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Review

A Review of Hybrid Renewable Energy Systems: Architectures, Battery Systems, and Optimization Techniques

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Abstract: This paper aims to perform a literature review and statistical analysis based on data extracted from 38 articles published between 2018 and 2023 that address hybrid renewable energy systems. The main objective of this review has been to create a bibliographic database that organizes the content of the articles in different categories, such as system architecture, energy storage systems, auxiliary generation components used, and software employed, in addition to showing the algorithms and economic and reliability criteria for the optimization of these systems. In total, 38 articles have been analyzed, compared, and classified to provide an overview of the current status of simulation and optimization projects for hybrid renewable energy systems, highlighting clearly and appropriately the relevant trends and conclusions. A list of review articles has also been provided, which cover the aspects required for understanding HRESs.

Keywords: hybrid renewable energy systems; battery energy storage system; optimization techniques; optimization algorithms

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1. Introduction

Renewable energies are those sources of energy that can be obtained naturally without depleting the planet's resources. These sources include solar, wind, hydro, geothermal, biomass, and biofuels. Unlike non-renewable energies, such as oil, gas, and coal, which are finite and emit large amounts of greenhouse gases, renewable energies are cleaner and more sustainable. Additionally, the technologies to capture and utilize these energies have improved in recent years, making their use increasingly viable and economical. Renewable energies are a key solution to combating climate change and reducing dependence on fossil fuels [1]. By investing in these energy sources, jobs can be created and sustainable economic development can be promoted. In summary, renewable energies are a key alternative to ensure a cleaner and safer future for future generations.

Hybrid renewable energy systems are those that combine two or more renewable energy sources to generate electricity. These systems are especially useful in places where there is no access to the conventional electrical grid, or where the connection is limited or unstable [2]. An example of a hybrid system combines solar and wind energies. During the day, when the sun shines, solar panels generate electricity that is stored in batteries for later use. At night, when there is no sun, wind energy conversion systems (WECS) harness the wind to generate additional electricity and charge the batteries [3]. Another example of a hybrid system combines solar and hydro energies. During the day, solar panels generate electricity that is used to pump water from a river or lake to a dam. At night, when there is no sun, the water stored in the dam is released through a hydro turbine to generate additional electricity [4].

Hybrid renewable energy systems can be more efficient and reliable than systems that use a single energy source [5]. Additionally, they allow for a better use of available resources and reduce the cost of generated energy. For these reasons, hybrid systems are becoming increasingly popular worldwide, especially in rural or remote areas [6].

The studies conducted on HRESs mostly address the methods to use the different structures for power distribution. To date, there are three variants, which are used depending on the application chosen by the system designer. These configurations are DC microgrid, AC microgrid, and AC/DC microgrid. A DC microgrid is a power system that uses direct current for power distribution instead of alternating current. It is composed of various renewable energy sources, energy storage systems, and DC loads. The use of DC for power distribution has several advantages, such as the elimination of AC–DC–AC conversions required in AC microgrids, which improves efficiency and reduces energy losses. In addition, eliminating the need for a distributed generator (DG) synchronization also simplifies system designs and reduces costs. DC microgrids can also integrate energy storage systems to improve efficiency and energy independence [7].

In an AC microgrid, an AC-to-DC converter is used to power the DC loads. Other renewable energy sources can also be incorporated through the appropriate interface of power converters. Each power source is connected to the AC bus through a separate power converter, allowing them to continue to operate even if one of them is disconnected, improving system reliability. However, synchronization is a major obstacle in this configuration [3].

The AC/DC microgrid combines the advantages of AC and DC microgrids to facilitate the integration of AC and DC loads with their corresponding sources. It can be used in two modes, off-grid or grid-connected, and is suitable for use in smart grids alongside the current grid. In addition, voltage transformation, economic viability, and harmonic control are other advantages of this configuration. Although it has some major benefits, in terms of overall performance, the hybrid AC/DC microgrid is a good option to address operational problems and challenges as it outperforms other types of microgrids [7].

Battery energy storage systems (BESSs) are a crucial part of the system for good optimization, as they allow electrical energy to be stored for later use when needed. This makes them especially useful for the integration of renewable energy sources, such as solar and wind power, into the power grid. In this way, the BESSs can balance the variability of renewable energy generation and provide power when demand is high or when power generation is low [8]. Battery energy storage systems (BESSs) have several advantages over other forms of energy storage. First, they are highly efficient and can store large amounts of energy. Second, they are flexible and can be used in a variety of applications, including backup power systems and energy management systems. Third, they are capable of providing grid services, such as frequency control and voltage control, making them valuable for grid stability. In addition, BESSs have a longer lifetime than other forms of energy storage and are less prone to failure. Overall, BESSs are an important part of the transition to a more sustainable and secure energy system [5].

Optimization techniques are fundamental to achieve an efficient and reliable energy management and storage system. These techniques consist of designing appropriate strategies to balance power generation and load demand, even when uncertain renewable sources are used. This is achieved through the use of control algorithms that can predict the availability of renewable energy and adjust the load accordingly. In addition, these techniques can also help optimize the use of energy storage systems, such as BESSs, to ensure that energy is stored and released effectively and efficiently. Overall, choosing the right optimization technique is crucial to maximize energy efficiency and system stability [9]. The modeling and optimization approaches used for HRESs can be classified into intelligent methods, iterative methods, and computational methods [5].

To achieve an optimal HRESs design, economic and technical criteria are considered. The economic criteria seek to minimize the costs associated with HRESs implementation, including energy cost and net present cost, while the technical criteria focus on the reliability, efficiency, and environmental benefits of HRESs. Overall, the goal is to find a compromise solution between the costs and benefits of HRESs [3].

This article was created to facilitate the understanding of the topic for beginners and provide classified and broken-down information. The difference between this summary compared to others found in the literature is that it refers to each characteristic of the systems used in each case study. This allows for a more detailed search and facilitates the location of articles according to the desired characteristics for the design of a hybrid renewable energy system (HRESs).

2. Methodology

The objective of this article is to understand the composition of HRESs systems, identify each part of the system, and explore all existing possibilities to design them most cost-effectively. The article provides a summary of how they are composed, the elements that can be used in their composition, and the techniques used to optimize and size these systems. To carry out this task, a search was conducted for articles published between 2018 and 2023 in various databases and search engines, such as IEEExplore, ScienceDirect, and others. A total of 38 articles related to optimization and sizing through various techniques and 33 review articles related to these hybrid systems were analyzed and classified. The article selection process is shown in Figure 1, where the steps followed for the selection of the 62 articles are explained. In the initial steps, the keywords "Hybrid Renewable Energy Systems," "HRESs Optimization," and "HRESs Sizing" were selected.

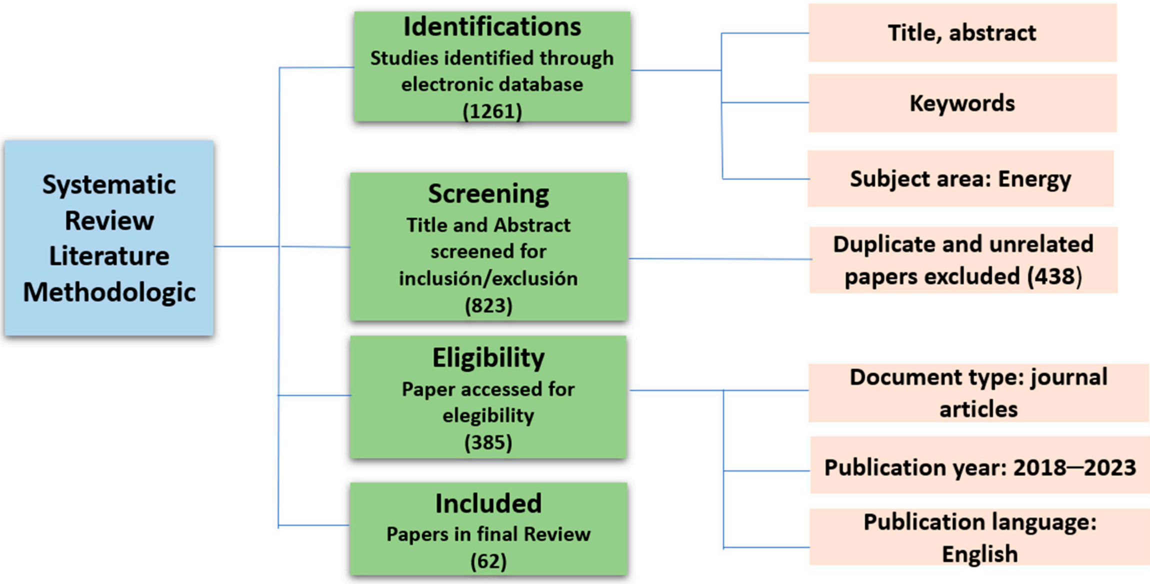

Figure 1. Eligibility criteria.

Figure 1 shows the methodology used for the systematic review of the literature. In its structure, four stages were used (identifications, screening, eligibility, and included) each with its own selection or search criteria. As can be seen in the figure, the search was initially started by titles and keywords ("Hybrid Renewable Energy Systems," "HRESs Optimization," and "HRESs Sizing"). The result was 1261 articles related to renewable energy systems. Then, in the screening, 438 papers were detected that were repeated or had no relation. For eligibility, the criteria of the type of document, the years of publication, and the English language were established, where 323 were discarded, and finally included, and a final result of 62 articles was obtained.

Tables 1 and 2 show some of the publications found, displaying the years, references, locations, and applications used in the case studies. The abstracts describe the nature and objectives of each article and present the conclusions reached. Figures 2 and 3 show the distribution by country and the proportion of applications used in the reviewed articles.

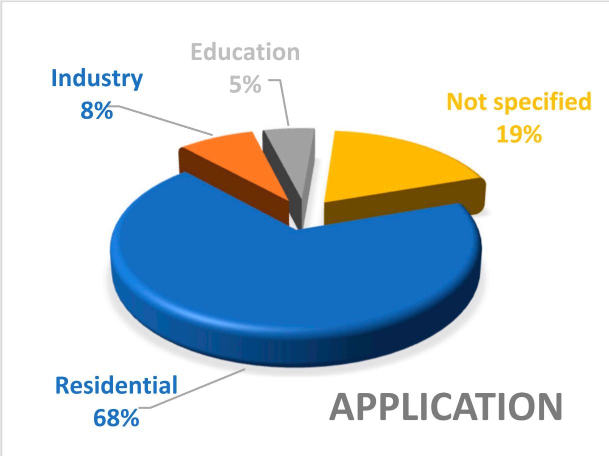

Figure 2. Applications in which HRESs are most frequently used.

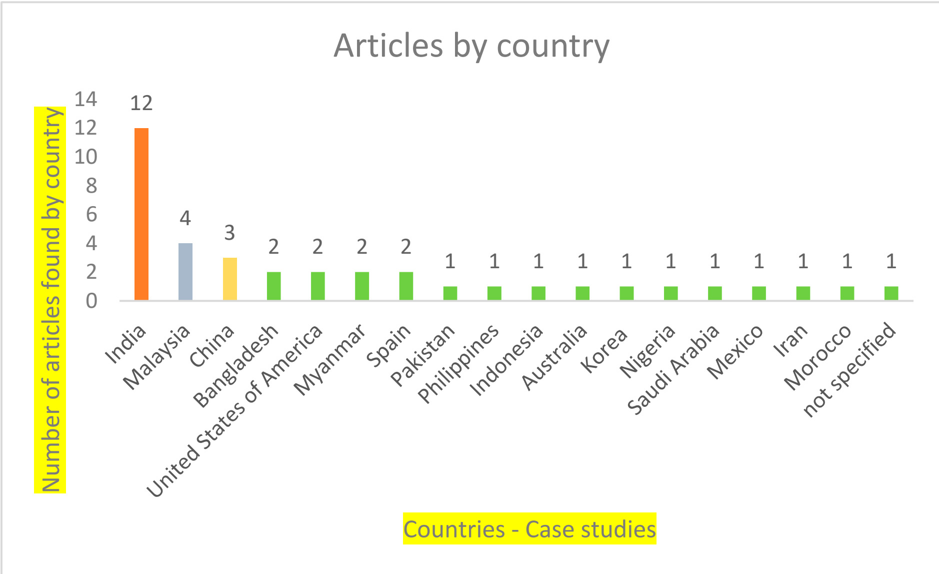

Figure 3. Origin of the articles found.

As can be seen in Figure 2, the trends in the uses and applications given to these systems are shown. Due to the great problem of delivering electricity to remote and difficult-to-access places, these systems are ideal for this type of use. The figure shows a better perception of how residential use is the highest type of energy use, according to 68% of the articles found, followed by industrial and educational applications.

Figure 3 shows the countries with the largest number of articles found in the review. However, this information is not necessarily representative on a larger scale. India was found to be the country with the largest number of articles on this topic. India is one of the most populated countries in the world and one of the largest consumers of energy. In addition, it has excellent climatic conditions for the use of renewable energy, with about 630,000 villages, some of which are poorly served by electricity, while others have no access to electricity [10].

Table 1 presents the review articles, together with the renewable energy sources used by the authors. The most used types of renewable energies can be observed, as well as the applications for which they were designed and the capacity of the systems used. In the scope of this review, it is observed that the most used energy sources were the combination of photovoltaic, wind turbines, battery systems, and diesel generators. As can be seen, these systems can reach large generating capacities, although most of them, being for residential use, are in the 100 kW range.

Table 1. Cases of studies found in the literature.

Ref	Title	Year	Energy Sources	Application	System Sizing
[11]	Use of a Hybrid Wind–Solar–Diesel–Battery Energy System to Power Buildings in Remote Areas: A Case Study.	2021	PV-WECS-BESS-DG	Rural residential area	32 kW for 20 households
[12]	Performance Analysis of Solar–Wind–Diesel–Battery Hybrid Energy System for KLIA Sepang Station of Malaysia.	2015	PV-WECS-BESS-DG	Not specified	56 kW installed for more than 50 homes and 6 stores
[13]	A Comparative Study of the Optimal Sizing and Management of Off-Grid Solar/Wind/Diesel and Battery Energy Systems for Remote Areas.	2021	PV-WECS-BESS-DG	Rural residential area	44.1 kW installed for 10 homes
[14]	Solar/Wind/Diesel Hybrid Energy System with Battery Storage for Rural Electrification.	2014	PV-WECS-BESS-DG	Rural residential area	40 kW installed for 150 households
[6]	Designing and Sensitivity Analysis of an Off-Grid Hybrid Wind–Solar Power Plant with Diesel Generator and Battery Backup for the Rural Area in Iran.	2022	PV-WECS-BESS-DG	Rural residential area	13 kW installed, number of households not specified
[15]	Research on Capacity Optimization of PV–Wind Diesel–Battery Hybrid Generation System.	2018	PV-WECS-BESS-DG	Not specified	38 kW installed, number of households not specified
[16]	Optimal Sizing and Performance Investigation of a Solar–Wind–Battery–DG-Based Hybrid Microgrid System Applicable to the Remote School of Bangladesh.	2020	PV-WECS-BESS-DG	Student buildings	4.6 kW installed for a rural school
[17]	Simulation and Optimization of Solar Photovoltaic–Wind–Diesel Generator Stand-alone Hybrid System in Remote Village of Rajasthan, India.	2020	A comparison is made between different energy sources	Rural residential area	Between 50 and 60 kW installed, for 41 homes
[18]	Design and Simulation of an Optimal Mini-Grid Solar–Diesel Hybrid Power Generation System in a Remote Bangladesh.	2018	PV-WECS-BESS-DG	Rural residential area	2574 kW installed, number of homes not specified
[19]	Techno-Economic Environmental Assessment of Hybrid Renewable Energy System in India.	2021	PV-WECS-BESS-DG	Student buildings	4 MW installed for 3 student buildings
[20]	Techno-Economic Evaluation of Off-grid Hybrid Photovoltaic–Diesel–Battery Power Systems for Rural Electrification in Saudi Arabia—A Way Forward for Sustainable Development.	2021	PV-BESS-AG	Rural residential area	7 MW installed, number of homes not specified
[21]	Optimal Configuration of Wind/Solar/Diesel/Battery Hybrid Energy System for Electrification of Rural Area.	2015	PV-WECS-BESS-DG	Rural residential area	From 250 to 280 kW installed, number of homes not specified
[22]	Cost-Effective Sizing of an AC Mini-Grid Hybrid Power System for a Remote Area in South Australia.	2018	PV-WECS-BESS-DG	Rural residential area	From 0.6 MW–1.15 MW installed, depending on the case study

Table 1. *Cont.*

Ref	Title	Year	Energy Sources	Application	System Sizing
[1]	Developed Approach Based on Equilibrium Optimizer for Optimal Design of Hybrid PV/Wind/Diesel/Battery Microgrid in Dakhla, Morocco.	2021	PV-WECS-BESS-DG	Industry	86.77 kW installed
[23]	Assessment of Hybrid Renewable Energy Systems to Supplied Energy to Autonomous Desalination Systems in Two Islands of the Canary Archipelago.	2019	PV-WECS-BESS-DG	Industry	50 kW installed in a desalination plant
[24]	A Flexible Metamodel Architecture for Optimal Design of Hybrid Renewable Energy Systems (HRESs) E-Case Study of a Stand-Alone HRESs for a Factory in Tropical Island.	2019	PV-WECS-BESS-DG	Industry	467 kW installed in a manufacturing plant
[25]	Challenges of Reaching High Renewable Fractions in Hybrid Renewable Energy Systems.	2023	PV-WECS-BESS-DG	Not specified	17 kW installed in some regions of the USA
[26]	Comparison of Different Hybrid Renewable Energy Systems with Optimized PV Configuration to Realize the Effects of Multiple Scheme.	2019	PV-BESS	Not specified	1.3 MW installed
			PV-BESS-DG		1.25 MW installed
[27]	The Impact of Energy Dispatch Strategy on Design Optimization of Hybrid Renewable Energy Systems.	2019	PV-WECS-BESS-DG	Rural residential area	7 MW installed, number of homes not specified
[28]	Modelling and Optimization of an Off-Grid Hybrid Renewable Energy System for Electrification in a Rural Area.	2020	PV-WECS-BESS-BG-BM-PEMFC	Rural residential area	317 kW installed
			PV-WECS-BG-BM- PEMFC		317 kW installed
			PV-WECS-BG-BM-BESS		260 kW installed
			PV-WECS-BG-BM		260 kW installed
[29]	Optimal Sizing of Smart Hybrid Renewable Energy System Using Different Optimization Algorithms.	2022	–	Rural residential area	23 kW installed for 140 households
[30]	Designing of an Optimal Standalone Hybrid Renewable Energy Micro-Grid Model through Different Algorithms.	2023	PV-WECS-BESS	Rural residential area	11 kW installed
[31]	Sizing and Economic Analysis of Standalone Hybrid Photovoltaic–Wind System for Rural Electrification: A Case Study Lundu, Sarawak.	2022	PV-WECS-BESS	Rural residential area	150 kW installed
[32]	HOMER-Based Optimal Sizing of a PV/Diesel/Battery Hybrid System for a Laboratory Facility.	2021	PV-WECS-BESS-DG	Rural residential area	53.8 kW installed
[33]	Techno-Economic Scrutiny of HRESs through GA and PSO Techniques.	2018	PV-WECS-BESS-DG-BM	Rural residential area	150 kW installed
[34]	Modelado y Simulación de un Sistema Conjunto de Energía Solar y Eólica para Analizar su Dependencia de la Red Eléctrica.	2012	PV-WECS-BESS-DG	Rural residential area	9.6 kW installed

Table 1. *Cont.*

Ref	Title	Year	Energy Sources	Application	System Sizing
[35]	Optimal Management Energy System and Control Strategies for Isolated Hybrid Solar–Wind–Battery–Diesel Power System.	2021	PV-WECS-BESS-DG	Not specified	40 kW installed
[36]	Optimal Structure Design of a PV/FC HRES Using Amended Water Strider Algorithm.	2021	PV-PEMFC	Rural residential area	24.35 kW installed

PV—photovoltaic, WECS—wind turbine, BESS—battery energy storage systems, DG—diesel generator, BM—biomass, BG—biogas, PEMFC—fuel cell.

Table 2. Summaries found in the literature.

Ref.	Article Title	Year	Abstract	Conclusions
[37]	A literature review and statistical analysis of photovoltaic–wind hybrid renewable system research by considering the most relevant 550 articles: an upgradable matrix literature database.	2021	A statistical analysis was carried out to identify the most relevant criteria in the optimization of hybrid systems, as well as the tools used for their development.	The countries with the greatest implementation of hybrid systems, the optimum climate for their performance, the most used auxiliary sources, the most frequent software, as well as the energy and economic criteria that influence their use were identified.
[7]	Optimal operation of hybrid AC/DC microgrids under uncertainty of renewable energy resources: a comprehensive review.	2019	An updated review on the optimal multi-objective design of hybrid energy systems was offered, providing relevant and updated information on this topic.	The objective functions, optimization algorithms, and design constraints used in previous research on the subject were reviewed.
[38]	Hybrid renewable energy sources (HRESs): a review.	2017	This article synthesized the use of hybrid renewable energy sources (HRESs) and the related studies on optimization techniques.	The use of different algorithms in optimization problems can lead to more efficient results.
[39]	Sizing, optimization, control, and energy management of hybrid renewable energy systems—a review.	2021	This review focused on the four fundamental categories of the hybrid renewable energy system: sizing, optimization, control, and energy management.	A hybrid renewable energy system (HRES) can be self-sufficient to power a specific load, and optimization was carried out by using artificial methods and commercial programs. In these systems, the most commonly used control method was MPPT.
[3]	Recent advances of wind–solar hybrid renewable energy systems for power generation: a review.	2021	A comprehensive review of wind–solar hybrid renewable energy systems was conducted, focusing on power architectures, mathematical models, power electronic converter topologies, and algorithms used for design optimization.	This study analyzed the system modeling, the different power converter configurations, and the algorithms used for optimal system design.
[40]	Hybrid renewable energy systems' optimization. A review and extended comparison of the most-used software tools.	2021	Several modeling techniques and computer simulation tools were developed.	This study provided insights into the renewable energy sources that are considered as primary by each software and the relevant dispatch strategy adopted.

Table 2. *Cont.*

Ref.	Article Title	Year	Abstract	Conclusions
[2]	A review on unit sizing, optimization and energy management of HRESs.	2018	This study focused on modeling hybrid energy resources, standby power systems, power conditioning units, and energy flow management techniques in detail.	Different design techniques for hybrid renewable energy systems were reviewed and classified according to the availability of meteorological data. In addition, advances in hybrid energy resource modeling research were discussed.
[41]	Hybrid renewable energy system for real-time power management techniques—a review.	2020	In the context of the hybrid power system, management techniques were used to ensure system reliability and stability.	This analysis provided an extensive compilation of the literature on hybrid renewable energy systems (HRESs), including various optimization techniques.
[42]	Hybrid energy storage review for renewable energy system technologies and applications.	2021	In this study, a comprehensive review was conducted on the different types of energy storage technologies (ESS), their structures, classifications, and advantages and disadvantages in microgrid applications.	This paper reviewed various energy storage system (ESS) strategies and how to use them to improve grid stability and continuity.
[10]	Techno-economic feasibility analysis of off-grid electrification for remote areas: a review.	2020	This paper provided a detailed analysis of the fundamental reasons and advantages driving the adoption of hybrid renewable energy sources (HRESs).	The study reviewed various aspects of hybrid renewable energy systems, including optimization, control, energy storage, reliability, economic and environmental assessment, demand-side management, uncertainty assessment, and others. Different types of consumers and system configurations were also considered.
[43]	Review on the state-of-the-art multi-objective optimization of hybrid standalone/grid-connected energy systems.	2020	The study reviewed the optimal state-of-the-art design of stand-alone or grid-connected hybrid energy systems.	Multi-objective optimization in hybrid energy systems was reviewed, including the objective functions used, optimization algorithms, and design constraints. The methods used to solve multi-objective optimization problems were also reviewed.
[5]	Review of HRESs based on storage options, system architecture, and optimization criteria and methodologies.	2017	The tools and limitations for optimizing HRES systems were reviewed and the types of storage and backup systems available were analyzed.	The literature review highlighted that reducing system costs is important in terms of economic constraints, while loss of power supply probability (LPSP) is a major challenge in terms of reliability constraints in HRES design.
[4]	A current and future state-of-the-art development of hybrid energy systems using wind and PV–solar: a review.	2008	The paper reviewed the design, operation, and control requirements of standalone wind–solar PV hybrid power systems with conventional backup.	The review showed that these renewable systems are not yet cost-competitive with conventional fossil fuel-based systems.

Table 2. *Cont.*

Ref.	Article Title	Year	Abstract	Conclusions
[44]	A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries.	2021	It analyzed the levelized cost of energy (LCOE) of different mini-grids and addressed the obstacles that may hinder their implementation.	It was noted that, although renewables are currently not cost-competitive with conventional fossil fuel-based systems, the costs of mini-grids will continue to decline and renewables will become more competitive on a commercial scale.
[9]	Review of optimization techniques for hybrid wind PV–ESS system.	2020	In this study, the minimization of power losses and energy fluctuations through the use of energy storage systems (ESSs) and optimization techniques was analyzed.	It was found that, with the installation of ESSs, power flow through the lines was reduced and grid congestion was alleviated. Deterministic planning was also used to achieve these objectives.
[45]	A comprehensive review of the integration of battery energy storage systems into distribution networks.	2020	It aimed to provide an overview of the integration of energy storage systems (BESSs) into distribution networks. The study highlighted points of interest, challenges, and limitations in the research of each of these aspects.	The article showed that energy storage systems have the potential to strengthen and improve the power grid in several ways.
[46]	A comprehensive state-of-the-art survey on hybrid renewable energy system operations and planning.	2020	This study focused on the specific motivations and benefits of adopting renewable energy systems.	It showed that most of the available studies on high-efficiency solar thermal energy focus only on its technical economic and environmental feasibility. In addition, economic and technical aspects were the most prominent criteria used for the selection and ranking of optimal HRESs.
[47]	A review on recent sizing methodologies of hybrid renewable energy systems.	2019	This article mainly reviewed the recent classification, evaluation indicators, and sizing methodologies of hybrid renewable energy systems.	The results showed that more than 80% of these systems were autonomous, and that large-scale grid-connected hybrid systems can be developed in combination with existing hydropower plants and pumped hydro-storage systems to ensure better power quality and meet electricity supply needs.
[8]	A survey of battery energy storge system (BESS), applications and environmental impacts in power systems.	2017	This article discussed the structure of energy storage systems (BESSs), their large-scale applications in the power grid and the benefits of their implementation in power systems.	It emphasized that BESSs allow for increasing the integration of renewable energy sources into the power system, but this requires optimizing the capacity and location of the BESSs according to the specific application.
[48]	Study of the different structures of hybrid systems in renewable energies: a review.	2019	The structure and operation of ESSs and their integration into the power grid were described. The advantages of their use, such as demand management, power quality improvement, and CO_2 emissions reduction, were also discussed.	The paper focused on the optimization of BESSs for use in generation distribution and smart grid applications, and highlighted the need to consider economic, technical, and environmental factors in their design and operation.

ESS—energy storage systems.

The objective of Table 2 is to present a list of reviews that fully cover all aspects to be considered for the design of these systems. Summaries can be found on battery systems, the different optimization algorithms, and connection configurations. In addition, the topics addressed and the results obtained are summarized.

3. Renewable Energy Hybrid Systems

Hybrid renewable energy systems are composed of several elements, which form a system capable of being autonomous. To achieve greater reliability and profitability, it is necessary to know the functions of each of its elements, as well as to know the different configurations necessary to make them more efficient. For this reason, the following is a review of each element of the system.

3.1. Composition of HRESs

The composition of the HRESs indicates the way in which the elements of the system will be distributed with the objective of reducing the conversion stages to reduce losses and the complexity of the control system. This is achieved without compromising the reliability and cost-effectiveness of the system.

Figures 4–7 illustrate the configurations used for these systems.

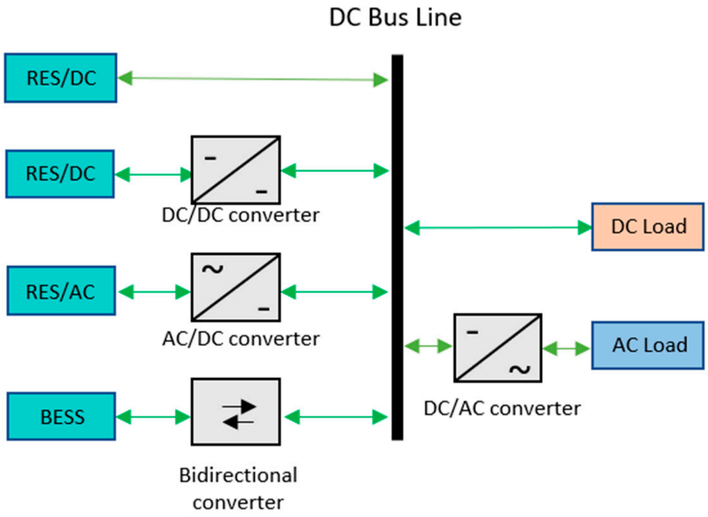

Figure 4. DC bus line configuration.

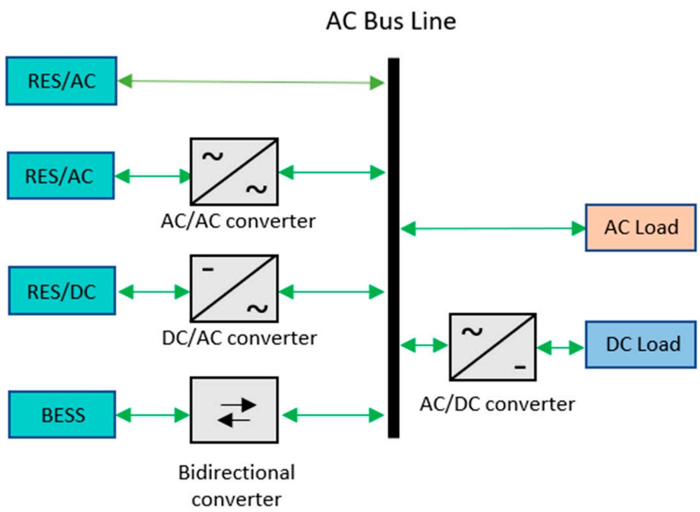

Figure 5. AC bus line configuration.

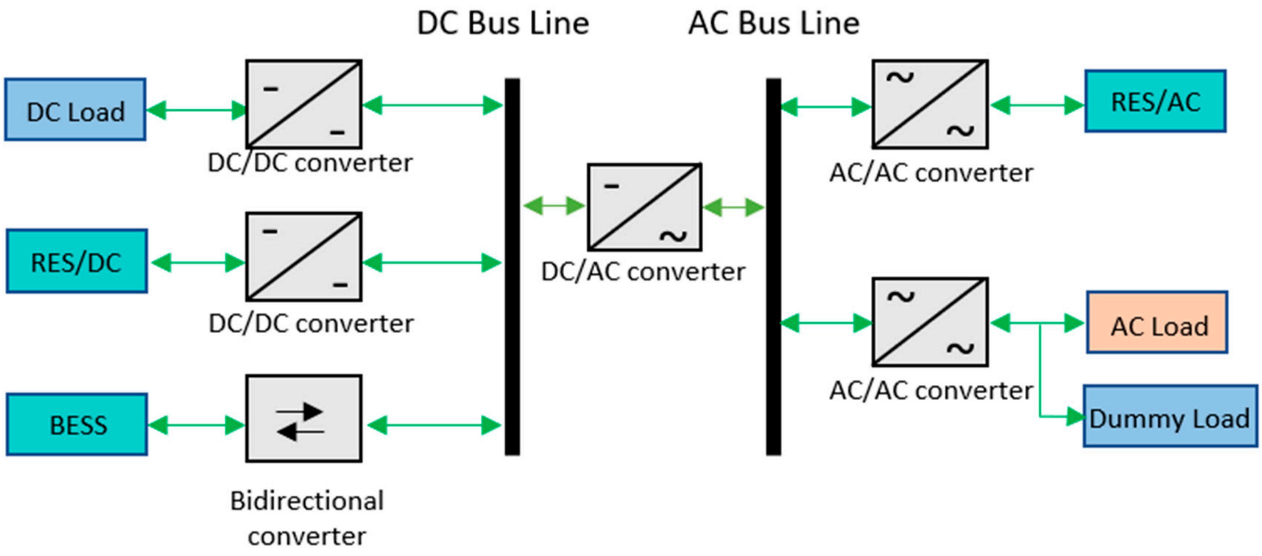

Figure 6. Isolated hybrid network.

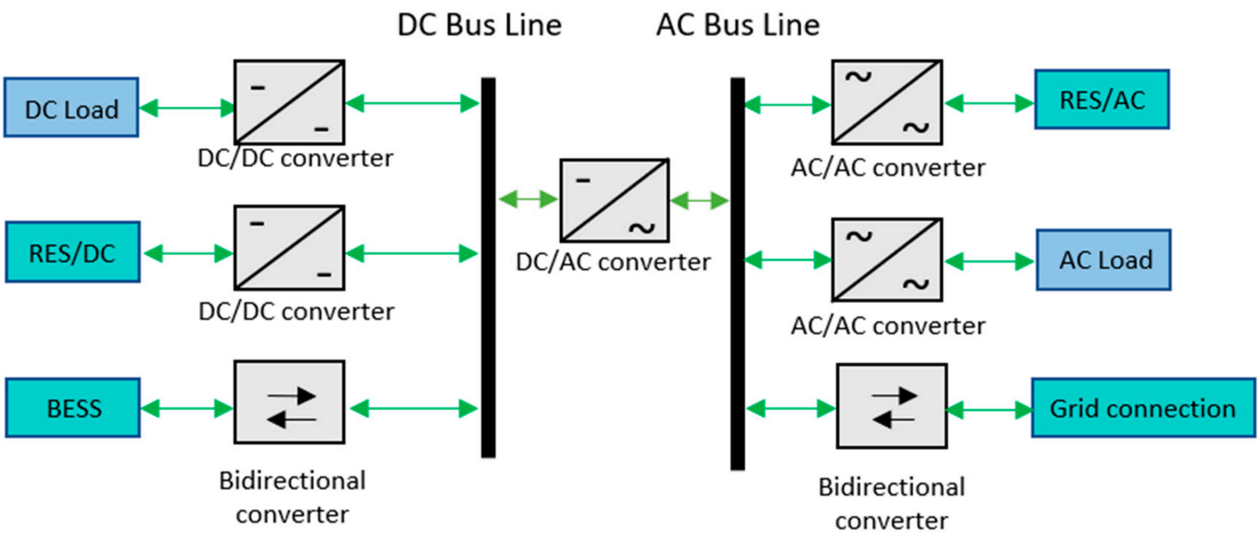

Figure 7. Connected hybrid network.

Table 3 shows the minimum and maximum number of converters that can be used for each topology, their advantages and disadvantages, and the articles that used each of them.

The review indicates that the most commonly used installation mode is an off-grid system, suggesting that most are designed to be installed in locations without access to an electrical grid.

- Thirty-six studies (94.73%) presented a system isolated from the network.
- Two studies (5.27%) presented systems connected to the network.
- Thirty-one studies (81.58%) presented an isolated two-bus system (AC–DC).
- Four studies (10.52%) presented an isolated single DC bus system.
- Three studies (7.89%) did not specify which systems they used.

Figure 8 shows the energy sources most commonly used in HRES systems in the search conducted.

Table 3. Summary of systems composition [3,5,7].

Configuration Type	Articles Related	Converters		Advantages	Disadvantages
		Min	Max		
Isolated DC Line	[15,27,31,49]	2	4	It is simple and not very complex	If the bus were to fail, the system would collapse
Isolated AC Line	Not found	2	4	This type of application is more appropriate for small-scale AC loads in real-life situations	The frequency of the AC bus needs to be synchronized with all AC components
Isolated Hybrid Network	[1,6,11–16,18–25,27,28,30,31,33,34,36,49–55]	2	6	Provides greater efficiency and reliability to the system	The complexity increases in the control and management of the system
Connected Hybrid Network	[56,57]	3	7	This configuration is more appropriate in semi-urban areas with network accessibility	When it comes to connecting to the grid, power quality management is a major concern

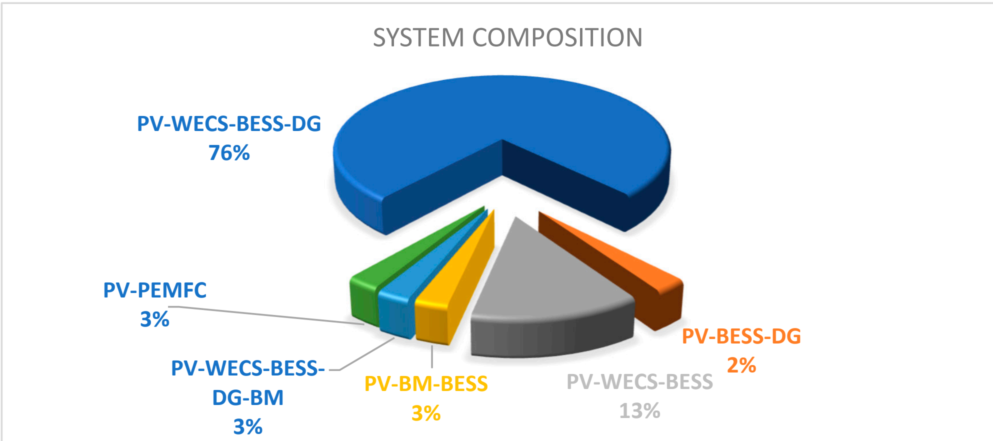

Figure 8. Shows the distributions found in the review, highlighting the configurations that are most studied.

3.1.1. Elements of Generation Used in Systems

Of the 38 articles reviewed, the distribution of the elements of each system was broken down, where it can be seen in Figure 9 that the most used generation sources are photovoltaic and WECS.

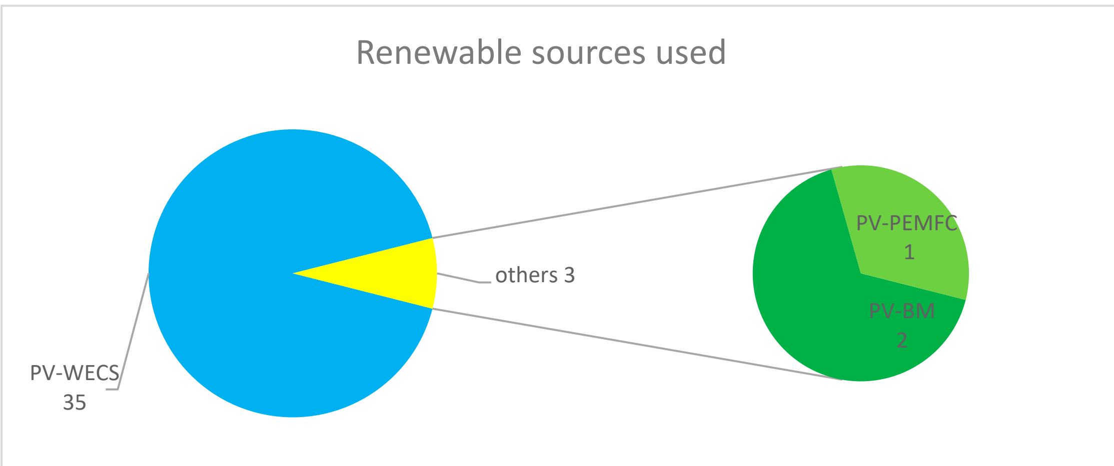

Figure 9. Number of articles according to the renewable sources used.

- A total of 100% of the studies reviewed used photovoltaic systems as one of the renewable energy sources.
- A total of 92.1% of the studies reviewed employed WECS and PV.
- A total of 5.26% of the studies reviewed used a biomass and PV generation source.
- A total of 2.63% of the studies reviewed utilized fuel cells and PV.

3.1.2. Energy Storage Sources of an HRES

The HRES system can include a BESS (battery energy storage system) to improve reliability. The BESS stores electrical energy generated by renewable sources, such as solar panels or wind turbines, and uses it at times of high energy demand or when renewable energy generation is reduced due to weather factors. In summary, the BESS is a key part of the HRES system to ensure a reliable and sustainable energy supply. Table 4 shows the most used BESSs in the current literature, their advantages, and disadvantages, and shows the identification of each technology used in the articles reviewed to facilitate the location of articles according to the desired technology.

Table 4. BESS types and advantages/disadvantages [5,42,45,58].

BESS	Advantages	Disadvantages	Articles Related to BESS
Energy storage in compressed air (CAES)	Lower cost, low self-discharge, high service life.	High initial cost, large scale, there are geographical restrictions that limit the installation of the system.	Not found
Battery Ni–Cd	Low maintenance requirement, high energy density and high reliability.	This product has high costs and suffers from a phenomenon known as "battery memory".	Not found
Battery lead–acid	This product has a medium energy density, low initial investment, and is widely available. In addition, it does not require a cell management system.	The characteristics of this product" include a low life cycle, low efficiency, ventilation requirements, and the need for proper disposal of used batteries.	[7,14,16–20,23,34,57,59,60]
Battery Li-ion	This product stands out for its high efficiency, high energy density, long life cycle, and relatively compact size. In addition, it is in an area where rapid technological advances are taking place.	The disadvantages of this product are its high initial capital costs due to the special packaging required and the potential risk of battery body rupture.	[25,32,53]
Hydrogen-based (HESS)	This product is almost contamination-free and has a wide power range.	This product includes low efficiency, low response time, high cost, and installation restrictions due to the hydrogen storage tank.	Not found
Supercapacitor (SESS)	It has high efficiency, long life cycle, and high power capacity.	It has a low energy density and a relatively high cost.	Not found
Flywheel (FESS)	It features high power capacity, long life cycle, and fast charging capability.	Disadvantages of this product include its high cost due to the need for a separate vacuum chamber, safety issues, high self-discharge, and high cost.	[22]

Table 4. *Cont.*

BESS	Advantages	Disadvantages	Articles Related to BESS
Gel batteries	This product is a good choice for applications that have high cyclic requirements due to its excellent recharge behavior, which gives it a long service life.	One of the disadvantages of gel batteries is that they have a lower current capacity compared to other battery technologies. They can be more expensive than some other battery technologies.	[13]

In a detailed review of the selected literature, several analyses of the information on BESSs were performed. Out of a total of 38 studies:

- Thirty-seven articles (97.36%) presented a BESS as an auxiliary system;
- Seventeen articles (44.73%) specified which type of BESS was used in the system.

Figure 10 shows the types of batteries used in the articles and their percentage of use in the review performed

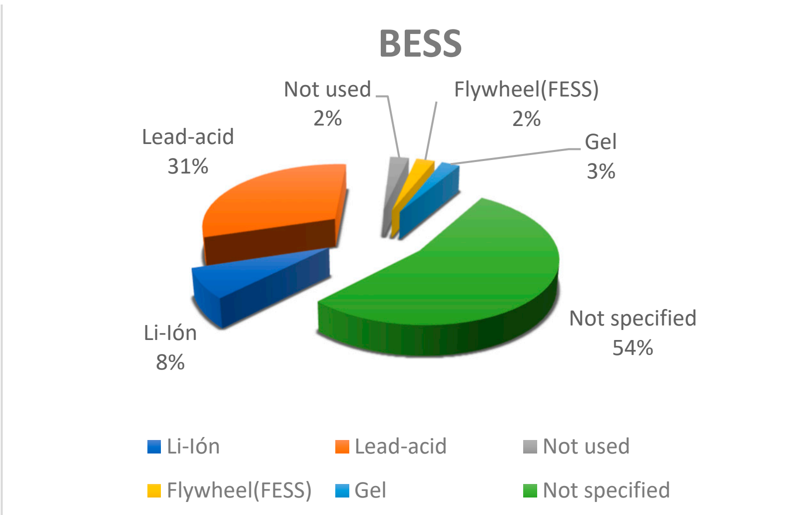

Figure 10. Types of BESSs found in the review.

3.1.3. Auxiliary Generation Systems

These auxiliary sources are typically used when the main source cannot generate enough power to meet demand at times of high demand or when the main source is inactive or unreliable. Common examples of auxiliary generation sources are diesel or natural gas generators. With regard to these elements, it was found that:

- Thirty studies (78.94%) used diesel generators;
- One study (2.63%) used a biomass generation source;
- Seven studies (18.42%) used no auxiliary generation sources.

3.2. HRES Sizing and Optimization

HRES optimization criteria can be divided into two categories: economic and reliability, and the selection of each depends on the research objectives and the desired tolerance level [5]. Economic criteria refer to the cost or size of the system, while reliability criteria focus on ensuring the continuity of load power supply. Tables 5 and 6 list the economic and reliability optimization criteria found in the literature, respectively, and identify the limitations that each may present. In addition, the criteria that are used in each of the articles analyzed in the review are identified and shown for a better identification according to the reader's search interests [40].

Table 5. Economic optimization criteria and constraints for HRESs [3,5].

Criteria	Type	Limitations	Articles Related to the Criteria
Annual system cost (ACS)	Economic	The cost estimate does not consider the possible variation of the interest rate and inflation.	Not found
Net current cost (NPC)	Economic	It is not possible to take into account fluctuations in fuel prices (in case conventional energy sources are included) and uncertainties in the durability of system components such as batteries.	[1,6,11,13,14,16–24,32,34,50–53,55–57,60–62]
Cost of energy (COE)	Economic	The cost of recovering system components at the end of their useful life is not included.	[12–14,16,17,19–21,23,28,30,32–34,50–53,55,56,60,62]
Levelized cost of energy (LCOE)	Economic	The cost estimation tool does not take into account external factors, such as volatility in fossil fuel prices and inflation.	[1,11,22,24,25,36,53,57]
Total net current cost (TNPC)	Economic	Changes in the cost of energy are not taken into account.	Not found
Life cycle cost (LCC)	Economic	Cost estimation is complicated by the difficulty of accurately predicting acquisition, operation, and long-term maintenance costs, which can affect the accuracy of the life cycle cost (LCC) analysis.	[13,15,31]
Cost of loss of battery life (LLCB)	Economic	Reduced battery performance as the battery ages is not included in the evaluation.	Not found

Table 6. Optimization criteria (reliability) and limitations for HRESs [3,5].

Criteria	Type	Limitations	Articles Related to the Criteria
Probability of loss of power supply (LPSP)	Reliability	It is defined for a specific load profile and does not take into account variations in that load profile.	[1,21,30,33,36,48]
Expected energy not supplied (EENS)	Reliability	The potential impact of variation in load demand is not taken into account.	Not found
Level of autonomy (LA)	Reliability	Normalized-to-total annual energy demand.	Not found
La probabilidad de pérdida de carga (LLP)	Reliability	A limitation in the assessment of power supply reliability is that long-duration load loss (LLP) only measures the probability of power supply interruption and does not provide a complete assessment of the reliability of the power system as a whole.	[52]
Deficiency in probability of power supply (DPSP)	reliability	For EPG < EL, it is the same as LPSP.	Not found

From the review of all the articles, the number of articles that used the aforementioned criteria was obtained, with COE and NPC emerging as the most used economic criteria and LPSP as the most used reliability criterion. Figure 11 shows the criteria found from the review and the number of times they were used.

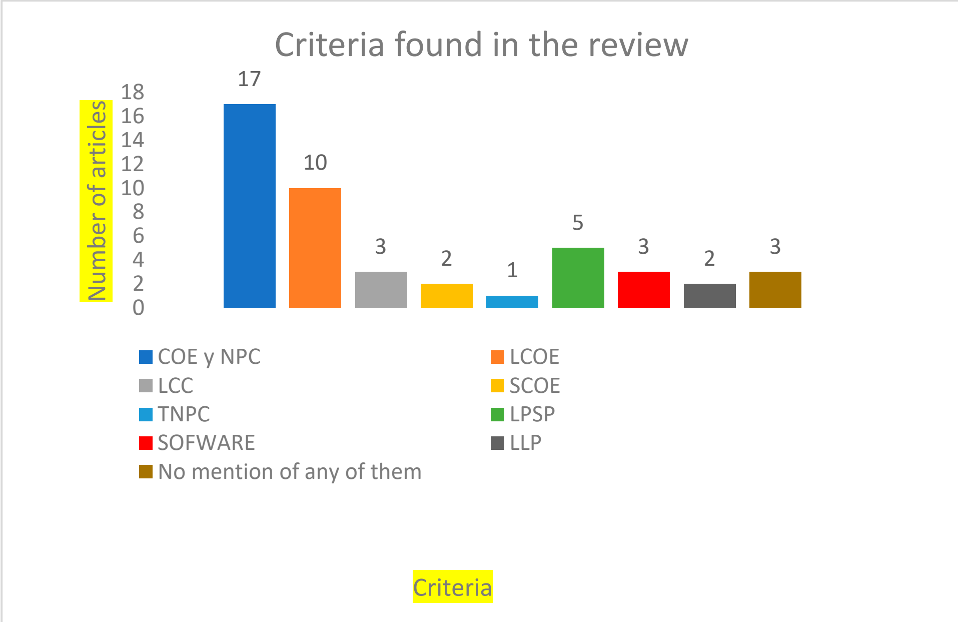

Figure 11. Number of articles using these criteria in the review.

- A total of 44.73% of the studies used the COE and NPC criteria.
- A total of 26.31% of the studies used the LCOE criterion.
- A total of 7.89% of the studies used the LCC criterion.
- A total of 5.26% of the studies used SCOE criterion.
- A total of 2.63% of the studies used TNPC criterion.
- A total of 7.89% of the studies did not use an economic criterion.
- A total of 13.15% of the studies used LPSP criterion.
- A total of 7.89% of the studies used some software.
- A total of 5.26% of the studies used LLP.

3.3. Optimization Algorithms

Three main categories of techniques for optimizing hybrid renewable energy systems (HRESs) can be identified: artificial intelligence methods, iterative methods, and software tools. Artificial intelligence methods include various techniques such as genetic algorithm (GA), particle swarm optimizer (PSO), Tabu search (TS), simulated annealing (SA), harmonic search (HS), and others. On the other hand, iterative methods may include electric bee colony system (ESCA), power PA algorithm (POPA), and generic algorithms (GA), among others. In addition, there are software tools such as the transient energy systems simulator (TRNSYS), the hybrid optimization model for electric renewable energy (HOMER), and Hybrid2, each with its underlying optimization technique [9]. Table 7 presents the applications of the optimization techniques in the literature reviewed.

Table 7. Applications of optimization techniques in the reviewed literature [3,5,40,41].

Optimization Techniques	Advantages	Disadvantages	Articles Related to the Optimization Techniques
PSO	The technique does not use derivatives and is less sensitive to the nature of the objective function, as well as less dependent on the set of initial points, presents high efficiency.	The technique lacks a solid mathematical basis and is a variant of stochastic optimization techniques that require more computational time.	[15,22,30,33,49]

Table 7. *Cont.*

Optimization Techniques	Advantages	Disadvantages	Articles Related to the Optimization Techniques
TS	The technique is highly compatible with other methods and, in addition, spends more time in the region where the solution is optimal. This is achieved by using deterministic motions that reduce the variability caused by the initial solution.	This technique requires a larger number of iterations, which may result in a slower convergence rate.	Not found
Coyote optimization algorithm (COA)	The technique has fast convergence and has proven to be effective on a variety of optimization problems, including those that are nonlinear and multimodal.	The COA may have difficulty finding accurate solutions and may stall at local optima, especially in problems that have multiple local optima. This is because the algorithm may become stuck on a suboptimal solution instead of finding the globally optimal solution.	[52]
SA	The method is capable of dealing with nonlinear models and is statistically guaranteed to find an optimal solution. Moreover, it is easy to code for complex systems.	Many initial constraints are required and the initial assumption can have a strong impact on the final solution.	Not found
HS	The method is easy to apply and requires less parameter tuning, leading to faster convergence compared to other optimization methods.	The complexity of optimization problems can result in premature convergence of the optimization algorithm used.	Not found
EO	It includes high exploration and exploitation search mechanisms to randomly change solutions.	-	[1]
GA	The genetic algorithm (GA) can solve problems with multiple solutions and can be easily applied to existing simulations and models.	If the initial population generated is not sufficient, the GA may stagnate at local minima.	[17,27,33]
POPA	The graphical interface makes it easier to understand and apply constraint problems.	The optimization method or technique can be used in a system consisting of a single power generating unit.	Not found
ESCA	This optimization method is inspired by the POPA algorithm and can handle systems with multiple generators.	The application of the technique becomes complex due to the optimization of multiple constraints.	Not found
AWSA	It is feasible to make changes to the AWSA to easily adjust it to various types of optimization problems.	The performance of AWSA can be significantly affected by the quality of the initial solution; in case the initial solution is poor, the algorithm may encounter difficulties in reaching the optimal solution.	[36]
HOMER	Visual representation of data can facilitate the understanding of the best combination of cost-effective systems, making it simple to implement a complex system.	Reliability analysis cannot be performed.	[6,11–14,16–21,23,25,28,32,34,53,55–57,59,60,62]

From the review carried out, we found the algorithms and software that have been used the most, where HOMER and PSO were the most used for system optimization. Figure 12 shows the number of optimization techniques found in the review and the number of articles in which they were used.

- A total of 63.15% of the studies used HOMER software;
- A total of 13.15% of studies used PSO;
- A total of 7.89% of studies used GA;
- A total of 5.26% of the studies used MATLAB;
- A total of 2.63% did not specify which software was used;
- A total of 21.5% used other algorithms.

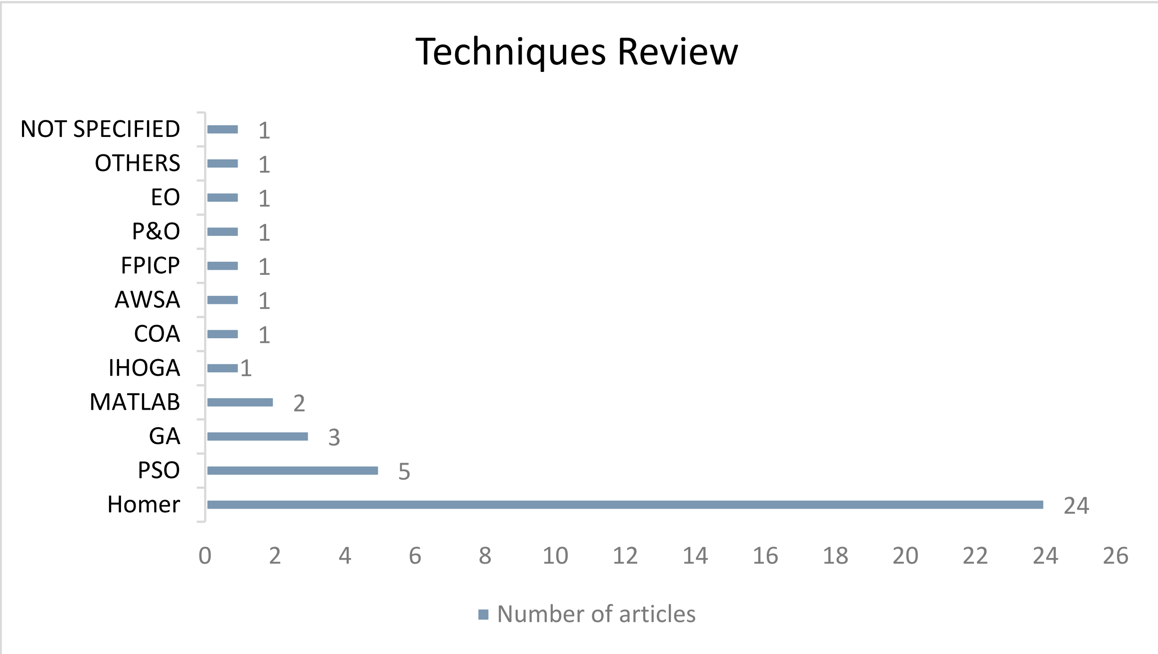

Figure 12. Frequency of use of optimization techniques in the review.

4. Future Trends for the Design and Operation of the Hybrid Energy System

With improvements in the research and development of solar and wind technologies, the cost of renewable energy sources is expected to decrease in contrast to the annual increase in the cost of conventional energy resources. Therefore, this hybrid system will be more economical in the future and it is also likely that the environmental benefits will encourage its use and acceptance. In addition, the inclusion of artificial intelligence in energy management is expected to further improve the performance of the hybrid system in the near future. Optimal resource allocation according to load demand and renewable resource forecasting can significantly reduce system operating costs. The application of advanced control techniques using a centralized controller also promises to improve the performance of modular hybrid power systems. Finally, the implementation of modern control techniques to monitor the operation of modular hybrid energy systems can further optimize the use of renewable resources and improve energy management.

5. Conclusions

Hybrid systems are considered a viable alternative for supplying power to a grid. To optimize the system, design strategies must seek an appropriate combination of critical parameters such as cost and system efficiency.

Hybrid renewable energy systems could benefit greatly from BESS technologies. Many experts are working on improving the coordination and development of BESS energy storage systems for use in microgrids to manage the energy balance between supply and demand by storing energy during off-peak hours at a lower cost. Although its potential is recognized, developing an efficient BESS suitable for microgrid applications remains a major challenge.

In the field of optimization, the literature review reveals that researchers have focused on three methods: classical, artificial, and hybrid. Classical methods are characterized by their speed and efficiency in techno-economic analysis but have the limitation of having a restricted optimization space. On the other hand, artificial methods are the most widely used in optimization due to their higher efficiency, accuracy, and fast convergence. However, one of the drawbacks of this method is the need to use complex processing programs.

The management methods applied in hybrid systems are selected according to the objectives of each study. Most researchers focus on techno-economic objectives, as they allow analyzing both technical (such as duration, demand fulfillment, and performance) and economic (such as minimizing system costs, increasing savings, and reducing the cost of energy) aspects of hybrid renewable energy systems to achieve an optimal configuration. To achieve these objectives, various algorithms, such as fuzzy logic, particle swarm optimization, neural networks, and commercial software such as HOMER, are employed to monitor the components of the hybrid renewable energy system. These approaches allow the performance and economic viability of hybrid systems to be effectively evaluated and optimized.

The statistical analysis carried out in this study has made it possible to identify the most relevant current research topics in the field of hybrid systems, highlighting the most focused topics:

- The most common use is in residential areas because the countries that most research these systems have many locations with poor or no electricity services. The most used architecture is the isolated hybrid network.
- The most commonly used generation source configuration was PV-WECS-BESS-DG, as they have shown the best reliability and cost–benefit.
- The battery is a commonly utilized supplementary element, utilized for both autonomous and networked systems. The most used storage sources were lead acid and Li-ion batteries.
- The most used auxiliary generation source was diesel generators.
- The energy analysis commonly employed the LPSP indicator, while the economic analysis mainly utilized the NPC and COE indicators.
- The most used optimization algorithms were PSO and GA.
- The most used software for optimization is HOMER.

The analysis carried out in this article allows us to identify the latest trends in HRESs and to provide the reader with a source of information that can be accessed already broken down according to their particular interest.

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