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Review

A Comprehensive Review on Techno-Economic Analysis and Optimal Sizing of Hybrid Renewable Energy Sources with Energy Storage Systems

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Abstract: Renewable energy solutions are appropriate for on-grid and off-grid applications, acting as a supporter for the utility network or rural locations without the need to develop or extend costly and difficult grid infrastructure. As a result, hybrid renewable energy sources have become a popular option for grid-connected or standalone systems. This paper examines hybrid renewable energy power production systems with a focus on energy sustainability, reliability due to irregularities, techno-economic feasibility, and being environmentally friendly. In attaining a reliable, clean, and cost-effective system, sizing optimal hybrid renewable energy sources (HRES) is a crucial challenge. The presenters went further to outline the best sizing approach that can be used in HRES, taking into consideration the key components, parameters, methods, and data. Moreover, the goal functions, constraints from design, system components, optimization software tools, and meta-heuristic algorithm methodologies were highlighted for the available studies in this timely synopsis of the state of the art. Additionally, current issues resulting from scaling HRES were also identified and discussed. The latest trends and advances in planning problems were thoroughly addressed. Finally, this paper provides suggestions for further research into the appropriate component sizing in HRES.

Keywords: hybrid energy system; reliability analysis; techno-economic analysis; optimization methods; energy storage option; energy management system

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1. Introduction

The electrical loads in residential, commercial, local, and industrial buildings have increased dramatically because of the increased reliability of fossil fuels for energy. Use of renewable energy sources for electric power generation supply should be prioritized in order to reduce electric load dependency on fossil fuels. Currently, crude oil, coal, and natural gas are used as alternative energy sources to meet about 70% of the global power demand [1]. Energy demand is skyrocketing in response to the world's growing economy and population. Consequently, fossil fuel consumption is also increasing very steeply. Conventional fuel stocks are limited and rapidly declining, which requires immediate action and long-term solutions to avoid a possible energy disaster in the years to come. Furthermore, fossil fuels are potential sources of hazardous emissions, such as greenhouse gases, which greatly contribute to warming the globe [2,3].

To be able to reduce global warming, one of the techniques is to raise awareness of the significance of reducing power usage in homes and industries and promote energy-efficient equipment. These concerns are being addressed by numerous researchers in a number of ways. The more dependable, economical, ecologically beneficial, and widespread alternative strategy is to support renewable energy systems and related technologies. The construction of various hybrids of renewable energy sources has received a lot of attention in an effort to enhance long-term energy supply systems. Hybrid renewable energy sources (HRES) are systems that are reliable, CO2-emission-free, and an effective solution for minimizing dependency on one renewable resource, which is important in areas where natural resources are limited [4]. In view of [5,6], the integration of renewable energy resources is an emission-free solution for energy generation that allows energy supply in a district's topography and also acts as a steady potential energy resource for isolated generation applications. The renewable energy capacity indicated includes large-scale wind, solar, and home photovoltaic (PV) systems. Most residential PV systems are grid-connected, meaning the output receives excess electricity from the grid during the day and sends out power at night. HRES can be utilized independently for each home or in microgrids (MGs), which link a number of residences to create a small power grid in outlying areas where grid expansion is impractical [7,8]. The second method is gaining traction in rural areas and islands [9] because it is cost-effective and can be used alternatively in areas where power infrastructure upgrades are prohibitively costly and fuel transportation is problematic [10]. Many researchers have carried out research to develop hybrids from diverse renewable energy sources in order to improve long-term energy supply systems. According to studies on geographic information systems (GIS), the global population of islands is projected to be over 740 million [11]. Energy consumption has risen in recent years in islands and isolated regions, making reliance on fossil fuels uneconomical. As a result, standalone HRES and RES are viable long-term solutions for clean and cost-effective electricity for expanding populations and enterprises in remote areas and islands [12–14].

Since RES generates the majority of its energy from the environment, it reflects the environment's intermittent character. A significant disadvantage of wind and solar energy is how dependent they are on the environment. However, this issue may be solved by creating an HRES, which combines two or more energy sources with a backup unit [15]. HRES can be used with elements like wind and sunlight that complement each other. Moreover, energy storage systems may be combined with conventional energy sources like diesel generators (ESS). HRES can give a certain application a more cost-effective and steady electrical supply [16,17]. The high initial cost, rising cost of maintenance, fluctuating rates, and depreciation are key difficulties involved with hybrid systems [18]. In addition, HRES design is influenced by the availability of energy sources and site characteristics, as well as by technological and societal limits [19–21], which affect the system's power generation arrangements and total energy production cost.

The appropriate size combination is crucial in this scenario for providing enhanced reliability at the lowest cost. Determining the optimal design of HRES is a difficult undertaking because it is based on data from energy sources, technical specifications, ambient conditions, and load patterns [22]. HRES models, configurations, sizing, and optimization procedures have been investigated for a variety of locations and constraints [22–26]. Because solar and wind hybrid systems work well together [27], the majority of the studies have utilized them. Methodologies for optimizing the size of solar and wind hybrid systems have been combined, resulting in greater precision in optimization and control approaches in both grid-connected and stand-alone HRES [28–32]. Novel single-algorithms, hybrid algorithms, and software tools designed for grid-connected or remote sites and islands, as well as critical performance comparisons for all solar and wind hybrid system scaling, are among these techniques. Research focused on the application of artificial intelligence techniques in scaling HRES has highlighted a few discrete artificial algorithms for standalone and grid-connected applications [33,34]. Integration settings, storage system options, size approaches, and independent HRES control and management were key areas of interest [35]. In [36], the author presented the case study of sustainable energy production from municipal solid waste in Oman. In [37], authors presented the study related to the challenges towards renewable energy production the Arabian Gulf region. Reference [38] provides a discussion of the optimal design for several artificial single-algorithms and software tools, as well as a number of hybrid combinations. For independent and grid-connected applications, Upadhyay and Sharma [39] explored the size of various hybrid system combinations using both artificial and conventional sizing methodologies. The author of [40] mainly discussed multi-objective optimization approaches for hybrid energy systems using energy sources from fuel cells, the sun, and wind. The author of [41] concentrated on employing artificial optimization approaches to examine, control, and model HREs. Based on a series of probable accessibility, cost effectiveness, and emission-free environmental evaluation findings, the solar-biomass hybrid system is acknowledged and generally acceptable among various forms of HRES [42–44]. The use of solar and local biomass in hybrid systems maximizes the use of both. It may be possible to enhance the local energy structure by implementing these renewable energy technologies. In hybrid solar-biomass energy systems, the majority of the biomass subsystems directly absorb either forest biomass or agricultural waste.

A renewable energy generation system based on biogas and solar PV was described by Tazvinga and Dzobo [45]. The major goal was to boost a solar PV system's efficiency throughout the day and also include battery storage and a biogas generator to make up for its unpredictability. According to [46], the decentralized electricity supply based on renewable energy has traditionally been viewed as a single technology with a finite quantity of supply to satisfy essential needs. The current study's objective is to combine solar energy and biogas to provide electricity for an off-grid, rural community as an example. According to Rahmana et al. [47], solar and biogas are insufficient to cover both thermal (cooking) and electric load requirements. Biogas and hybrid solar energy applications are rather limited, despite their appealing potential. It is critical to examine the economic merits of these two resources, as well as their aptitudes to cope with needs and physical limitations, in order to enable their integration into rural energy planning and stimulate distribution by fully maximizing their potential. The maximum potential of solar PV energy and biogas may be used for solar PV-biogas hybrid power generation. Ansori and Yunitasari [48] recently explained how to electrify rural areas using a solar PV–biogas hybrid power generation system. The literature does not critically compare the various sizing optimization strategies' efficacy despite covering a wide spectrum of sizing optimization and a thorough study that included the most recent single and hybrid sizing optimization methodologies and software tools. A comparison of the efficiency of freestanding hybrid solar and wind systems for remote locations and islands has not yet been published. HRES are of potential use, especially for standalone systems, which are designed for remote and island areas as well as grid-connected systems for unreliable national grid demands. Because of this, the current study also intends to give a thorough review of recent advancements in single algorithms, hybrid algorithms, and software tools for the ideal size of HRES and evaluation characteristics including economic, reliability, environmental, and social considerations. Furthermore, this research assesses the size optimization methodologies employed by various researchers, and it has been thoroughly reviewed for standalone and grid-connected HRES with various energy sources and storage systems.

This paper has been structured into the following sections: Section 1 contains a detailed description of the components of a hybrid renewable energy system; Section 2 contains the paper's contribution; Section 3 contains the design parameters for a hybrid renewable energy system; Section 4 contains energy production unit sizing optimization; Section 5 contains energy storage system integrations on HRES plants; and Sections 6 and 7 contain the discussion, recommendations, and conclusions.

Contribution of the Paper

This paper concentrated on hybrid renewable energy systems and their optimal sizes, which can operate as either national grid-connected or remote electrification systems. Considering the limitations and challenges identified in the above analysis, the contribution is made in the following ways:

- A description of the problem of selecting the best size for hybrid renewable energy systems
- Examining the present state of the art in hybrid renewable energy systems and the optimal size in relation to economic issues
- Organizing and categorizing existing research on the appropriate sizing of hybrid renewable energy systems with energy storage systems
- Identifying current technical challenges with reference to the optimal sizing of hybrid renewable energy systems with energy storage systems
- On the basis of numerous study fields, a full-scale constructive analysis of potential optimal sizing strategies and optimization methodologies was examined, highlighting objectives, major discoveries, and research gaps.
- Future research trends in the appropriate sizing of hybrid renewable energy systems with energy storage systems are likely to emerge.

2. Overview of the Review Procedure

The review procedure for this research is depicted in Figure 1. There were four primary steps in completing this study. In order to identify the problem, the first step was an examination of feasibility constraints, components, objective functions, and methods. The second step analyzed and classified existing research on the topic using significant variables such as component, goal function, and approach. Shortcomings in this research were emphasized and thoroughly spelled out. Furthermore, the third step identified and discussed recent developments accordingly. The process's fourth and final step discussed future trends in optimal component planning for remote location power supply.

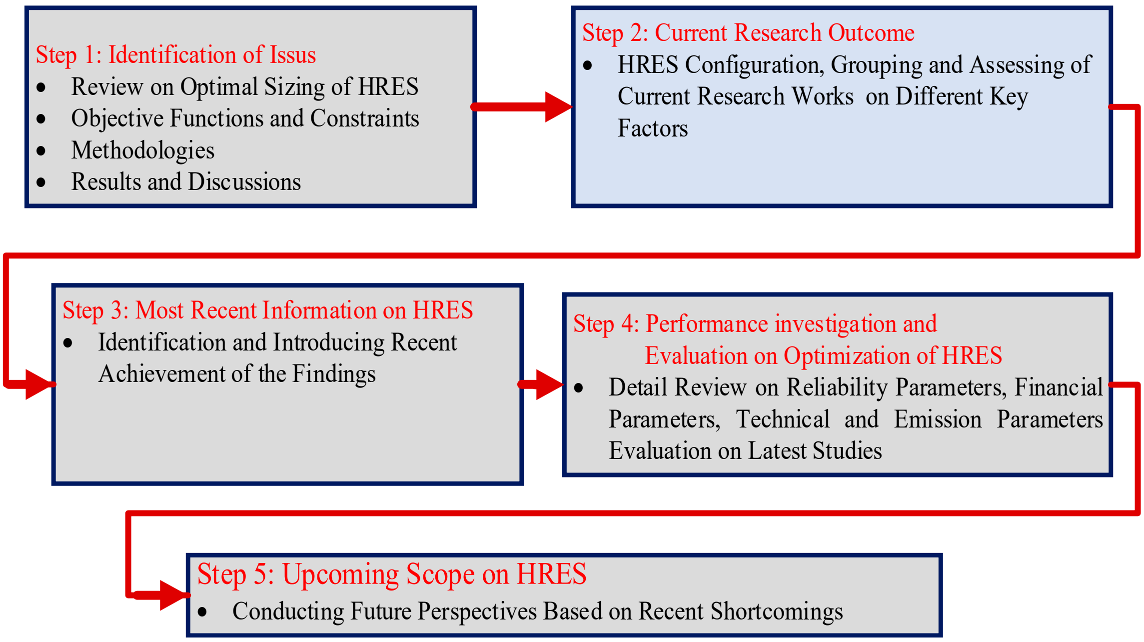

Figure 1. General approach for reviewing the study on HRES system sizing.

3. Overview of HRES System Optimal Sizing

Some of the optimal sizing challenges associated with HRES systems are estimating system components with the most capacity and at the same time considering feasibility and reliability constraints. It's worth noting that the HRES grids are expected to be implemented in this analysis, and only optimal generating and storage unit sizing is considered by using optimization methods [49,50]. Such is the case where HRES networks are typically built and developed by governments. Consequently, the distribution of grid installation on HRES systems lacks sufficient data for cost analysis. In addition, generation and storage units are generally located near rural locations, and the HRES grid has a far lower cost than traditional power networks [14,46,51]. Figure 2 depicts a generic technique for HRES system sizing optimization. The system's input data was used to start the optimal sizing algorithms for HRES system design. The HRES system setup was then defined. The sizing problem was stated using the optimization algorithm. In the next step, the HRES system's functionality was assessed. After the HRES system became operational, the feasibility limitations were checked for satisfactory results. The objective function was then calculated to complete the optimization problem, provided all the constraints had been met.

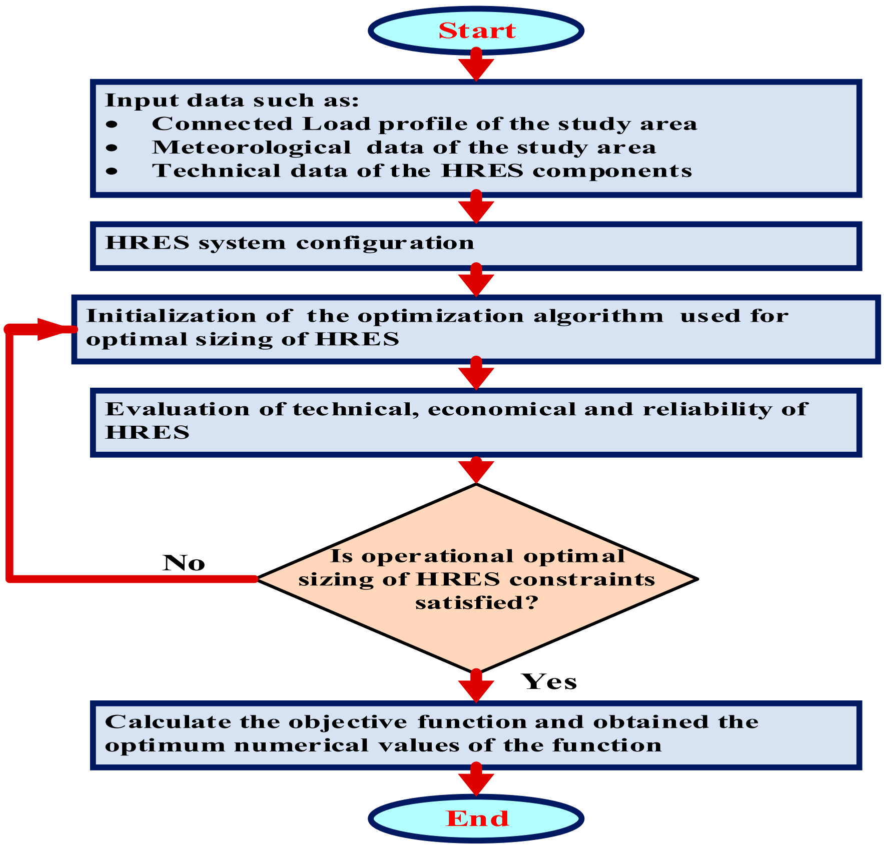

Figure 2. A general approach for optimal HRES system sizing.

3.1. Hybrid Renewable Energy System Components

HRES has higher upfront costs, regional limitations, and a high degree of intermittency [52]. ESS is required to tackle the intermittency issue, even if the cost of HRES is decreasing [53]. However, the ESS cost is highly significant, especially when large-scale renewable power plants require a lot of capacity. For a cost-effective and ecologically friendly system, a hybrid diesel generator/HRES/ESS combination is recommended. A multi-component hybrid remote area electrification system, on the other hand, is a complex system that necessitates careful planning. In order to produce a reliable, cost-effective system, the concept of optimal planning is paramount. A hybrid renewable system [49,52,53] is the most cost-effective way to store and use natural power without interruption. Due to their dependability and cost-effectiveness in supplying energy to rural and remote areas, researchers have increasingly focused their attention on HRES integrated with ESS. Several studies [54–58] have examined resource utilization and techno-economic performance. Two or more renewable energy generation units, a backup fuel cell power generation unit that is optional, power conditioning units, and a storage unit are all components of an HRES production configuration system [59–63]. The most common schematic diagram of an HRES plant is shown in Figure 3, in which the load is fed first and foremost by solar and wind generators, with the biogas generator serving as a backup. The battery ensures power flow balance in the system as well as optimization.

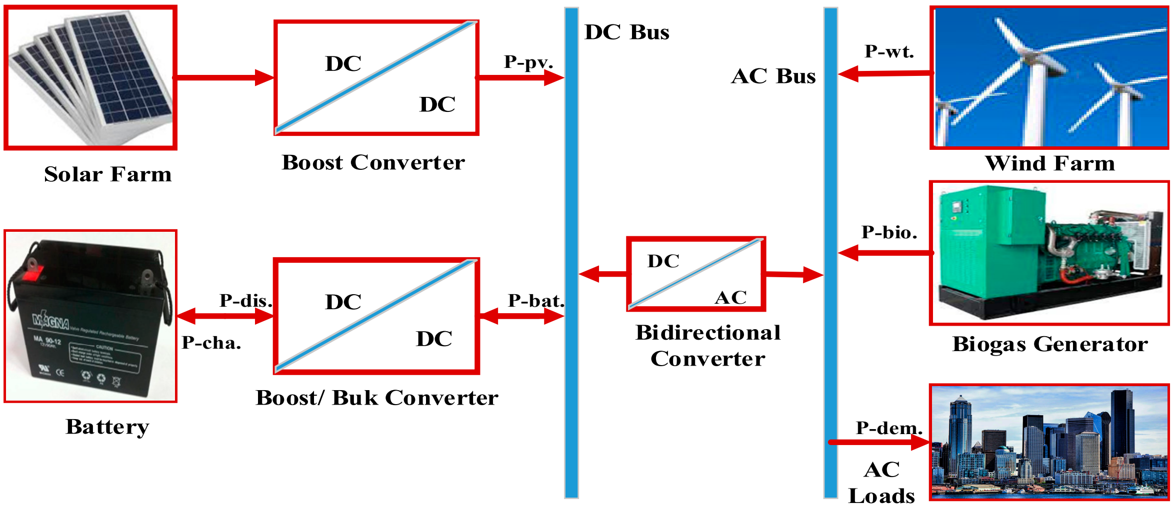

Figure 3. Schematic diagram of an HRES system.

Components using fossil fuels to provide energy, such as diesel or gas generators, contribute considerably to greenhouse gas emissions. A range of renewable energy components has recently become available that can be incorporated with distant area electrification and national grid interconnection systems. The most readily available and appropriate components for far-flung electrical and national grid interconnected systems include solar PV, wind turbines, hydropower, and biogas generators. Their use, however, is strongly dependent on the geographic location of the research site [64–66]. Due to the abundance of biomass in rural regions, biogas producers will attract greater attention in the near future [66]. Figure 4 presented the system components in HRES systems.

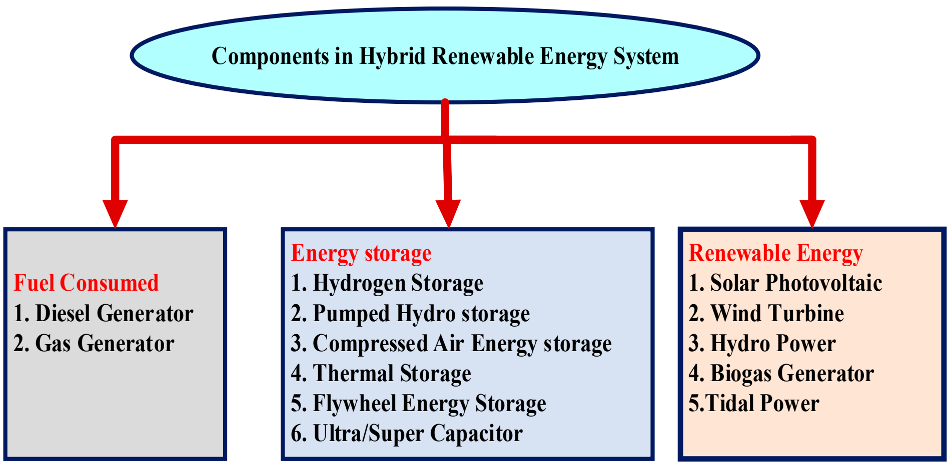

Figure 4. System components in HRES systems.

3.2. Design Parameters of HRES System

When constructing a hybrid renewable energy system, the most important elements to consider are cost and reliability. These variables are related to emissions and technological challenges. The type of objective function utilized was based on the type of investigation. Often times, economic objectives take precedence. If the project's budget is limited, reliability becomes a major problem. Emissions have drawn a lot of attention in several situations. Because the objectives are so different, optimal sizing in hybrid renewable energy systems can be achieved by using optimization techniques to solve a single-objective or multi-objective optimization issue. A compromise between the objective functions is required for multi-objective issue solutions expressed as Pareto fronts [67].

As shown in Figure 5, the different categories of objective functions are presented. Nowadays, most researchers give priority to economic factors, then reliability factors, and end with technical and emission considerations. Each of the above objective functions' categories are explained in detail below.

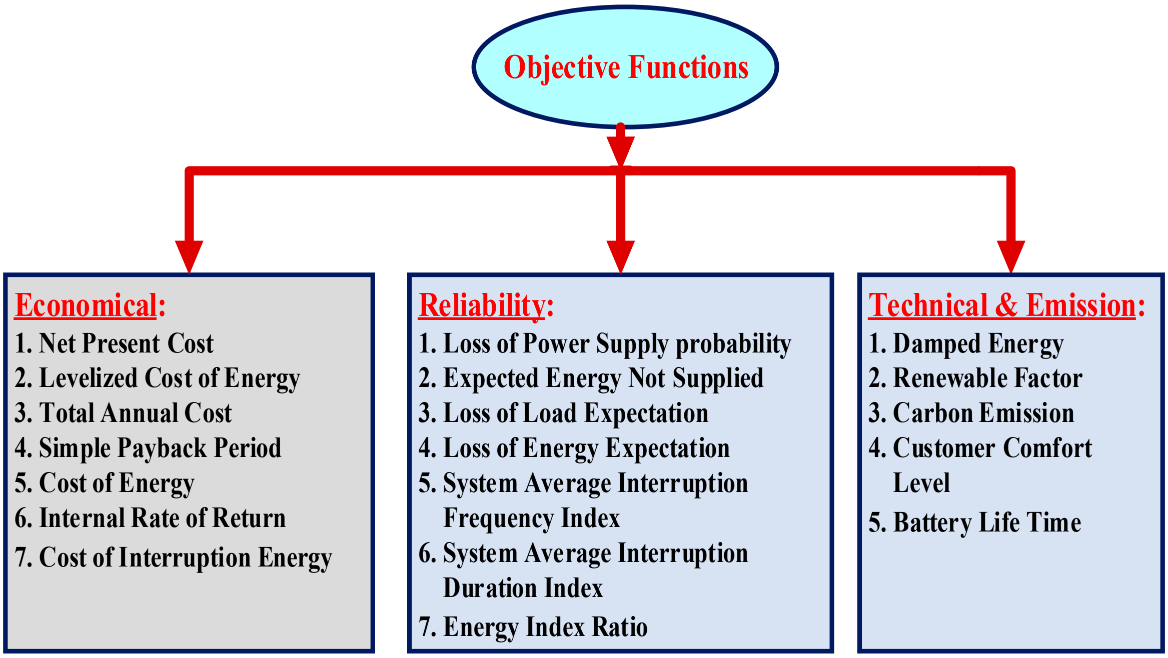

Figure 5. HRES system sizing based on objective functions.

3.2.1. Objective Functions of Finance

Financial goals include the net present cost (NPC), levelized cost of energy (LCOE), total annual cost (TAC), simple payback period (SPP), and internal rate of return (IRR). The NPC of a diesel generator is calculated by adding up all current capital, maintenance, replacement, salvage, and fuel consumption costs [68]. The capital recovery factor is multiplied by the NPC over the system's yearly energy consumption to determine the LCOE [69]. To calculate TAC, yearly construction and maintenance costs are compounded by annual fuel prices [70]. The SPP measures how long it will take for yearly profits to cover component capital expenses [71]. The discount rate at which the net present value (NPV) of all future cash flows is zero is known as the IRR [72]. The mathematical formulation of each economic objective function for the hybrid renewable energy system size is as follows:

(a) NPC: The present value of all benefits and costs that will occur throughout the project's lifetime is known as the net present cost [73].

$$F_1 = \text{Minf}(NPC) = NPC_k + NPC_f \tag{1}$$

$$NPC_k = PC_C + PC_m + PC_r - PC_s \tag{2}$$

$$NPC_f = \left(\frac{(1+r)^n - 1}{r(1+r)^n}\right) \times \left(\sum_{t=1}^{T}\left(f(t).C_f\right)\right) \tag{3}$$

(b) LCOE: It represents the system's entire yearly cost per kWh of useable electrical energy [74].

$$F_2 = \text{Minf}(LCOE) = \frac{NPC_k + NPC_f}{E_p} \times \frac{r(1+r)^n}{(1+r)^n - 1} \tag{4}$$

(c) TAC: It is the annualized cost of all power system components, which includes replacement and fuel expenses in addition to capital, operating, and maintenance costs [75].

$$F_3 = \text{Minf}(TAC) = \sum_{t=1}^{T}\left(f(t).C_f\right) + AC_k \tag{5}$$

(d) SPP: It is the amount of time needed to recoup an investment's cost [73].

$$F_4 = \text{Minf}(SPP) = \frac{PC_c}{AP} \tag{6}$$

(e) IRR: In a discounted cash flow analysis, it is a discount rate that sets the net present value (NPV) of all cash flows to zero [76].

$$F_5 = Maxf(IRR) \tag{7}$$

$$-PC_c + \sum_{y=1}^{Y} M_Y \times (IRR)^y = 0 \tag{8}$$

3.2.2. Objective Functions of Reliability Evaluation

The following are some of the most common measurements and target functions for HRES optimal sizing dependability.

1. Loss of power supply probability (LPSP)
2. Expected energy not supplied (EENS)
3. Loss of load expectation (LOLE),
4. Loss of energy expectation (LOEE)

Further, the system average interruption frequency index (SAIFI) and system average interruption length index (SAIDI) are two other dependability indices that have received less attention for optimal sizing of HRES. The likelihood of an unmet load over the whole energy demand of a grid-connected or stand-alone hybrid renewable energy system is known as the LPSP [77]. The EENS is the energy that is supposed to be provided by a hybrid renewable energy system but is not [78]. The LOLE, also known as the loss of load probability (LOLP), is the number of hours per year that the energy exceeds the capacity of the HRE generation system [79]. The LOEE [80] stands for the total energy not delivered by the grid-connected or stand-alone hybrid renewable energy system. Over the course of a year in the HRES project, SAIFI can be defined as the average number of times a client witnesses power outages. Throughout the life cycle of the project, the SAIDI index measures the total average customer's interruption time. For hybrid renewable energy systems, we explain the mathematical calculation of reliability objective functions.

$$F_1 = \mathrm{Min}f(LPSP) = \frac{E_p + E_d + E_{b,ch} - E_{re} - E_f - E_{b,dis}}{E_p} \tag{9}$$

$$F_2 = \mathrm{Min}f(EENS) = \sum_{t=1}^{T} L_P D_P \tag{10}$$

$$F_3 = \mathrm{Min}f(LOLE) = \sum_{t=1 Ses}^{T} \sum F_s T_S \tag{11}$$

$$F_4 = \mathrm{Min}f(LOEE) = E_p + E_d + E_{b,ch} - E_{re} - E_f - E_{b,dis} \tag{12}$$

$$F_5 = \mathrm{Min}f(SAIFI) = \frac{\sum \lambda_i N_i}{\sum N_i} \tag{13}$$

$$F_6 = \mathrm{Min}f(SAIDI) = \frac{\sum U_i N_i}{\sum N_i} \tag{14}$$

3.2.3. Objective Functions of Emission and Technical

The following are the other groups of objective functions:

1. Renewable factor (RF)
2. Carbon emission (CE)
3. Battery longevity (BL)
4. Customer comfort level (CCL)
5. Discharged energy (DE)

The RF shows how much of the energy demand is fulfilled by HRES [81]. The CE represents the total quantity of CO_2 emitted by the envisaged HRES system over the project's duration [82]. The BL is the battery's lifespan in HRES that has been shortened due to deterioration. In order to avoid battery damage and thus increase battery lifetime, a proper installation plan should be developed. The mathematical formulas for emission and technical objective functions are offered in Equations (15)–(19) in the HRES optimal sizing issue. However, the demand response solution for this study has an impact on CCL formulation. The number of hours required to achieve the greatest CCL might be decreased, for instance, if load shifting is considered. The inverter management system, which reduces power fluctuations and provides a consistent power supply, is taken into consideration when calculating the EFR. For the optimum size of a hybrid renewable energy system, the emission and technical objective functions are mathematically formulated.

$$F_1 = M\inf(RF) = \left(1 - \frac{E_f}{E_p}\right) \times 100 \tag{15}$$

$$F_2 = \mathrm{Min}f(CE) = \alpha + \beta \sum_{t=1}^{T} P_f(t) + \gamma \left(\sum_{t=1}^{T} P_f(t)\right)^2 \tag{16}$$

$$F_3 = Maxf(BL) = 1 - D_b \tag{17}$$

$$F_4 = Maxf(CCL) \tag{18}$$

$$F_5 = \mathrm{Min}f(DE) = E_{re} + E_f + E_{b,dis} - E_p - E_{b,ch} \tag{19}$$

3.3. Consideration of Feasibility Constraints

There are two types of feasibility restrictions for hybrid renewable energy system sizing. These include (1) component-related restrictions and (2) system-level technological constraints. The feasibility constraints on remote area electrification and the optimal sizing difficulties of the national grid interconnection system are shown in Figure 6.

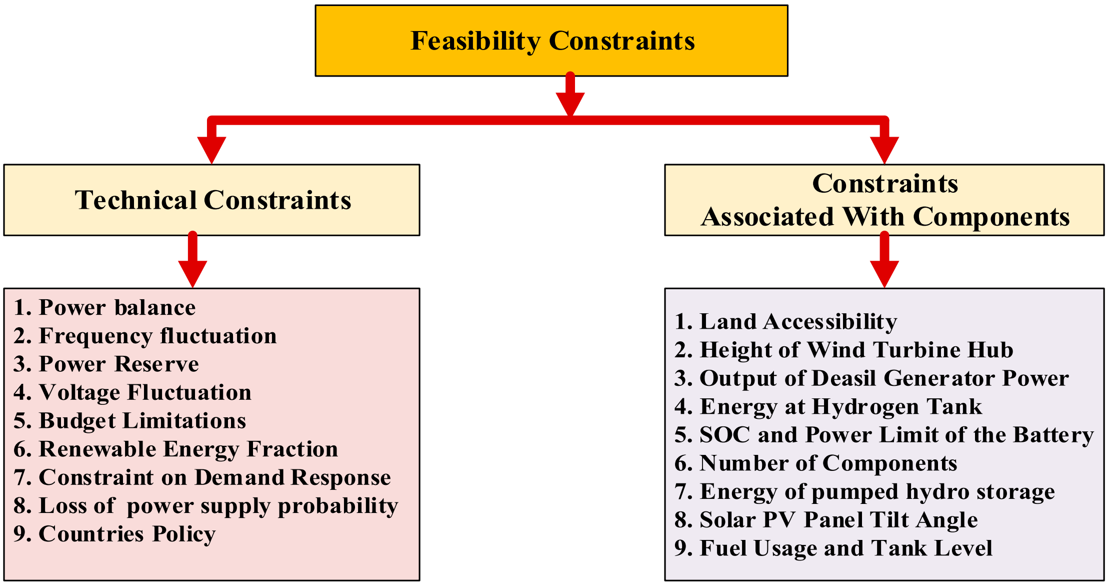

Figure 6. Constraints on optimal sizing of HRES.

4. Sizing Optimization of Energy Production Unit

References [83–85] provide a comprehensive examination of the critical unit sizing difficulty for hybrid renewable energy systems. It is a technique for estimating hybrid system component sizes that also lowers system costs and increases system reliability [86]. Oversizing can raise the cost of the system, whereas under-sizing could lead to a power supply breakdown or inadequate power being delivered to the load. There are several techniques for sizing the appropriate hybrid renewable energy system. Among the various options, there are two that are more common and commonly used.

(1) Simulation and optimization software

(2) Meta-heuristic optimization techniques

4.1. Simulation and Optimization Software

Simulation tools are the most widely utilized instruments for assessing the performance of hybrid systems. By evaluating the efficiency and cost of energy generation of various system configurations using computer simulations, the ideal design may be found. Just a few of the software tools that may be used to create hybrid systems are HOMER, HYBRID2, HOGA, and HYBRIDS. The HOMER (Hybrid Optimization Model for Electric Renewables) tool from the National Renewable Energy Laboratory is easy to use. It assesses hybrid renewable energy using hourly simulations and environmental data, then optimizes the system using the net present value. Many studies utilizing HOMER [87] have been undertaken on the best design of hybrid renewable energy systems without ESS. HOMER was used to optimize a diesel generator-PV-Wind-battery hybrid [88], a PV-Wind hybrid [89], a mini-hydro-wind hybrid [90], a solar-biomass hybrid [91], and a hydro-wind-solar hybrid [92]. The PV-WT-DG-biogas system was sized by HOMER for a community service power application since it is simple to operate [93]. In [94], the researcher optimizes the design of a biogas generator for a hybrid remote area electrical system in a distant village with a WT-PV-DG. Due to the intermittent nature of solar irradiation and wind speed, this hybrid system was unable to deliver a steady supply for the connected demands. To address the dependability issue, hybrid renewable energy systems should incorporate energy storage technologies.

Numerous academics are looking at how to best construct hybrid renewable power plants using HOMER software, integrating energy storage devices with remote region electrification systems, and linking the national grid system. The ideal HRES system size determined by the HOMER software optimization tool is summarized in Table 1. The optimal WT-PV-DG-BES size with the optimal levied energy cost was developed for use in islands, rural remote locations, and off-grid communities [95–98]. The PV-WT-BES system is the most commonly discussed method for remote area electrification and grid interconnection [99]. Other technologies used in clean distant regions for electricity and national grid connectivity, in addition to PV and WT, include fuel cells, super- and ultra-capacitors, and pumped hydro. Long-term and short-term energy storage systems are divided into two categories. Long-term energy storage includes pumped hydro and fuel cell systems, whereas short-term storage includes batteries and ultra- and super-capacitors. The majority of studies recommended combining solar with long-term energy storage systems on a large scale [100]. HESS has been extensively researched for remote electrification and national grid connectivity systems. In South Africa, a hybrid FC-SC HESS with a photovoltaic system was used for commercial remote loading [101]. With a hybrid PV and WT system, the optimal size was found to be a combination of BES and FC [102]. To create a clean hybrid system with more electricity supply flexibility, a biogas generating unit has been combined with a PV-WT-BES system [103]. In [104], an agricultural farm's biomass-biogas system was sized to perfection. HOMER [105] was also used to examine the use of biogas-producing units in conjunction with hydropower in clean remote area electricity systems as well as national grid connectivity systems.

Table 1. Optimal sizing of HRES systems by using HOMER software optimization tool.

Ref.	Decision Variable	Optimization Method	Objective Function	Design Constraints	Electricity Tariff
[106]	Wind/PV/FC/BES	Homer Pro	NPC, COE, initial investment cost, and operating cost	Power balance and budget	Time of use
[107]	PV/wind/Biogas/FC	HOMER Pro	COE and NPC	Power balance and budget	Time of use
[108]	PV/Wind /BES/DG	HOMER	NPC, COE, and RF	Load demand, diesel fuel price, project lifetime, and interest rate	Time of use
[109]	PV/Wind/ BES/DG	HOMER	NPC and LCOE	Electricity production, emission, operating cost, fuel consumption	Time of use
[110]	DG/PV /Micro hydro	HOMER	Operating costs and return on capital	Power balance and budget	Stepwise Real time pricing
[111]	PV/Biomass /BES/DG	HOMER	LCOE	Required electrical load and available energy resources	Time of use
[112]	Wind/DG/PV/BES	HOMER	NPC	Single criterion-total net present cost	Not specified
[113]	PV/Wind/ DG/BES	HOMER PRO	NPC and COE	Capital cost, energy generated, excess energy, unmet load, life cycle emission, renewable penetration	Time of use
[114]	PV/wind /BES	HOMER, QRod™& PROSPER™	NPC and LCOE	Load demand, capital cost, available energy resources, and energy generated	Not specified
[115]	PV/DG/BES	HOMER Pro	COE and NPC	Load demand, capital cost, available energy resources, and configuration of RES	Time-of-use

The essential strength of each study project is the authors' strategy to deal with the community's issues with a shortage of power, as mentioned in the review articles in Table 1. According to the decision variables, every hybrid system, excluding references to the community's issues with a shortage of power, as mentioned in the review articles in Table 1, according to the decision variables, has a diesel generator. Diesel generators are not only not environmentally friendly, but they are also not economically viable. Besides, BES is not completely economically feasible. A future study should take all of the aforementioned features and drawbacks into account and make sure to address them in the brand-new, exclusively green hybrid system configuration that will be used on the system. Additionally, to deal with both the objective function and the constraints, the future researcher should handle the issues utilizing metaheuristic optimization approaches.

4.2. Meta-Heuristic Optimization Techniques

It is critical for designers to develop a practical optimization technique for determining the best system size and configuration for hybrid renewable power plants. For constructing a hybrid renewable energy system, there are numerous optimization techniques available, the most popular and accurate of which is metaheuristic optimization. Metaheuristic approaches are commonly used to achieve appropriate HRES sizing. Existing metaheuristic technique studies are categorized into one or more objective optimization studies. The reference number, decision variables, optimization methods, objective function, design restrictions, and electricity tariff of extant metaheuristic studies on single-objective and multi-objective optimal design of HRES are shown in Table 2. Metaheuristic approaches were used to size the hybrid PV-WT-DG-BES system, which lowers the cost of energy production [116]. The LPSP was employed as a constraint to increase dependability [117–120]. The number of components and the power balance between generation and consumption were the most commonly used feasibility restrictions. However, the researchers suggested a system with a PV-WT-DG-BES that was both cost- and size-optimized [121,122]. Numerous methods were examined for improving the RF, unit commitment, and proportion of renewable energy [123–127]. The aforementioned studies were peer-reviewed and have only one objective.

Furthermore, Table 2 demonstrates that the reference numbers represent the single-objective optimal design of a hybrid renewable power system, whereas the remaining references represent the multi-objective optimal design of a hybrid renewable power system. Many researchers have economic goals as their first priority. Furthermore, objective functions linked to pollution and reliability were the most commonly used. The researcher also recommended that three objective functions, such as renewable factor (RF), carbon emission (CE), and life cycle cost (LCC), be evaluated jointly to build a hybrid renewable power plant ideally [127]. However, because CE and RF belong to the same type of emission-minimization target functions, it is unnecessary to consider them for optimal sizing. The researcher in [128] took into account three objective functions as well as new limitations such as the WT hub height and PV tilt angle.

As stated in the previous two paragraphs, metaheuristic approaches are used as a single objective and a multi-objective for the optimal design of a hybrid renewable power plant in a clean energy production system. However, in the best design of a hybrid renewable power plant, the emission objective functions are removed as a result of the limited diesel generators available for clean energy production schemes. In [129], the researcher designed a WT-PV-BES system optimized in a group of twenty households, resulting in cost-effective and emission-free energy generation with reduced energy costs. In other studies, such as [130], four distinct algorithms were utilized to examine the performance of the metaheuristic algorithm for optimal sizing of hybrid renewable power plants. Using a PV-thermal system, [85] evaluated the supply of thermal loads in addition to the electric loads. Furthermore, a natural gas backup boiler was optimized in addition to the renewable system [131]. Both the hybrid grey wolf optimizer-sine cosine approach and the modified bee algorithm were used to determine the ideal HRES size [132,133]. Particle swarm optimization was used to improve the PV-WT-BES and biogas-PV-WT systems [134,135]. A PV-WT-PHS system was created in [136] to provide loads in a seaside village. Due to the abundance of water for PHS, such a system is extremely effective in coastal regions. The method with the most popular and greatest applications was the particle swarm optimization technique, which had several objectives. The current research considers objective functions such as volatility [137] and minimization of the total energy cost and loss of power supply probability [138]. The most commonly studied HRES configurations were WT-PV-FC [139], WT-PV-PHS [140], WT-PV-BES [141], WT-PV-FC [142], and PV-FC-BES [143]. However, reference [144] presented an improved two-component PV-BES system.

Table 2. Single and multi-objective capacity optimization for HRES with meta-heuristic optimization techniques.

Ref.	Decision Variable	Optimization Method	Objective Function	Design Constraints	Electricity Tariff
[145]	PV/Wind/ FC	Hybrid firefly-harmony search optimization	NPC	Power balance and techno-economics	Time of use
[146]	PV/Wind/ FC	Hybrid grey wolf optimizer-sine cosine algorithm	LCC		Time of use
[147]	PV/wind/ BES/PHS	Four algorithms	NPC	Number of components, battery's energy and SOC	Time of use
[148]	PV-Thermal/WT/micro-turbine/ EES/Thermal energy storage/Natural gas boiler	Evolutionary PSO	TAC	Investment, replacement, fuel, and operation and maintenance costs. Energy management system prioritizes the application	Time of use
[149]	PV/wind/ /PHS	Genetic algorithm	LPSP	Power balance and techno-economics	Time of use
[150]	PV/Wind/ PHSS	Whale optimization algorithm (WOA)	COE	Power balance and budget	Time of use
[151]	PV/wind/ BES	Crow and particle swarm as a hybrid	Reduction of energy production cost	Distribution of energy supply-demand planning	Time of use
[152]	PV/Wind/ Biogas/DG/BES	Hybrid PSO-GWO	COE and LPSP	Optimal configuration according to the cost	Time of use
[153]	Wind/PV /BES	Genetic algorithm-III (NSGA-III)	Total cost, end-user satisfaction loss, and tie-line power fluctuation	Power balance and budget	Time-of-use
[154]	PV/Wind/FC/BES	Proximal policy optimization (PPO)	Overall economic cost saving and carbon emission reduction	Power balance and techno-economics	Time of use
[155]	PV/Wind/ BES/DG	Multi-objective multi-verse optimization (MOMVO)	COE, RF, and LPSP	Required electrical load and the techno-economic feasibility	Time-of-use
[156]	Wind/PV/FC/ BES	WOA	COE, NPC, and LPSP	Produce an adequate electrical supply to the load demand with low cost	Time-of-use
[157]	PV/Bio-waste /FC	WOA	NPC) and LPSP	Electrical load, optimal configuration, and techno-economic feasibility	Not specified
[158]	WT/PV/Biomass/Pump-Hydro	WOA	COE and LPSP	Reliability and operational constraints	Time of use
[159]	PV/Wind/ BES/DG	NSGA-II	NPC, COE, and CO2 emissions	Power balance and techno-economics	Time of use

The researchers' approach to addressing the community's problems with a lack of electricity, as noted in the review articles in Table 2, is the key strength of each research project. Regarding its economic and environmental implications, references [147], [149], [150], [158], and [159] are significantly superior to the other articles provided. Diesel generators are not both economically and environmentally feasible in a hybrid system. BES is also totally uneconomically viable. Future research should include the aforementioned benefits and drawbacks and make sure to address them specifically in the green hybrid system configuration that will be employed on the system.

5. Application of the Integration of Energy Storage System in HRE Plants

The main disadvantage of using renewable energy is limited to the fact that it cannot deliver reliable electricity as a result of its intermittent nature [160]. Energy storage systems (ESSs) are the most effective way to store power during off-peak hours and supply energy during peak hours [161]. For the load to get an uninterrupted supply of power, storage technology is crucial and required [162]. Alternatives for energy storage in HRES include CAES, PHS, FWES, SC, SMES, and BES.

These devices are often employed in large-scale networks, which require significant capital. However, they can be used to ensure a consistent energy supply during worse HRES conditions [163]. One of the most widely utilized ESSs is the battery energy storage system (BESS) [164]. Consequently, combining HRES and BESS is a potential on- and off-grid solution, not just in India but internationally. MGs have become more popular in recent years as people have become more interested in using them in power distribution networks using small-scale HRES. Moreover, the microgrid idea has been regarded as a superior alternative for countryside electrification, and many hybrid MG designs for HRES have been given in the literature [165,166]. MGs are frequently recognized as the most dependable, consistent, economical, and environmentally friendly energy sources. An MG is a standalone electrical system that may provide electricity to a household or community. The abundance of HRES makes utilizing these sources as a remote area electrification option a strong prospect [167]. Hybrid configurations, particularly MGs or HRES, can combine energy conversion systems such as PV and wind turbines. These hybrid topologies will reduce generation, investment, and storage system size fluctuations and simultaneously boost system reliability and performance [168]. As a result, the ESSs offer backup energy when the HRES' output power fluctuates. The HRES's resilience is improved, and total expenses are reduced by the integration of the ESS [169]. Table 3 surmises the optimal sizing of HRES with ESS systems by using meta-heuristic optimization techniques. Furthermore, the HRES' reliability is ensured by its continuous power delivery to the load [166]. Using a diesel generator (DG) ensures uninterrupted power loading during HRES. Renewable energy-based MGs can run in island mode, reducing reliance on fossil fuels. It also provides significant economic and environmental benefits [169]. For this reason, localized HRES integrated with ESS is a better solution for satisfying the energy demands of load centers in a reliable way.

Table 3. Optimal sizing of HRES with ESS by using meta-heuristic optimization techniques.

Ref.	Decision Variable	Technique	Objective Function	Constraints	Electricity Tariff
[170]	Wind/PV/ BES	Firefly-inspired algorithm	COE	Energy of battery, number of components, and load dissatisfaction rate	Time of use
[171]	Biogas/PHES /PV/BES	Water cycle algorithm	NPC	LPSP, number of components, SOC, upper reservoir volume	Time of use
[172]	WT-PV-FC	Artificial bee swarm optimization	LCC and LPSP evaluation	Load interruption probability, number of components, energy at tank	Time of use
[173]	PV-BES	Mutation adaptive differential evolution	LCC, LOLP & LCOE	SOC	Time of use and stepwise real time pricing
[174]	PV/wind/BES	Multi-objective grey wolf algorithm	COE, LPSP, DE	SOC	Time of use
[175]	PV-WT-BES-PHS	Multi-objective grey wolf A.	COE, LPSP	Energy of battery and pump-hydro storage	Time of use

The researchers' approach to addressing the community's power problems with intermittent forms of electricity production like solar and wind, as noted in the review articles in Table 2, is the key strength of each research project. In terms of economic implications, BES outperforms the other ES system significantly. In addition, PHS, FC, and BES do not respond quickly when there is a peak load occurring in milliseconds, so researchers should include fast response ES systems like SMES and FWES on the intermittent HRES. Future research should include the aforementioned benefits and drawbacks and make sure to address them specifically in the green hybrid system configuration that will be employed on the system.

The technical and financial aspects of various energy storage systems used for renewable and hybrid energy alternatives are shown in Table 4. People often think that dispatchability, efficiency, durability, availability, quick response time, energy capital cost, and so on are the most important things for a storage system to have. In contrast to battery storage technology, which can only make 0 to 40 MW of energy available, the PHES can make 100 to 5000 MW of energy available. Compared to thermal and chemical energy storage methods, it is more efficient. The PHES's longer lifespan than any other storage system is one of its best qualities. When compared to other storage methods, PHES has a low capital cost for energy. According to Hino and Lejeune [176], PHES plants have quick start-up and shut-down times, quick load changes, the ability to handle frequency changes, and stable voltage. Nazari et al. [177] discuss that PHES systems are useful tools for making sure that there is always power. In general, PHES has a much lower LCOE than other ways to store energy. Based on these qualities, it's clear that the PHES system is better than all other storage systems. In [178], Zhang et al. proposed the Mo6+–P5+ co-doped Li2ZnTi3O8 anode for Li-storage in a wide temperature range and applications in LiNi0.5Mn1.5O4/Li2ZnTi3O8 full cells. In [179], Chen presented research on the use of digital twin technology for collaborative innovation of important common technologies in the new energy vehicle industry. Future low-carbon and zero-carbon fuels for marine engines were studied in [180] from the perspective of thermal efficiency. In [181], Liu et al. conducted a numerical analysis of the ammonia combustion and emission properties in a low-speed two-stroke marine engine. A thorough analysis of smart distribution network situation awareness for high-quality operation and maintenance was published by Ge et al. in [182]. Li et al. presented the digital economy's driving mechanism in [183] based on a regulation algorithm for the growth of low-carbon sectors. The improved algorithm of drift compensation for olfactory sensors was presented by Lu et al. in [184]. The semi-supervised extreme learning machine approach based on the new weighted kernel for machine scent was introduced by Dang et al. in [185]. The asymmetric encoder-decoder model for Zn-ion battery lifetime prediction was introduced by Lu et al. in [186].

Table 4. Economical and technical criteria for various energy storage technologies.

ES Technology	Capital Cost ($/kW)	Power Rating (MW)	Energy Density (Wh/kg)	Power Density (W/kg)	Life Cycle	Response Time	Life Span	Efficiency (%)	Ref.
Lead Acid Battery	300–600	0–40	24–45	180	1500–2000	5–10 ms	3–12	70–90	[187] [188]
SC	100–300	0.01–1	0.1–5	800–2000	100,000+	<5 ms	10–20	85–95	[189] [190]
FWES	110–330	0.01–10	10–30	400–1500	10,000–100,000	seconds	15–20	70–95	[191] [192]
FC	500–10,000	0.001–50	300–1200	500+	20,000+	min	5–20	20–50	[193] [194]
CAES	400–800	5–300	30–60	-	8000–12,000	min	20–40	70	[195] [196]
SMES	200–300	0.1–10	0.5–5	500–2000	100,000+	<5 ms	20–30	90–98	[197] [198]
PHS	600–4300	100–5000	0.5–1.5	-	10,000–30,000	min	30–60	65–85	[199] [200] [201]

6. Discussion and Recommendations

With increased electricity demands and the intermittent nature of single renewable energy sources, it is increasingly difficult to provide dependable power to linked loads. By minimizing maintenance expenses, which decrease the system's overall operating costs, an effective and long-lasting energy storage technology can address the issue of HRES's intermittent nature. Simultaneously, hybridization, in conjunction with energy storage technologies, can address the intermittent nature of HRES. Energy storage possibilities in HRES include the following options:

1. Compressed air energy storage (CAES)
2. Pumped hydro energy storage (PHS)
3. Hydrogen fuel cells (FC)
4. Flywheels
5. Super capacitors (SC)
6. Superconducting magnetic energy storage (SMES)
7. Battery banks (BB)

PHS units have different advantages over CAES, SC, SMES, FC, flywheels, and BB units, such as lower prices and less environmental impact.

PHS is the most effective way to store media among several options. It has several advantages over traditional energy storage systems, including fast response time, quick starting and stopping, ease of handling load changes, high-efficiency power supply at a base load power plant, and decreased discharge losses. In both experimental and computational studies, PHS has been used as a bulk energy medium for HRES by a number of researchers. Numerous studies have established the efficacy of PHS in various configurations. It is considered to be one of the most reliable and technologically possible off-grid as well as grid-connected HRES power sources for use in any electricity demand sector.

The solar-wind-PHS combo is considered a reflection of enormous solar and wind potential due to increasing installed capacity and peak demand and supply. The COE, LPSP, environmental impact, and payback period may all be decreased using the integrated system. Researchers have also found that combining a solar-biogas system with a PHS system provides advantages such as lower investment costs, improved operating performance, and smooth power generation. Furthermore, hybrid systems that are connected to the grid have the best COE in the majority of circumstances. The reasons can be summed up in the lower cost of kWh gained from the grid compared to the initial expenditures obtained from renewable energy sources. However, acceptable rate reductions in the initial prices of renewable energy have been observed in recent years.

PHS is now combined with PV-wind-biogas-based HRES for a continuous and stable power supply, with an internal combustion engine acting as a backup energy source. Hybrid-PHS configurations were also researched by several researchers.

The integrated system offers improved round-trip efficiency, enhanced power supply dependability, decreased revenue losses, cost savings, a low investment cost, maximum accessible energy, a greater life span, and fewer greenhouse gas emissions when compared to a battery and other storage systems. Prior studies have revealed that PHS and freshwater resources appear to be among the most practical HRES storage solutions.

The following suggestions have been provided to overcome the above challenges to optimal sizing of HRES adoption with ESS integration:

- The current state of HRES technology, interconnected with ESS, can address many of the issues that the prior technology had, such as reliability, efficiency, and capacity. The scope of this technology's ongoing development for future use in MG technology has been determined. Energy sizing, costing, safety, and effective management are increasingly the focus of research.
- For HRES and ESS system components to be sized optimally, intelligent techniques (meta-heuristic approaches) must be combined with the proper control settings, or more effective methods must be developed. It may be said that the hybrid GWO-PSO and WOA optimization strategies are the best for achieving the aim of an HRES combined with ESS that is dependable, economical, and environmentally benign.
- The components of renewable energy and the life cycle of storage devices are determined by the materials utilized. Capacity, energy and power density, life cycle, corrosiveness, and charging and discharging properties may all be significantly influenced by the materials. With better energy efficiency, reliability, and stability, a cost-effective long-term advanced technology can lead to the material selection of HRES and ESS in MG applications.

- To combine HRES with ESS and the current electrical power network, the power electronic interface (PEI) can be employed. Because it possesses the requisite organization for power conversion, PEI has a variety of features. Size, ripples, expense, flexibility, and efficiency are all shortcomings of the current PEI system.
- Sharing the power allows for the optimal distribution of power in the HRES with the ESS structure. PHS, FC, CAES, and Li-ion batteries are just a few of the ESS that can be modeled for large-scale integration. Thermal energy storage systems, SMESs, flywheels, and flow batteries all perform well for medium-scale energy management. A quality management system could be utilized to boost the overall efficiency and cost of present ESS management for HRES applications that have consistent and reliable quality.
- Different ESS technologies are quite large and expensive in terms of size and cost. An ESS that is too large is not appropriate. Installation and maintenance costs are included in the price. It also significantly contributes to storage permanence. Their integration can boost the storage system's capacity. Implementing a comprehensive energy storage policy would be a big issue for both renewable and conventional networks.
- In order to improve system stability and dependability and simultaneously lower power quality concerns, HRES requires an ESS that combines the traits of a high-power and a high-energy storage system. High-energy devices have a slower reaction with a longer duration, but high-power ESS devices benefit from rapid responses at high rates for a short period of time. The advantages of achieving excellent power quality with linked loads may be realized by combining these two kinds of ESSs.
- A predetermined operating policy should be implemented to assess the site's long-term viability. Many restrictions can be overcome with technological advancement. Transmission losses can be reduced by choosing the right PHS site. Additionally, PHS's integration with solar farms that are almost entirely self-sufficient will reduce transmission costs between the two businesses. In order to boost the new PHS's societal acceptance, it is important to spread awareness about the project's efficiency and viability as a source of power. Furthermore, community communication and consultation can help increase public interest. The success narratives of successfully completed projects must be shared with the public in order to raise awareness and recognition.
- The emission of greenhouse gases and other hazardous emissions decreases as the amount of energy supplied by renewable sources grows. Hybrid ESS can incorporate intermittent HRES into the power system, lowering fuel usage and hazardous emissions. Despite the fact that 100% renewable energy production is expensive, experts are working to lower installation and maintenance costs.

7. Conclusions

In this work, the state of the art for HRES system optimum sizing was investigated. The current research on the subject was divided into categories using HRES, optimization methods or software optimization, and single- or multi-objective problems. The most recent advancements in HRES integration with ESS system optimal sizing, as well as current issues, were reviewed. Future views were offered to scholars as a way of highlighting new research topics. The following are some of the main results of this review paper.

Based on many research findings, FITs for loads in grid-connected HRES should be implemented by sending surplus energy to the grid system. This increases the proportion of HRES that uses renewable energy resources. Consumers can therefore sell their excess energy to the grid through the FIT, which lowers electricity costs and generates revenue for the community.

To optimize the size of components based on economic, reliable, and emission functions, new meta-heuristic optimization approaches and software tools are needed.

Meta-heuristic optimization techniques are more efficient for sizing HRES. However, current software tools, such as the HOMER software family, are unable to address multi-objective issues. Additionally, demand-side management response systems are difficult to deploy with this software. As a result, software could be deployed, offering designers the flexibility to size HRES systems more efficiently.

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Abbreviations

AC_k	Annual Cost of Components
AP	Annualized Payment of HRES
CAES	Compressed Air Energy Storage
C_f	Fuel Price
COE	Cost Of Energy
C_r	Cost of Fuel
D_b	Battery Capacity Degradation From Charging/Discharging Cycles
DG	Deiseal Generator
D_P	Unmet Load Duration
$E_{b,ch}$	Total Energy Output from Charged Battery
$E_{b,dis}$	Total Energy Output of Discharged Battery
E_d	Total Dumped Energy
EENS	Expected Energy Not Supplied
E_f	Diesel Generator Energy Output
E_p	Overall Energy Demand
E_{re}	Total Output From Renewable Energy Sources
ESS	Energy Storage System
f	Fuel Utilization
F_S	Probability Of Meeting States
HOMER	Hybrid Optimization Model for Electric Renewable
HRES	Hybrid Renewable Energy Sources
IRR	Internal Rate Of Return
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
LOLE	Loss of Load Expectation
LOEE	Loss of Energy Expectation
L_P	Average Yearly Load
LPSP	Loss of Power Supply Probability
MG	Micro-Grid
M_Y	Net Cash Flow For The Year
N	Project's Lifespan
N_i	Number Of Customers for Site
NPC	Total Net Present Cost
NPC_f	Fuel Usage
NPC_k	Grid Integrated or Remote System Components
NPV	Net Present Value
PC_C	Capital Costs Present Value
PC_m	Maintenance Costs Present Value
PC_r	Replacement Costs Present Value
PC_s	Salvation Costs Present Value
P_f	Power Generated by the Diesel Generator
PHS	Pumped Hydro Storage
PV	Photo Voltaic
R	Discount Rate
S	All Loss of Energy States
SAIDI	System Average Interruption Length Index
SAIFI	System Average Interruption Frequency Index
SMES	Superconducting Magnetic Energy Storage
SPP	Simple Payback Period
T	Project Time Duration
TAC	Total Annualized Cost
T_S	Loss of Load Duration
U_i	Duration Of Power Outage
$\alpha\beta\gamma$	Approximate Emission Coefficients
λ_i	Rate of Power Interruption

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