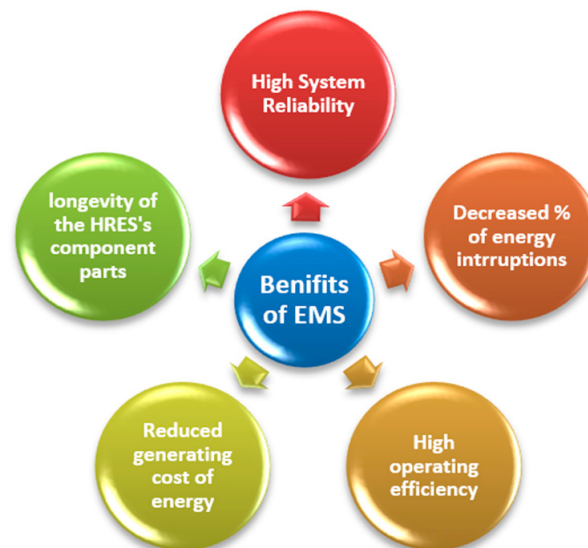


Figure 15. Benefits of EMS.

6. Challenges and Future Possibilities

The challenges and future possibilities in HRESs are discussed in the following sub-sections.

6.1. Barriers/Challenges in Adopting HRES

The implementation of HRES systems faces several challenges as demand for this HRES technology increases. Concerning research and innovation, renewable energy technologies have made significant progress. However, several roadblocks remain in the way of their effectiveness and maximum utilization. This section provides an overview of a few of the most important challenges encountered during the development and implementation of HRESs [184], and also those experienced by the designers [185]. The different types of barriers/challenges in adopting HRESs are given in Figure 16.

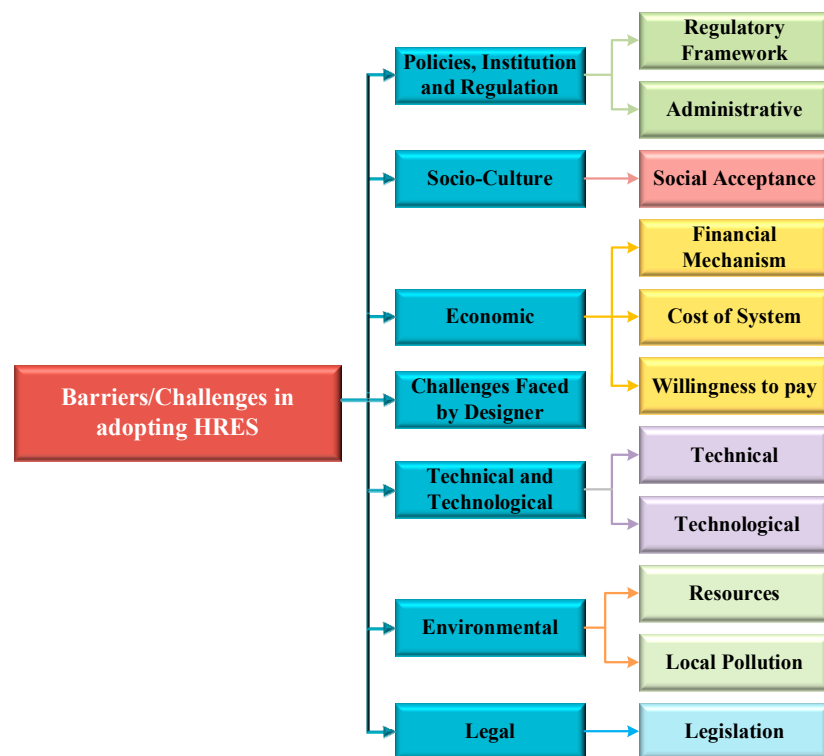


Figure 16. Barriers/Challenges in adopting HRES.

6.1.1. Policies, Institutions, and Regulations

The stranglehold that the primary significant firms have in the present energy sector and infrastructure has resulted in a heavily centralized system that is resistant to emerging technologies producing any adverse changes in the market. Countries' regulations, rules, and policies are still based on these monopolized energy suppliers. These regulations are intended to safeguard the widespread and centralized energy generation, transmission, and distribution systems, preventing any progress by renewable energy technology. Many smaller renewable energy project plans were rejected owing to regulatory size requirements [186]. Present rules and regulations must be amended to enable the widespread use of renewable energy technologies, particularly HRESs, and their incorporation into the energy system. Governmental and executive frameworks are the parameters considered while assessing policy barriers for HRES deployment. The lack of a particular policy and regulatory framework for the growth of mini-grids, and the laws governing interconnection between a mini-grid and the main grid are issues faced in this area (upon grid arrival) [187]. Researchers have also noted administrative aspects as the main barriers to the advancement of mini-grids. The insufficiency of devoted organizations for remote electricity generation, the accessibility of sparse and incorrect information, and bureaucratic licensing procedures, like difficult, drawn-out, or opaque authorizing methods [188,189], are hindering the further progress of HRES implementations.

6.1.2. Economic and Financial Challenges

Due to the obvious high initial capital cost of HRESs, many potential investors are hesitant to participate, particularly in developing countries. Many emerging countries do not contemplate HRESs because of the significant financial risk and the uncertainty surrounding future power costs [190]. These concerns result in expensive research, development, and implementation costs. The capital cost of efficient equipment is frequently much more than the standard option, and the depreciation period or monetary return may be insufficient [191]. Economic barriers in the context of financial assessment involve low expected returns on investments, restricted accessibility to financing sources, limited access

to credit facilities, and unsecured sources of income to cover operating expenses. Along with having a high initial capital expense, there are also higher tariffs when compared to the tariffs for the main grid and poor revenue (remote residents often being unable to afford electricity services) [192].

6.1.3. Challenges Faced by the Designers

Sources of renewable energy, like solar PV and FCs, require novel technologies to extract more usable electricity. Soar's low efficiency is a crucial impediment to their widespread adoption. Since the high initial cost results in a more extended payback period, sources of renewable energy production costs must be significantly reduced. It should be guaranteed that electrical power equipment loses as little power as possible. Innovative technologies must be used to extend the life of storage technology. These stand-alone systems are much less able to respond to changes in load. Significant variations in load might cause the overall approach to fail.

6.1.4. Technical/Technological Barriers

Technical barriers consist of the absence of provision for operation and maintenance, insufficient skill capability, an absence of standards and certification, and a lack of research and advancement transfer. Furthermore, remote places' demographic distribution patterns have an impact on the technological design requirements. From a technological perspective, people with significant technological knowledge (installers, developers, and maintenance personnel of HRES's setups) are necessary [187].

6.1.5. Environmental Barriers

Lack of solar radiation data, shortage of natural and sustainable resources, and topographical circumstances are taken into consideration in defining environmental barriers. Geographical position, earth-sun movement, the tilt of the planet's rotational axis, and air attenuation from dispersed particles all affect how much solar radiation strikes the surface of the earth. Since there is a lack of precise solar radiation information needed to develop solar power installations, adoption of HRESs in significant areas is further hindered.

Countries like India and China, where the human population has grown at an unprecedented rate [193], are fueled by equally enormous natural resource utilization and cause ecological effects in the conversion of enormous areas of the natural world to human use. The occupancy of natural space has repeatedly highlighted challenges as to whether the natural resource base of the globe can support such growth. Solar and wind energy are unpredictable in many countries, due to the country's topographical and meteorological conditions. Again, taking India as an example, there are various types of topographical aspects, like sea shores, rivers, deserts, mountains, valleys, tablelands, and flat terrains that demand highly skilled and technologically sound systems to be used for HRESs. Climatic conditions, such as temperature, wind speed, etc., vary according to topographical aspects and this plays a vital role in choosing HRES projects or not. In the context of solar energy, sunlight hours are restricted, and geographically the solar resources are distributed unequally; solar power is intermittent. Likewise, wind energy also varies according to geographic conditions [194].

6.1.6. Legal Barriers

In cases where there are legal obstacles, the legal parameter is evaluated, including the absence of clear and explicit laws for financial and tax incentives (subsidies) for mini-grid development. Furthermore, the legal system is uncertain and also conflicting. It is necessary to evaluate the current tariff structure, which can be unattractive or prohibitive.

6.1.7. Challenges in Socio-Culture

Challenges might arise due to a lack of response to cultural and societal issues concerning HRES advances. The traditional mode of power supply in Nigeria, which uses pipelines

of oil in the southern area, is an example. Oil spills in riverine regions, contamination of rivers, and harming of marine life are among the pipeline's negative consequences. This has a severe impact, not just on the ecology but also on the lifestyle of the local people. Furthermore, the exploration and exploitation of this energy and economic assets cause significant environmental deterioration and pollution, negatively impacting local people's agricultural production and well-being. This, combined with the reality that indigenous people are not monetarily rewarded, has resulted in the development of Niger Delta militants. The delta rebels regularly vandalize and destroy oil pipelines, causing the country to lose a significant amount of income and resources. As a result, factors such as compensations, contracts, and systems for the impacted and dislocated residents must be made for developments in HRES. This may necessitate a large amount of land and other assets, potentially disrupting agricultural production and well-being of residents in certain areas and also reducing potential areas of land for urban growth [195]. The success of the project's execution, as well as the longevity of such systems, are both greatly influenced by community acceptability. This might be hampered, also, by a lack of available information that contributes to misperception. One barrier to the growth of RESs, for instance, is a lack of public knowledge [196].

6.2. Future Prospects of HRESs

Renewable Energy technologies, particularly HRESs, have a considerable amount of potential. The potential of HRESs is infinite as further research progresses and technological breakthroughs are achieved. An SG is an electric power distribution network that employs digital telecommunications technology to identify and respond to regional operational changes. It is an SG network that uses smart meters, smart devices, renewable energy resources, and energy-efficient assets. Since smart grids employ digital technologies to improve electricity production, transport, and distribution, using HRESs in SG would be the most effective utilization technology. SGs include procedures such as automatic load balancing/adjustments and have a high level of flexibility to accommodate highly variable RESs, like solar and wind power, without the need for an energy storage unit. In SGs, HRESs enable the safe, efficient, and dependable aggregation of dispersed and renewable energy resources. Smart cities rely heavily on smart grids to provide a continuous energy supply for their functions, which is greatly aided by HRES implementation. Additional Research and Development innovations in solar PV and wind systems will minimize the COE of RES. The COE of traditional energy resources escalates year after year. Renewable technology will be economically viable in the future. Apart from the expense, the ecological benefit is likely to enable these systems to be more commonly used and accepted.

HRES has a lot of potential in aviation systems as well and is thought to become the way of the future. The integration of solar-wind-powered resources and jet-fueled aircraft engines to power the aircraft's electronics are examples. The solar impulse solar-powered exploratory aviation project demonstrated the viability of solar power as an energy source. The solar impulse aircraft completed a round-the-world journey using solely solar energy, which heightened the feasibility of HRESs. Significant development is being achieved in this sector by combining a solar-wind hybrid with jet-fueled engines, and the core idea is to harness solar energy to produce solar fuel to power the machines. The world's current trajectory requires drastic efforts to decrease carbon emissions in order to prevent climate change. As EVs become more common, they are increasingly displacing gasoline-powered vehicles for the conservation of biodiversity. With electric automobiles the prospect of employing renewable energy technologies like HRESs to power them assumes importance in the context of green power generation. Current EVs feature batteries that necessitate charging at on-grid charging stations within a specific service area. The application of HRESs eliminates these coverage constraints because the cars are fully autonomous and not limited to operating inside a particular zone. Furthermore, because global RESs would fuel cars, they could work effectively on the grid. An EV with energy storage powered by

solar PV and wind is an example worth mentioning to attract many researchers to work in the area of HRESs.

7. Conclusions

This study offers a succinct and insightful overview of the strategies that researchers have been utilizing for decades to optimize HRESs, whether grid-tied or not. In this review's analysis, it was clear that traditional approaches can better optimize the sizing field than commercial software, produce faster results, and address MO problems. Still, they are complicated and limited in flexibility. An overview of optimization techniques/software used in different HESs in the last two years, like PV_Wind_Other, PV_Other, and Wind_Other, was carried out, along with a comparison of the various optimization techniques in each category. The comparison of optimization techniques revealed that hybrid methods utilize the benefits of each approach to optimize performance and decrease processing time. Despite all of these benefits, the most significant challenge to hybrid techniques lies in design and algorithm development complexity. MH techniques and HOMER software are mainly used in the field of sizing, control, power management, and optimization of HRESs.

The different control strategies and power management in HRESs were also critically analyzed in terms of challenges, benefits, and drawbacks of each approach. Finally, the opportunities, barriers and challenges in adopting HRESs, and future directions, were thoroughly reviewed. This review paper inspires researchers to determine the effectiveness of newly proposed optimization techniques in the use of sizing, control strategies, and power management in HRESs.

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