A review on recent standalone and grid integrated hybrid renewable energy systems: System optimization and energy management strategies

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Abstract

Fossil fuels greenhouse gases emissions for remote and island electrification and transport application have led to the study of hybrid renewable energy systems. These comprise renewable energy generation units (Solar Photovoltaics, Wind Turbines, etc.), storage units (Battery, Hydrogen Storage Tanks), and other components (compressors, inverters, pressure regulators, etc.). Component selection is key for reducing the negative effects on the system's cost, reliability, environmental, and social impacts, and reaching its full potential. The aim of this study is to review recent advancements in the architecture sizing and energy management strategies of hybrid renewable energy systems, considering various locations and applications, and based on technical, reliability, environmental, and social factors. The employed optimization formulation frameworks based on various linear and non-linear objective functions, equality and non-equality constraints, and decision variables are also investigated. Optimization methods including tools and solvers used to solve complex hybrid renewable energy system optimization problems are also explored. The study's important results include identifying various components that could help optimize the performance of hybrid renewable energy systems. Additionally, the study highlights the potential of optimization-based energy management strategies to enhance the reliability and efficiency of these systems. Trends in the studies of the implementation of grid-integrated or off-grid hybrid renewable energy systems in remote, island, or urban locations are highlighted. It could also aid in the development of methodologies for designing sustainable energy infrastructure that is resilient and environmentally friendly. Furthermore, the study could inspire future research that addresses the identified research challenges and areas of interest.

Keywords: Hybrid renewable energy systems, Energy management of microgrids, Hydrogen ecosystem, Hydrogen based hybrid renewable energy systems

1. Introduction

Global population growth, reaching 8 billion [1], inevitably increases energy demand. Most of the world's population relies on fossil fuels, such as coal, gas, and petroleum products for power and heating, Energy consumption is remarkably high in the industrial, residential, and transportation sectors, which still rely on oil products, natural gas, and coal [2]. As a result, global warming and ozone layer depletion are noticed with effects like heat waves, untimely floods, melting of glaciers on the mountains, unexpected weather changes, etc. At COP26 in Glasgow, 2022 [3], the high-level climate change conference targeted reducing greenhouse gas emissions to zero and limiting the planet's temperature to 1.5 °C by 2030.

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Nomenclature

AC/DC	Alternating/Direct current
BEV	Battery electric vehicle
BM	Biomass
Bt	Battery
COE/COH	Cost of energy/hydrogen
DPSP	Deficiency of power supply probability
DRP	Demand Response Program
EENS	Expected energy not supplied
Elz	Electrolyzer
EMS	Energy management strategy
FC	Fuel cell
FCV	Fuel cell vehicle
G	Grid
GD	Grid dependence
H2	Hydrogen
HP	Hydropower
HRES	Hybrid renewable energy system
HS	Hydrogen storage
HTL	Hydrogen tank level
HV	Hybrid vehicle
LA	Level of Autonomy
LCC	Life cycle cost
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
LCR	Load Cover ratio
LDP	Load deficit probability
LOEE	Loss of energy expected
LOLP	Loss of load probability
LPSP	Loss of power supply probability
NPC	Net present cost
OC	Ocean thermal
Opex	Operational cost
PV	Solar photovoltaic
SA	Standalone
SCR	Self-consumption ratio
SOC	State of charge
SSR	Self Sufficiency Ratio
ST	Solar Thermal
TAC	Total annual cost
TE	Tidal energy
TOC	Total operating cost
TS	Thermal solar
TSC	Total system cost
WT	Wind Turbine

Climate change's ambitious goals prompted the search for cleaner and more sustainable sources of energy. In general, sustainable energy production involves acquiring energy without emitting greenhouse gases. Such a system consists of Solar photovoltaic (PV), Wind turbines (WT), Hydropower (HP), Biomass (BM), Solar thermal (ST), Ocean thermal (OC), Tidal energy (TE), etc. Compared to previous years, renewable energy has gained a significant share of energy production [2]. Despite Covid-19 stalling renewable energy development, growth is evident and will undoubtedly increase in the years to come. Positive actions are taken like the addition of 314.5 GW of renewable energy in 2021 which was depicted as having the capacity to power all households in Brazil [4]. In addition, the Russian-Ukraine conflict, in 2022 and the global energy crisis, triggered oil and gas prices. Even though high energy prices affect Europe, the US, and Asia, the impact on Africa is dramatic [5]. With the global energy crisis, the world advanced in developing reliable energy solutions.

The primary objective of power production is to meet the power demands of consumers without interruption. The power demand of the consumers must be fulfilled at the time it is needed. Then the power production and distribution must be fitted to comply with this constraint. Nuclear, gas, fuel, and coal power plants are highly utilized to meet the power demands of consumers at the given period. This is because they are dispatchable, which means that they are capable of delivering constant power output at any time adjusting, fully or partially. Solar photovoltaics (PV) and wind turbines (WT) are intermittent by nature, and therefore hybrid energy production is developed by combining more than one renewable energy source and followed by storage of the produced energy, known as a Hybrid Renewable Energy System (HRES) [6]. The objective of HRES is to satisfy the power demand of the end consumers without causing any interruptions. To configure the HRES most optimally, it is necessary to have an in-depth understanding of the energy generation, storage systems, technical specifications, environmental conditions, and load profiles [7]. A large number of studies have already been conducted considering the reliability, technical, economic, and environmental challenges faced by HRES studies. Speaking generally, a wide scope range is associated with HRES studies, such as their size, energy management, energy cost reduction, reduction of greenhouse gas emissions, demand forecasting, application fields, locations, etc., and the studies are primarily focused on these aspects. Our aim through this work is to present a review of the last developments in HRES applications and their different aspects of development.

The hybrid renewable energy system (HRES) topic has been addressed under the focus of different areas of interest. In [8], authors discussed the sizing and energy management of standalone wind HRES. The authors of [9], attempted to model the system through energy management strategies (EMS) to meet the load demand of the grid-connected HRES. To determine the best energy mix and configuration, techno-economic analysis and sizing of different HRESs were performed [10]. For an Italian farm, [11] studied the sizing and EMS of solar photovoltaic(PV)-wind turbine(WT)-hydropower(HP)-battery(Bt)-hydrogen(H2) HRES. H2 system in HRES studies includes components such as an electrolyzer (Elz), hydrogen storage (HS), and fuel cell (FC) for the production, storage, and utilization of H2. In [12] authors presented a method for improving hydrogen production for grid-connected PV-Bt-H2 HRES for vehicle applications considering battery management. In [13], authors examined the modeling and operation of PV-BM-Bt-H2-natural gas generator HRES for 1500 inhabited areas of Marseille, France including social aspects in their study along with technical, economic, and environmental aspects. In [14], authors presented optimization based on the sizing of PV-Bt-H2 HRES integrating diesel generator (DGn) taking into consideration of technical, economic, and environmental factors. The authors of [15] examined the sizing and energy management of standalone PV-WT-H2 HRES for residential applications in a small village in Iran, considering a variety of technical and reliability issues. A study in [16] examined the simulation methodology for standalone PV-Bt-

Elz-based HRES, which focused on the modeling and control of system capacity. A new control strategy was developed that minimizes the cost of hydrogen, which was the focus of the study. Authors also studied the design of an autonomous data center powered solely by local renewable energy coupled with storage [17].

Besides sizing, energy management, and control, other possibilities lie in HRES for the better study of the system, for example, demand forecasting to facilitate better energy management and sizing, power supply and demand mismatch analysis, power shaving strategies to transfer power from peak to low consumption period, the presence of uncertainties concerning various factors, such as solar radiation, wind speed, or even costs. In [18], authors developed a holistic approach for energy demand prediction, design, and scheduling optimization. In [19], authors examined resource and demand assessment in PV-H2 HRES. Authors of [20] attempted to solve the problem of supply and demand mismatch resulting from renewable energy's intermittent nature. Based on different cost circumstances on the power supply on an hourly and monthly basis, they attempted to compare the configurations that considered hybrid storage systems and only one storage system. Authors of [21] attempted to determine the optimal dispatch of storage facilities consisting of battery (Bt) and hydrogen energy storage (HS) concerning the cost of PV-Bt-H2 HRES. [22] presented a study focusing on finding the optimal HRES configurations using seven different hybrid systems based on Tidal, PV, WT, and FC in terms of cost and reliability. Another study [23] examined the optimal sizing of a PV-Bt system with or without hydrogen production slashing peak power demand, [24] introduced HRES design based on solar parabolic concentration panels, electrolyzer (Elz), and fuel cell (FC) for hydrogen storage. The authors of [25] proposed a stochastic optimization model for determining the capacities of PV-Bt systems based on uncertainty in solar irradiation. Authors of [26] introduced the heat-integrated hydrogen storage unit that is equipped with liquid organic hydrogen carriers for the storage of hydrogen. A proposal was presented in [27] to optimize the operation of hydrogen refueling stations and battery charging stations to maximize profits.

A multitude of reviews have been conducted in the past concerning Hybrid Renewable Energy Systems (HRES), covering a wide range of topics. These encompass sizing and optimization of HRES, energy management, control strategies, forecasting, environmental assessment, policy-making, economic analysis, and software tools. Table 1 presents a comprehensive compilation of previous reviews that have explored various aspects associated with HRES and includes the topics of this study.

Table 1: Review studies of HRES in different periods

Studies	***Year***	***Sizing***	***Forecasting***	***Energy/Demand-side Management***	***Sensitivity/Uncertainties***	***Optimization formulation***	***Optimization Techniques***	***PV-Wind -Integration***	***Battery Integration***	***Hydrogen system Integration***	***Control Strategies***	***Economic Analysis***	***System reliability***	***Environmental Impact Assessment***	***Policy making***	***Grid Integration***	***Social acceptance and adoption***	***Life cycle assessment***
This study	2023	✓	✗	✓	B	✓	✓	✓	✓	✓	B	✓	✓	✗	✗	✓	✗	✗
[28]	2023	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	B[1]	✗	✓	✗	✗
[29]	2023	✓	✗	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓	✗
[30]	2022	✗	✗	✓	✗	✗	✓	✓	✗	✓	✓	✓	✗	✓	✗	✓	✗	B
[31]	2022	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	B	B	✓	B	✗
[32]	2022	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✗	✗
[33]	2020	✗	B	B	✓	✗	✓	✓	✓	✗	✓	✓	✓	B	B	✓	B	B
[34]	2020	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✓	✗	B	✗	✗	✗
[35]	2019	✓	✗	B	B	✓	✓	✓	✓	✗	B	✓	✓	✗	✗	B	✓	✗

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[1] B : In brief

[36]	2018	✗	✗	✓	✗	✓	✗	✓	✓	✓	✗	✓	✗	✗	✗	✓	✗	✗
[37]	2018	✓	✗	✗	B	B	✓	✓	✓	✗	B	✓	✓	B	✗	✓	✗	✗
[38]	2018	✗	✓	✓	B	✗	✗	✓	✓	✗	✗	✓	✓	B	B	✓	B	B
[39]	2018	✗	✓	✗	✓	✗	✗	B	B	✗	✗	B	B	✗	✗	✗	✗	✗
[40]	2018	✓	✗	✗	✗	✗	✓	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗	✗
[41]	2017	✓	✗	B	B	✗	✓	✓	✓	B	B	✓	✓	✓	✗	✗	✓	✗
[42]	2016	✓	✗	✗	✗	✗	✓	✓	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗
[43]	2016	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✗	✓
[44]	2016	✓	✗	✗	✓	✗	✗	✓	✓	B	B	✓	B	B	✗	✓	✗	✗
[45]	2016	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	B	B	✗	✗	✓	✗	B
[46]	2015	✗	✗	✓	B	B	B	✓	✓	B	B	B	B	B	B	B	B	B
[47]	2015	✓	✗	✗	✗	✗	✓	✓	✓	✗	✗	✓	✓	✗	✗	B	✗	✗
[48]	2014	✓	✗	✓	✓	✓	✓	✓	✓	B	✓	B	B	✗	✗	✗	✗	✗
[49]	2014	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗
[50]	2014	✗	✗	✗	B	B	✓	✓	✓	B	✗	B	B	B	✗	✓	✗	✗
[51]	2014	✓	✗	✓	B	✓	✗	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✗
[52]	2014	✓	✗	✗	✗	✗	B	✓	✓	✗	B	✓	✓	✓	B	✓	B	B

A review of size optimization methodologies for standalone PV-WT HRES was done in 2017 [41] by a research group in Australia. They tried to study the research works based on various solar, wind, and other renewable and conventional energy sources including energy storage. The selection of research articles to review concerned mostly work from 2012-2016 and concluded that the PV-WT-DGn-Bt was preferable for islands and remote areas. In the results, they also observed that most studies (25 papers) were based on PV-WT-DGn-Bt HRES, PV-WT-Bt HRES on 23 articles, and PV-WT-FC-HS only on 8 articles. They also put their views on the high costs associated with island grid extension. It can be noticed that HRES-H2 with or without grid integration was not discussed broadly. It can also be seen that island-based HRES was studied most of the time in review articles, however, the possibility of HRES to fulfill the urban power demand which also carries the possibility of grid integration was less studied in the past. The optimization solvers and tools mentioned were based on developments up to 2016. The trend of using a hybrid algorithm for optimization was increasing slowly at that time. In the domain of Hybrid Renewable Energy Systems (HRES) studies, accurate sizing and forecasting of renewable energy resources, such as solar irradiance and wind speed, are integral for effective energy management. Energy management assumes a pivotal role in achieving a balance between energy demand and supply within HRES. By employing energy demand forecasting, the energy management system can optimize the scheduling and dispatch of diverse energy sources and storage systems to align with the load requirements, thereby ensuring system stability and reliability. Previous review studies have provided comprehensive analyses encompassing sizing, forecasting, optimization, and energy management [34] [43]. However, it is noteworthy that these studies did not encompass the integration of HRES-H2 systems within their purview.

Along with HRES sizing, energy management, and optimization review studies, in 2014, a group of authors [50] introduced a comprehensive list of 19 computer software tools that were available for studying Hybrid Renewable Energy Systems (HRES). Among these tools, some of the well-known ones included HOMER, TRNSYS, RETSCREEN, HYBRID2, ARES, and i-HOGA. However, the analysis and comparison of these tools were not detailed enough. Additionally, the description of widely used programming languages like MATLAB and Python, which are highly preferred for solving HRES optimization and Energy Management System (EMS) problems in recent times, was insufficient.

In 2019, a research group in Malaysia reviewed standalone PV-WT-FC focusing on their optimization and EMS [53]. Optimization solvers and tools weren't detailed here. In addition, only a basic overview of standalone and grid-integrated HRES architectures was discussed. The selection of research articles to review was mostly based on past years up to 2018. Despite that, they presented an optimization formulation framework with various design variables, constraints, and objective functions including system costs and reliability. Optimization methods and EMS were described well considering various technical, and economic decision factors. It was predicted that the production of H2 from renewables or the H2 economy could be interesting future research topics as H2 production was relying heavily on fossil fuels at that time. They also suggested EMS of HRES needed to be robust and real-time with additional considerations. From their conclusions, it can be seen that the H2 technology was still not considered substantially in HRES studies and even renewables like PV and WT were not up to perform at their full potential due to technological barriers until 2019.

Recently [31], in 2022, a research group from China published a review article on more recent optimization strategies for hybrid renewable energy systems with hydrogen technologies: state of arts, trends, and future development. The study has mainly focused on the review of the research articles based on the HRES-H2 system with the reviewed articles from 2016-2020. They mentioned that no review articles were found in recent years broadly discussing optimization techniques of HRES along with H2 technology. However, HRES along with the H2 technology study had been done multiple times in the past [36] [45]. They analyzed various economic, reliability, environmental, and social aspects of HRES-H2 applied by the research community in the past decade presented a comparison of the optimization methods, and described the optimization solvers and tools related to the HRES-H2 system. However, they didn't precise the development of other HRES structures without the H2 system. In fact, several recent studies are under development without integration of the H2 system. Moreover, their research articles were mostly based on past studies before 2020 which lacked to describe the progression of HRES-H2 in recent years 2021-2022. In this study, the authors provided a brief overview of additional factors, such as environmental impact assessment, policy-making, and social acceptance. However, it is worth noting that these parameters have not been extensively investigated or comprehensively addressed in previous reviews. Specifically, the presentation of policy-making in relation to HRES studies has been limited to only a few studies [33]. Recent review studies [28], [30] have demonstrated a noticeable trend toward the study of HRES-H2 integration. However, there remains a gap in the examination of grid integration, energy management and control strategies, uncertainties and sensitivity analysis of associated costs, policy-making, and social acceptance within HRES-H2 studies. These areas present potential avenues for future research and warrant further investigation to enhance our understanding of the comprehensive implications and potential challenges of HRES-H2 integration. Furthermore, recent targeted studies have not provided clear insights into the application areas of HRES-H2, the specific locations where these studies were conducted, and the diverse application fields in which HRES-H2 systems can be deployed. Additionally, the potential integration of HRES-H2 systems with Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs) into the grid has not been adequately explored. These aspects present promising opportunities for future research to explore the potential synergies and benefits of integrating HRES-H2 systems with BEVs and FCEVs, and to identify suitable application areas and locations for their implementation.

Table 1 indicates that previous review studies on Hybrid Renewable Energy Systems (HRES) have mainly focused on sizing, energy management, PV-Wind integration, and optimization formulations. However, since 2016, there has been an increasing interest in exploring the integration of hydrogen systems in off-grid or grid integrated HRES. This highlights the potential of hydrogen as an energy carrier and its role in reducing carbon emissions in energy systems. Furthermore, optimization techniques have become more prevalent in recent years, indicating the growing recognition of the importance of optimization models and algorithms in maximizing the efficiency and effectiveness of HRES. In contrast, earlier review studies placed less emphasis on policy-making and grid integration. However, there has been a noticeable increase in their inclusion since 2018, indicating a growing understanding of the importance of policy frameworks and grid integration strategies in enabling the widespread adoption of HRES. Despite this progress, rigorous studies are still needed to fully present these findings.

Considering the past studies and reviews, this review article highlights a growing trend in the field of HRES studies including its applications and components scope. During the past few years, HRES-H2 has been studied extensively, both with and without grid integration. In conjunction with the development of Elz, FC, and storage technology, H2 technology is developing at a rapid pace these days in integration with HRES. Nevertheless, this does not imply that the other HRES studies without H2 integration have diminished. Several HRES studies can be conducted with choices in renewables such as (PV, WT, HP, BM, etc.), storages (Bt, HS), and generators (FC, DGn). This review aims to shed light on the exciting developments in the field of HRES and the promising direction that future research is likely to take. Embarking on a noble mission, this study is driven by the ambition to contribute towards the achievement of the United Nations' Sustainable Development Goal 7 (SDG 7). By delving into the realm of renewable energy systems, the study aims to make a meaningful impact on global sustainability efforts. It also expects to identify recent application fields and locations where different HRES are being employed.

Considering the complexity of HRES studies, which include the synchronization of various power-generating and storage components, it is inevitable that modern optimization algorithms will be required to solve complex optimization problems. In addition, algorithms are also evolving and developing over time. During the last few years, several metaheuristics and exact methods have been developed to solve the complex linear and non-linear optimization problems associated with HRES studies. Also, it is noteworthy that computer tools like HOMER and i-HOGA have been developed to assist in the solution of HRES problems. In addition to providing an overview of growing classical and modern optimization methods, this article also examines the emergence of a trend in the choice of tools such as MATLAB, GAMS, Python, etc. which can be used to solve linear, non-linear, single, and multi-objective optimization problems. In this article, the potential application of open source, python-based modeling and optimization tools, such as PyPSA, and FINE which includes Pyomo as an optimization package are discussed to power system analysis.

Literature Selection

A substantial amount of literature exists on the topics of sizing, modeling, managing energy, control strategies, comprehensive reviews, etc. as mentioned in the previous paragraphs. As many research studies related to hybrid renewable energy systems (HRES) and optimization have been carried out in the past, a set of criteria has been applied to the selection of these studies in this review article. The research papers were selected primarily through https://www.sciencedirect.com/, http://scholar.google.com/, and https://www.researchgate.net/ with the following keywords: Hybrid renewable energy system (HRES), Optimization and energy management strategies(EMS) in HRES, Storage methods in HRES, PV-WT-H2 HRES as described in the methodology approach for selecting the reviewed articles presented in figure 1.

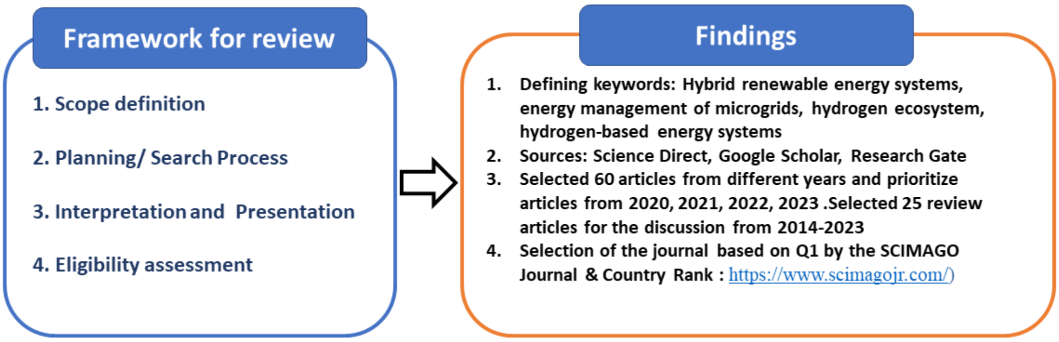


Figure 1: Methodology approach for selecting the reviewed articles

Among the 60 research articles from different years (2008-2022), the most recent articles related to HRES and energy management strategies (EMS) were given the highest priority. The analysis of those articles was performed to survey the development and progression of HRES studies according to time, the most recent studies were prioritized and tabulated. The results are also compared based on the progression of HRES studies with time. We reviewed papers and recorded the relevant information such as HRES components, year of publication of the article, locations, application fields, energy management strategies, optimization solvers, and frameworks in MS EXCEL. This article presents an in-depth analysis and presentation of those recorded studies.

The rest of the paper is structured as follows: In Section 2, the paper presents an overview of current HRES system architectures and configurations for isolated and grid-connected microgrids. In Section 3, recent HRES applications are discussed. In Section 4, a recent HRES vehicular application is presented. Section 5 provides an overview of recent energy management and control strategies. In Section 6, you will find a description of a recent framework for optimizing formulations. In Section 7, recent optimization methods, and solving tools are categorized. The results of the study and their discussion are presented in section 8. Finally, Section 9 concludes the review.

2. HRES system architecture

As far as primary energy sources are concerned, the goal is to make renewables a primary energy provider despite their intermittency. Due to the global availability of solar irradiance and wind energy, solar photovoltaics (PV) and wind turbines (WT) are particularly popular renewable energy sources. Furthermore, PV and WT are technically mature and widely available these days [54]. PV and WT combination has been extensively studied in the hybrid renewable energy systems (HRES) [15], [17], [55]–[70] combining hybrid PV and WT as energy sources. As far as the energy system is concerned, the challenge has always been to provide power regularly to satisfy consumer power demands. It is possible that the electricity generated by PV and WT will not be enough to meet all the demands. This is why renewable energy systems like PV and WT integrate other energy generators powered by fossil fuels or natural gas to meet power deficits and store surplus power in energy storage units i.e. battery (Bt), and hydrogen storage (HS), to face the variations in loads. In addition, recently, it can be noticed that the concept of the H2 system has been dominantly researched and progressively integrated into HRES. It is integrated with modern renewable energy sources like PV and WT to produce green H2 by supplying the electricity produced by them to the electrolyzer (Elz) where the water molecules get split into hydrogen and oxygen. The produced H2 gets stored in various forms (liquid, gas, and solid) [71]. The stored gaseous hydrogen then gets charged to the fuel cell (FC) to produce electricity for stationary and transportation applications. Table 2 summarizes recently studied grid-integrated and standalone HRES architectures including the possibilities that lie in HRES architecture choices.

Table 2: Recent HRES-studied architectures

	PV	WT	ST	BM	HP	Bt	DGn	Elz	HS	FC	G	SA	Year
[72]	O					O	O				O	O	2021
[12]	O					O		O	O	O	O		2021
[13]	O			O		O		O	O	O	O		2021
[60]	O	O				O		O	O	O	O		2021
[19]	O						O	O	O	O	O		2021
[73]	O					O		O	O	O	O		2021
[21]	O					O		O	O	O	O		2021
[55]	O	O						O	O	O		O	2021
[74]		O						O	O	O		O	2021
[75]	O					O		O	O	O		O	2021
[20]	O					O		O	O	O		O	2021
[68]	O	O				O	O					O	2021
[56]		O				O		O	O			O	2021
[26]	O					O		O	O	O		O	2021
[10]	O	O	O			O	O				O		2022
[76]	O	O					O	O	O		O		2022
[63]	O	O						O	O		O		2022
[77]				O				O	O	O	O		2022
[56]	O	O				O		O	O	O		O	2022
[16]	O					O		O				O	2022
[78]	O					O		O	O	O		O	2022
[79]	O					O						O	2022
[17]	O	O				O		O	O	O		O	2022
[18]	O	O		O				O				O	2022
[24]			O					O	O	O		O	2022
[80]		O	O					O	O	O		O	2022
[25]	O					O	O					O	2022
[81]	O	O			O	O	O					O	2022

2.1 Solar, Wind, and Battery

Hybrid PV-WT-Bt systems are highly preferred in studies for rural applications [58], [64], [65], [67], [79], [82], [83]. Numerous studies examined hybrid renewable energy systems (HRES) using the battery (Bt) for energy storage. According to [58], an optimal sizing of a PV-WT-Bt hybrid power system was proposed to be applied to the weather station in Troyes-Barberey, France. The system met the demand requirements with minimal total cost. Although PV-WT-Bt systems are cost-effective, various factors might affect the optimal sizing, reliability, and costs of this system. For example, considering the WT outage rate might have a high impact on the costs and reliability of the system [65]. In addition, considering demand-side management in the PV-WT-Bt system can reduce the operation cost of the system [82]. In brief, there are choices to consider in HRES studies regarding various parameters to size the system. The sizing of the system should incorporate the most possible parameters regarding components, reliability, and costs to obtain optimal results. Similarly, the load profiles also have an impact on the sizing of the system. Load profiles can be forecasted or can be used from the measured, existing data libraries. Using PV-Bt systems in residential and building applications in Africa and Europe, [79] examined the impact of different seasonally, monthly, and daily adjusted load profiles. The choice of load profiles had a direct impact on energy costs. There was a direct correlation between the load profiles and the energy costs. Moreover, PV energy generation had a direct impact on the costs and Bt capacities in addition to load variability. The choice of load profile may also influence the selection of storage components since Bt has a low energy density and is not considered effective for storing seasonal energy. However, from all the mentioned research works, it can be concluded that PV-WT-Bt HRESs are capable of providing cost-efficient energy solutions for remote applications.

It has been demonstrated that PV-WT-Bt has the potential to satisfy the power demand of power consumers in some studies. The undeniable fact is that the utilization of the battery in this kind of system highly depends on the battery’s energy capacity and state of charge (SOC). The energy capacity of the battery is defined as the amount of energy that can be stored. Furthermore, Bt SOC is fixed between 0 and 100 percent and depends on the voltage, current, and temperature of the battery cell. At a specific point in time, SOC measures the amount of energy left in the battery compared to its maximum capacity. In addition to overcharging and deep discharging, charging at a high capacity rate, storing at full SOC, and operating and storing at high temperatures affect the battery’s health and cause it to degrade. Thus, in HRES systems, Bt should be handled with care to ensure that the battery maintains an optimal SOC, which leads to less degradation. When one battery fails in the PV-WT-Bt system, the other battery can be used to supplement it [9]. In addition, intermittency that lies in solar and wind power can negatively impact the Bt capacity, so it is the responsibility of HRES studies to ensure that the power generation is maintained. To achieve this, many PV-WT-Bt systems incorporated a diesel generator (DGn) as a solution. Further, they have proven to be cost-effective and reliable for the fulfillment of remote energy demands. Authors in [62], [68], [72], [84] studied different PV-WT-Bt-DGn HRESs.

2.2 Solar, Wind, and Hydrogen

Batteries (Bt) are often seen as an energy storage solution for renewable sources because of their technological maturity. However, because of their low energy density and high self-dispatch rate, they are not always the most suitable option to address the seasonal mismatch between energy production and load [85]. As a result, hydrogen storage (HS) is found to be advantageous. Since HS has a high energy density and a low discharge rate, they can be used for seasonal energy storage and to satisfy seasonal power demand [86]. In addition to storing daily and seasonal loads, HS can be combined with Bt as a hybrid energy storage system, giving priority to batteries for daily storage and hydrogen for seasonal storage. Moreover, the priority for charging and discharging the Bt and HS system depends on the energy management strategy [20]. Supercapacitors are also used to store energy, major benefit of supercapacitors is their ability to deliver energy rapidly due to their high power density [56]. For the stable power supply at a given time, as mentioned before, diesel generators(DGn) are also found integrated into HRES. PV-WT-Bt-DGn-H2 configurations were studied recently in [14], [56], [57]. Authors of [57] pointed out that battery technology is more mature and economically superior to hydrogen storage technology. Furthermore, authors demonstrated that the PV-WT-Bt-DGn-H2 configuration is economically feasible and environmentally friendly, as it assures a high renewable fraction [14]. In addition, it is found that the PV-WT-Bt-DGn-H2 system is reliable and cost-effective for long-term projects [56]. Overall, DGn and HS with PV-WT-Bt were found to be cost-effective, however, in terms of environmental considerations, the DGn is still not a viable option due to its high carbon emission rate. In comparison to the H2 system, batteries proved to be a more economical storage method, however, HS is advantageous in terms of the seasonal storage and distribution of energy. This is the reason why many studies have attempted to implement both hybrid Bt and H2 systems in HRES.

Several articles [16], [17], [56], [61], [73], [75], [78], [87]–[90] have studied solar photovoltaic (PV)-wind turbine (WT)-battery (Bt)-hydrogen (H2) systems. In [81], authors studied PV-WT-Bt-H2 HRESs to minimize their life cycle costs (LCC). WT-H2, PV-H2, PV-WT-H2, WT-Bt, PV-Bt, and PV-WT-Bt have been investigated, with WT-PV-Bt proving to be the most cost-effective. In [56], for different locations in Canada, the authors proposed the study of these systems based on real-time solar and wind data. Fuel Cell (FC) costs were predicted to be more sensitive to market changes than other components. Furthermore, researchers studied the implementation of the PV-WT-Bt-H2 system for inland transportation through the Nile river [78], which increased overall system efficiency. In this study, an onboard renewable energy system with a PV-Bt-H2 system was proposed in which H2 was generated, stored, and consumed. Similarly, the system proposed in [75] reduced the energy loss by 7 % for the heat application of the standalone house located in Tahiti, French Polynesia. The overall efficiency of the system is improved in studies; albeit the complexity of the H2 system integrated with HRES has been poorly explained in terms of system cost and reliability. However, the study in [16] talked about the H2 system cost which concluded that the price of water electrolyzers affects the cost of green H2 production. From the mentioned studies, it can be seen that the H2 system is promising, but renewables with Bt are still considered the most cost-effective option. Integrated H2 systems with HRES rely heavily on FC and Elz costs, according to research. In addition, the H2 system is depicted as vulnerable to emerging markets [91]. However, to make H2 systems feasible in HRES for different stationery and transport applications, research is still underway realized by various authorized stakeholders to reduce the Levelized cost of energy(LCOE) and Levelized cost of hydrogen (LCOH).

Various studies were conducted considering PV, and WT integrating H2 systems in HRES without considering any other storage methods like batteries(Bt). Several research works presented the sizing and optimization based on the PV-WT-H2 system including electrolyzer, hydrogen storage, and fuel cell [66], [15], [57]. However, the consideration of intermittency that lies on the electrolyzer was overlooked. In studies, electrolyzers were supposed to function at constant working conditions, and hydrogen production was considered directly proportional to the electrolyzer's efficiency. Electrical power was supposed to be supplied from renewables like PV and WT directly considering that they were able to maintain the rated power of the electrolyzer for the production of hydrogen without taking into account any other storage options. A study was conducted in 2014 [66] to determine the optimal PV-WT-H2 configuration. In this study, the authors stressed the need for a large hydrogen storage capacity. This probably would have increased the system’s cost, but green hydrogen’s use had a positive impact on the environment. In [15], authors concluded that PV-WT-H2 systems could be cost-effective and reliable in Iran. Moreover, PV was discovered more economical, and WT was suggested to be used as an auxiliary energy source. Based on a case study involving a remote village in India, [57] also concluded that PV-WT-H2 systems were economical in terms of cost of energy (COE). It seems that the H2 system integration into PV-WT HRES is found well-suited in places with high solar irradiation and wind speed, such as Iran and India. In these studies, it is shown that integrating the H2 system into PV-WT HRES offered significant potential in cost minimization and reliability. However, the intermittency that lies on the electrolyzer to produce the hydrogen at a constant rate was not presented. In addition, the detailed analysis of intermittency presented on electrolyzer, electrolyzer shutdown conditions, and degradation was less studied which can be the prospect for future HRES studies.

2.3 Solar, Wind, Other renewable energy sources and storage

Numerous studies, as shown in table 3 considered renewable energy generators integrated with solar photovoltaic (PV) and wind turbines (WT). Generators like methanol fuel cells (FC), hydropower (HP), biomass (BM), solar thermal collectors (ST), etc. can be noticed. Authors of [11] examined PV, WT, and HP as separate distributed energy generation units. HP was integrated into the generation unit with PV to maximize power production in the system. In this study, HP systems demonstrated the highest efficiency in energy management and system sizing as they directly supplied energy to the consumer without requiring Bt storage. Based on the authors’ belief, the system would be a suitable solution for sparsely populated and mountainous areas to meet their energy demands. In addition, [22] conducted a study of a WT-PV-Tidal-DGn-H2 microgrid to determine the most cost-effective and reliable hybrid system based on Tidal, PV, WT, and FC. The power generated by Tidal-PV-WT sources exceeded the load demand, according to a study. Despite this, study did not address the technical difficulties associated with tidal power generation. Apart from HP sources, BM and ST sources can also be integrated into a PV-WT microgrid. To reduce H2 supply costs, [70] studied a PV-WT-ST-BM-H2 microgrid. [77] developed BM-based hybrid H2-thermal energy storage systems for H2 vehicles and buildings. Using this microgrid, energy expenditure and carbon emissions were minimized. It can be predicted from the research that it is possible to integrate biomass (BM) with PV-WT as a viable energy source in HRES, but it may not be as efficient as HP, WT, and PV in terms of environmental impacts by observing the overall lifecycle analysis of BM energy conversion technology: co-firing with peat and combined heat and power systems [92].

Table 3 PV-WT with other renewables in recent HRES studies

	PV	WT	ST	BM	HP	Bt	DGn	Elz	HS	FC	G	SA	Year
[13]	O			O		O		O	O	O	O		2021
[22]	O	O			Tidal			O	O	O		O	2021
[77]				O				O	O	O	O		2022
[76]	O	O		O				O				O	2022
[10]	O	O	O			O	O				O		2022
[24]			O					O	O	O		O	2022
[80]		O	O					O	O	O		O	2022

2.4 Solar, Wind, Grid integrated microgrids

At present, the power grids are responsible for meeting a large portion of power demand. In 2019, almost two-thirds of global grid electricity was derived from fossil fuels, 26.6% from renewable energy, and 10.4% from nuclear power [93]. There is a great deal of stress placed on utility grids due to the pressure to meet the needs of consumers without interruption. Due to the long distances involved in the transmission and distribution of electricity, power losses are inevitable in centralized grids. For this purpose, microgrids have been introduced to provide energy for local places such as universities [14], residents [16], data centers [61], weather stations [58] etc. Due to their capability to reduce grid stress, microgrids are a reliable and flexible alternative for energy transition [94]. In addition, it can be both grid-connected and standalone.

Microgrids that are connected to the grid are mostly able to handle power deficits as the grid ensures the provision of insufficient power that is not fulfilled by the microgrids. The surplus power generated by the microgrids in addition can be sold to the grid. Although the integration of microgrids with grids is accompanied by several control problems, this is becoming less of an issue with the advancement in control system technology [95]. As described in [96], the PV-WT generated energy was first fed into the grid and then the excess was used to produce H2. By increasing the self-sufficiency of HRES and reducing the extraction of power from the grid as much as possible during peak power demand, authors intended to reduce the grid's dependence on the load [97]. Three scenarios were considered in [20], in which the grid was integrated with the PV-BT system. In the first study, only the grid was considered to meet all load requirements, while in the second study, PV-Bt-H2 systems were considered to meet all load demands in terms of power consumption. This study found that grid integration with HRES was a more cost-effective solution. During peak power, when microgrids were not able to meet the load demand, grids were found used as a backup power source in the studies. Authors integrated the grid into HRES so that during times of energy shortage when the HRES was unable to meet the load demand, the grid was able to assist [21]. While, presenting the grid as a backup power source normally increases the stress on the grid, which has been overlooked. In studies, grids were also found considered an infinite power source which meant the surplus power from the other power sources can be fed to the grid, and during peak demand, grids were supposed to meet all the necessary power demands regardless of the grid capacity and time. That is not the practice in reality though. In [85], authors incorporated the grid into HRES to analyze the costs and revenues so that excess power could be sold to the grid and power deficits could be met by the grid.

As an alternative to the grid as a backup power source, the study may also focus on taking the grid as a major power source to meet the power demand. The provision of power to the grids can be considered in light of the number of distributed energy resources or microgrids, including solar photovoltaics, wind, hydropower, natural gas generators, batteries, and H2 system. As a result of which, grids may eventually be capable of meeting all the power needs of consumers all year long. However, it is not an easy task to maintain the consistent power flow from several distributed energy systems incorporating several microgrids to the power grids which may result in frequent grid congestion. Overloads of power to the grid may also damage the grid, resulting in blackouts. That is why the stress on the grid, grid flexibility, environmental and societal acceptance of distributed energy systems to grids, and grid congestions can be possibilities for future studies in HRES.

In some ways, the grid-integrated HRES system can be considered a safe haven for HRES systems, which takes into account power deficits and surpluses, ensuring that load requirements are met. Although grid integration is advantageous in terms of reducing energy costs, voltage and frequency mismatches during the feeding of surplus electricity from renewable sources may pose a challenge. Therefore, modern technologies are used to address voltage or frequency mismatches, including a variety of control strategies, optimization techniques, energy storage devices, and fault current limiters. Furthermore, the grid may not be available to all locations in which small villages or islands are located. A standalone microgrid is preferred to meet the energy load demand in areas where the grid is not available. Various HRESs were studied [56], [57], [75], [78], [59], [88], [90] to meet the energy demand for independent houses, dwellings, buildings, islands, etc. Depending on the size and location of the system, standalone studies may have different objectives. In [59], authors studied system sizing and energy management, and in [88], authors studied system sizing for standalone use.

3. Recent application fields of HRESs

The energy demand of standalone islands, commercial buildings, houses, data centers, weather stations, etc. has been addressed by numerous research projects. The study of [68], [65] in Paris, France, and Uttarakhand, India included a study of a single house. For the Sahline village of Tunisia, [59] studied the application of pumping water to agricultural fields. Furthermore, some research studies proposed HRES to satisfy the energy demand of commercial buildings at various locations including universities and high-rise buildings [14], [16], [19], [21], [72], [77], [98]. Studies have often encountered energy demand satisfaction on a small scale such as a single house, one building, or a small village, but authors presented the grid-integrated HRES system which could meet the needs of 2500 dwellings in Brussels, Belgium [97]. Similarly, authors presented their study for Marseille, France, which had 1500 people living in it [13]. According to the research, the energy demands of data centers, weather stations, and telecommunication centers can also be fulfilled with HRES. Three papers presented standalone HRES microgrids for data centers in [61], [59], [80], while [58] highlighted HRES for meeting weather station load demands. Recent research works demonstrated that HRES is being applied in a wide range of application fields and locations as shown in Table 4. It shows the potential of green energy emerging technology development to sort out the energy crisis and reduce fossil fuel use.

Table 4 Recent HRES studied application fields and locations

	Continent	***Location***	***Study Area***	***Year***	***G***	***SA***
[55]	Asia	Gujrat, Lamba, India	150 households	2021		O
[60]	Asia	Hong Kong	High-rise building, Transportation	2021	O	
[99]	Asia	Qingdao, China	Island	2022		O
[76]	Asia	Siba, Gansu Province, China	Residential, Transportation	2022	O	
[19]	Asia	India	Institutional building	2021	O	
[72]	Asia	India	College	2021	O	O
[100]	Asia	West Bengal, India	Ghoramara Island,	2023		O
[101]	Asia	Tamil Nadu, India	Coastal village	2022		O
[102]	Asia	Pakistan	Cities	2022		O
[103]	Asia	Bangladesh	Community	2022		O
[104]	Asia	Maldives	Offshore energy transition	2022	NA	NA
[105]	Asia	Vietnam	Warehouse	2023	O	
[20]	Asia	Johar Bahru, Malaysia	250 residentials	2021		O

[106]	Africa	Kano, North Nigeria	Healthcare center	2022		O
[107]	Africa	Farafra, Egypt	Region	2023	NA	NA
[108]	Africa	Iseyin, Sokoto, Maiduguri, Jos, Enugu, and Port-Harcourt, Nigeria	Health Clinic	2021	O	
[109]	Australia	Perth, Adelaide, Melbourne, Sydney, and Brisbane	10 types of buildings	2023	NA	NA
[110]	Australia	Western Australia	Remote community	2020		O
[111]	Europe	Resadiye, Sakarya province, Marmara region, Turkey	5 poultry farms and 150 houses	2022	O	O
[13]	Europe	Marseille, France	1500 inhabited region	2021	O	
[75]	Europe	Tahiti, French Polynesia	Single house	2021		O
[16]	Europe	South Finland	Building	2022		O
[68]	Europe	Paris	Single house	2021		O
[8]	Middle East	Eastern Iran	Case study	2021		O
[10]	Middle East	Tabuk, Saudi Arabia	Whole region	2022	O	
[112]	Middle East	Iran	Residential	2022		O
[81]	Middle East	Iran, Kuwait	Island	2022		O
[22]	Middle East	Gorgan, Urmia, Razd Iran	Remote region	2021		O
[17]	NA	NA	Data centers	2022		O
[18]	NA	NA	Residential	2022		O
[73]	NA	NA	Residential	2021	O	
[21]	NA	Remote Islands	Buildings	2021	O	
[24]	NA	NA	Grid-level energy production	2022		O
[80]	NA	NA	Data centers	2022		O
[77]	NA	NA	Building/hydrogen vehicles	2022	O	
[113]	South America	Ecuadorian Amazon region	Region	2023	NA	NA
[114]	South America	Cuenca, Ecuador	aircraft-type buildings	2022		O
[56]	North America	Canada	Pelee, Wolfe, and Saint Pierre Island	2022		O

4. Recent HRES studies and transportation applications

Currently, HRESs are being extensively studied to meet the electricity and H2 needs of battery-electric vehicles (BEVs) and fuel cell vehicles (FCVs). The advantages and disadvantages of BEVs and FCVs have been widely discussed. BEVs require electricity to charge their batteries, whereas FCVs require H2 to generate electricity. Both electricity and H2 demand can be met by using HRES in vehicular applications. Charging stations for BEVs can be powered directly by PV or WT, while H2 for FCVs can be generated by electrolysis. It has been reported that some studies examined both the electricity and H2 requirements of BEVs and FCVs simultaneously [115], [116], [117] where the electricity and H2 demand was met by PV or WT: H2 was produced by electrolysis. Intermittency lying on the electrolyzer was not mentioned though. In addition, the surplus energy from renewables can also be fed to Bt in FCVs if Bt is integrated into it [118]. By using the excess energy generated by PV and WT, H2 can be produced and stored. Later on, stored H2 can be used to power the FCVs or the FCs can use H2 to meet the energy demands of the houses, residents, etc. [119]. Additionally, when the FCVs are at rest, such as at night when no one is using them to travel, they can be used as a source of energy to power the residents' homes. It is commonly referred to as a vehicle-to-grid (V2G) application. In the V2G application, the vehicles are used as a source of energy during rest. It has been noted that V2G applications have been studied extensively [115], [118]. Having FCVs operate at night to provide electricity to residents reduces the amount of electricity imported from grids [120], which may reduce the amount of power consumed during peak periods. Additionally, Bt present in BEVs can also be used as an additional storage mechanism when they are at rest, which may improve the system's reliability as well [121]. Table 5 presents a variety of recent research works related to HRES with vehicle applications. Stationary and vehicular applications require large amounts of electricity and H2 if they operate simultaneously for large-scale operations. It may necessitate a large number of energy-producing components, such as PVs, WTs, storage devices, and Elz. A challenge in itself is selecting the electrolyzers for the production of H2 at a large scale to vehicles' H2 needs. This is because the rated power of the electrolyzers must be considered to produce the purest H2 to reduce the degradation of FCs in FCVs. These factors can be considered in future studies.

Table 5: Recent HRES transport applications

	Key Remarks
[118]	Satisfy BEVs electric and FCVs hydrogen loads, V2G applications
[117]	Satisfy BEVs electric and FCVs hydrogen loads, V2G applications
[119]	Satisfy a house electric and FCVs hydrogen loads of a single house
[122]	Grid to HVs, FCVs as storage in rest
[123]	HVs as a load, hydrogen storage scheduling, and charging demand

5. Energy Management Strategy (EMS)

Since renewable energy resources are intermittent, storage devices are required as backup sources. Nevertheless, hybridization of the system components requires strategies to control the power flows and to ensure that the load demand is met. To coordinate the power flow in HRES, the control strategy is known as the Energy management strategy (EMS). The primary goal of the EMS is to satisfy the energy demand, maximize the use of produced energy, reduce associated costs, increase system lifespan, and maximize efficiency [6]. In this section, EMS adopted in various recent scientific literature is presented. Depending on the study's goals, HRESs consider different EMS. In some studies, EMS is implemented just to meet energy demand without considering the degradation of system components and minimization of costs. Most HRES use simple rule-based EMS, which takes into account H2 storage capacity, H2 SOC, Bt storage capacity, Bt SOC, and power flow from production to consumption. In this case, the surplus energy produced by the generators can be stored in the storage and released from the storage to meet the load demand during a power deficiency. Priority is assigned to storage systems based on SOC and energy capacity. In some cases, DGn is also used to secure the power flow.

Authors in [89] tried to size a WT-PV-H2 system that could manage excess and shortfall of energy from PV and WT. Similarly, in [62], surplus power from generators was fed to the Elz, while deficit power was provided by FC. HS was used to store the H2 so that H2 can be charged to the FC in case of power deficiency. As described in [9], authors presented EMS where the priority was PV-Bt-H2-G, which meant that surplus PV electricity was fed first to the Bt, then to the H2 system, and finally to the grid with the remainder. Energy deficits were met by Bt, FC, and the grid consecutively. Authors of [15] discussed hybrid PV-WT-FC system sizing and EMS. In this study, surplus electricity from PV-WT was fed to the Elz to produce H2. In times of energy deficit, stored H2 in the tank was charged to FC. In addition, [79] presented a simple rule-based energy management strategy for PV-Bt systems. PV excess electricity charged the Bt based on its SOC, whereas the Bt provided deficit electricity based on its depth of discharge. In [59], authors analyzed different PV-WT-H2-Bt configurations for the optimal sizing of the system. Charge and discharge of energy were prioritized according to lack or surplus PV-WT energy generation. Bt or FC was discharged during energy shortages, while Elz and Bt were charged during surplus energy. Authors of [85] proposed three strategies for PV-H2-Bt-grid systems, namely conventional, peak shaving, and hybrid strategies. Conventionally, surplus electricity from the PV system was stored first in the storage system and then exported to the grid if it was full. Electricity was first provided by storage and then by the grid to make up for the insufficiency. In peak shaving, the hydrogen was stored in warm months when the production of energy from PV was high and preserved for peak shaving during cold months. As a final step, in the hybrid strategy, Bt and HS were used by conventional and peak shaving strategies. In these studies, the degradation of system components or improvement of a component’s lifetime was not taken into account. EMSs were only focused on meeting energy demands.

Contrary to the EMS mentioned previously, some research has been conducted on EMSs considering the improvement of the system and degradation to improve its functionality over a long period. A multi-objective robust stochastic energy management model was developed by authors in [80] to meet the energy demands of data centers, residential, and commercial buildings. To improve the system’s performance in terms of cost and reliability, they proposed an energy management model based on WTs and power market uncertainty. The epsilon-constraint and fuzzy-based decision-making methods were applied to choose the leading solution among the Pareto set. The epsilon-constraint method is generally used to solve the multi-objective functions in order to obtain the trade-off condition between conflicting multi-objective functions. The problem is solved by considering one objective function as a major objective function and the other as the constraint of the major objective functions. The fuzzy technique normalizes the conflicting objective functions and the solutions are selected by trading off the results of multi-objective problems. Additionally, [90] presented a dynamic H2 management strategy that ensured the uninterrupted provision of H2 to the demand side. The study was conducted using the WT-Bt-H2 system. Under different reliability and technical constraints, EMS considered Bt to assist Elz in maintaining its rated power over long periods of low wind conditions. WT’s low power production shut down the Elz and in that case, HS supported to fulfill the H2 demand until the HS reached its minimum level. In the case of high Bt SOC and average WT power, Elz obtained power from WT. The power was also sent to the dump load when Bt SOC was maximum in case of high WT and Elz power. The operating limits of the components were considered for the overall system performance.

Similarly, energy users were encouraged to shift their consumption from peak periods to other periods using demand management strategies based on fuzzy techniques to reduce expenses to the greatest extent possible [82]. In light of the technical limitations of the components, it considered improvements in system performance. EMS with the fuzzy technique was also applied in [67] to enhance the life of Bt based on the Bt SOC. PV and WT power was fed into the DC grid to supply DC loads. When there was a power shortage, AC grids were activated. During a power outage, the Li-ion battery was discharged first and provided power for short periods, whereas the FC provided power only for long periods. It was charged by excess power on the DC grid. Further, [24] introduced the peak shaving and load leveling strategy to determine the best configuration for producing hydrogen during peak demand periods using concentrated solar collectors and hydrogen gas. At peak times, H2 was utilized to run the FC and the power generated by the FC was fed to the grid. In [23], PV-Bt systems with or without H2 production were presented. To minimize energy loss and improve performance, a simple rule-based energy management strategy was employed which takes into account the fulfillment of the energy demand without considering the possibility of component degradations and economic analysis. In this case, when the battery was full, the excess power generated by the PV was decided to produce hydrogen rather than dump the energy into the dump load.

A component economic analysis was also conducted in [21] by considering PV, Elz, FC, and HS costs, as well as satisfying energy demands. [124] proposed a PV-BT-FC hybrid energy system and evaluated the presence of a demand response program (DRP). Normally, electrical loads participate in DRP to reduce operation costs and transfer some amount of load from peak periods to other periods. In this study, DRPs were shown to improve the economic performance of the systems, minimize the total costs associated with the systems, optimize the operation of distributed energy sources, and reduce dependency on upstream grids. A standalone microgrid with electric and hydrogen loads was also considered. In [73], the following two EMS were proposed as EMS 1: PV>Bt>H2 system prioritizing energy supply to the load. The excess energy from PV was used to charge the Bt while HS was charged and discharged only when Bt was full. During a power deficit, Bt was discharged first and then the H2 system followed. EMS2 introduced an additional stage to the start of EMS1 as HS (for H2 demand only)>PV>Bt>H2 system prioritizing storing H2 in the tank first. Solar tracking systems were tested to determine their economic feasibility by comparing their performance with PV systems with fixed tilts, tilt angle adjustment systems, and tracking systems. In this case, EMS1 was concluded to be economically feasible when the energy wastage was not taken into account however, the result was just the opposite in the case of EMS2. In addition, a microgrid with EMS2 equipped with an east-axis PV tracking system was concluded to reduce the LCOE compared to a fixed-tilt PV system. To reduce peak consumption, demand-side management strategies based on peak load shifting were used [19]. Under multi-criteria decision analysis, the best-worst approach was used to determine the optimal energy configuration.

Additionally, [125] examined EMS for smart grids using renewable energy and hybrid energy storage technologies based on H2 and biofuels. It included equipment dynamics, operating and maintenance costs, equipment lifetime, power quality, frequency control, voltage control, and power set-points for the Elz, FC, and grid power exchange. Power set-points are defined as the electric power settings at which the components operate optimally without degradation. It is recommended for the components to function around the power setpoints because the variation may lead to the degradation of components. In European utility grids, set points for the frequency are normally 50 Hz. The change in production and generation of power changes the frequency on the grid. It is necessary that the grid functions on the frequency setpoints. In [12], the authors presented a new EMS for hybrid electric vehicle charging stations that were based on a biogeography-based optimization (BBO). BBO is a nature-based optimization method motivated by the geographical distribution of species and ecosystems [126]. In this EMS, the energy available in the HS and Bt was optimized without considering the total amount of H2 generated and consumed. To maximize H2 production, [11] studied EMS based on control of the Bt SOC as well as strategies based on hysteresis bandgaps. The hysteresis band control method is a set of algorithms designed through heuristic rules to handle the energy mismatch in the microgrids [125]. Electrolyzers and fuel cells follow this method in which their values can be defined according to the maximum or minimum state of charge of the energy storage unit. In this study, Elz operated in surplus energy to produce H2, FC operated in deficit energy, and hysteresis bandgap was designed to reduce the operation of battery banks increasing the use of a fuel cell and electrolyzer including their reduction in the number of shutdowns and start-ups when needed.

As far as HRES sizing and energy management are concerned, the viable power solution will not be achieved until and unless the system provides an optimal result in terms of its power, components, and reliability based on the load demand and locations. Because HRES consists of multiple components, it is challenging to size and manage each component to meet the power demands. HRES sizing and energy management largely depend on the component selection, location, load demand, selection of decision variables, constraints, and objectives defined. Based on these frameworks, results will be generated. It is for this reason that optimization frameworks should be chosen carefully based on the goal of the study to provide HRES with viable power solutions.

6. Optimization Formulation Framework

6.1 Decision variables

Decision variables are selected in an optimization problem based on the nature of the problem. Variables can be discrete, continuous, or a combination of both discrete and continuous. There are numerous system components involved in an optimization problem in HRES, including energy generators such as solar photovoltaic (PV), wind turbine (WT), hydropower (HP), biomass (BM), etc., storage devices like a battery (Bt), hydrogen storage (HS), and energy conversion devices such as electrolyzer (Elz), fuel cell (FC) and inverters. PV and WT generators are sized according to the area, number, rated power, etc. Bt and HS depend on the charging and discharging capacity. Furthermore, Elz and FC are also affected by rated capacity, area, and numbers. Various decision variables used in the research studies are tabulated in Table 8.

6.2 Constraints

In optimization problems, constraints are an imperative factor to consider. Before choosing the right optimization algorithm, constraints must be identified. Optimization algorithms may differ based on linear or non-linear constraints. In essence, constraints define the boundaries of optimization problems. Within the search space defined, there will be an optimal solution. Within the maximum and minimum boundaries, many decision variables are controlled. The search space of the HRES system that includes battery and hydrogen storage is limited by the minimal and maximum levels of charge and hydrogen tank level (HTL). Within the search space of maximum and minimum state of charge and hydrogen tank level, [9], [11]–[14], [17], [21], [61], [88], [89] formulated optimization problems. [89] formulated the linear constraints on the number and power of the fuel cell and electrolyzer. [22] had various linear power balance constraints. A hybrid renewable energy system (HRES) deals with lots of constraints that are summarized in Table 8.

6.3 Objective functions

The objective function is defined in all optimization problems. Depending on the study's objective, it can be linear or nonlinear. The majority of studies in HRES focus on technical, economic, and environmental objectives. The objective function can be single or multiple depending on the studies. For the analysis of hybrid renewable energy systems (HRES) [8], [10], [15], [22], [26], [65], [79], [82], [89], [115], [124] developed a single objective function. On the other hand, [12], [13], [19], [62], [63] presented multi-objective problem formulations. Multi-objective functions can be solved in different ways. The classical method to solve the multi-objective function is based on the weighted sum method [127]. Using various weighting coefficients in each objective, the weighted sum approach adds all the objective functions together. Authors in [11] presented the weighted sum method for solving multi-objective optimization problems in which the final objective was to minimize the cost per unit of electricity. Different weighting coefficients were presented to the partial objective functions as unmet loads, dump energy, and differences between the final and initial capacity of short and long-term energy storage. Similarly, authors in [25] provided optimal PV array capacity, battery size, and expected diesel fuel cost so that the weighted sum of the annual capital cost and fuel cost was minimized. Except for the weighted sum approach, the Epsilon-constraints method is also used to solve multi-objective optimization problems. Following the different objective functions, the HRES system deals with lots of costs as shown in Table 6, and reliability factors as shown in Table 7. However, environmental and social factors are found to be less studied. In addition, the sensitivity analysis in relation to costs and reliability is less presented in the studies. Table 8 presents the objective functions of various HRES studies.

6.4 Sensitivity Analysis :

Sensitivity analysis serves as a valuable technique employed to ascertain the influence of independent variables on a particular dependent variable within a given set of assumptions. Numerous studies within the field of Hybrid Renewable Energy Systems (HRES) delve into the realm of sensitivity analysis. For instance, an insightful review study [43] expounds upon sensitivity analysis by encompassing diverse economic parameters, including interest rates, battery prices, and carbon emission costs. This study elucidates the sensitivity aspects concerning the evaluation of HRES's economic viability, thereby facilitating informed decision-making for policymakers and investors regarding HRES deployment.

In another notable publication [44], the authors present an extensive sensitivity analysis incorporating various factors such as wind speed, solar radiation, component costs, fuel prices, emission penalties, electricity prices, rate of return, annual interest rates, and more. This comprehensive analysis sheds light on the sensitivity aspects encompassed within multiple studies. Likewise, [72] offers a meticulous examination of sensitivity analysis pertaining to both grid-connected and off-grid HRES, specifically by augmenting the load profile and comparing the outcomes with an existing hybrid energy system implemented at an educational institution in India.

Furthermore, the authors of a different study[128] investigate sensitivity in relation to inflation and discount rates, various carbon tax prices, fluctuations in load proportion, and capacity shortage proportions. They conduct an in-depth sensitivity analysis of PV/pumped hydro storage/ micro gas turbine energy systems, meticulously varying each input variable such as wind speed, solar radiation, and energy costs.

Moreover, an additional study[129] showcases the integration of a grid-connected PV/Bt energy system for charging electric vehicle batteries and powering a supermarket. Within this context, a sensitivity analysis is conducted with regard to the energy consumption of the supermarket, renewable energy availability, and carbon pricing. The review study [31] emphasizes the utilization of various sensitivity analysis methodologies, including the One Factor at a Time (OFAT) approach, which involves altering one input variable while keeping others constant. Furthermore, Monte Carlo Simulation (MCS) is employed, entailing random sampling of input parameters from their respective probability distributions, followed by multiple simulations of the HRES model. Lastly, the study discusses Latin Hypercube Sampling (LHS), which provides a more efficient sampling strategy by dividing the range of each input parameter into equally probable intervals and randomly selecting one value from each interval for each simulation run. These techniques are predominantly applied to parameters such as solar radiation, wind speed, hydrogen storage capacity, and load demands, considering their economic implications.

It is noteworthy that most of the literature within the HRES field aims to evaluate and optimize numerous criteria encompassing economics, reliability, environment, and social aspects, typically focusing on specific locations, cities, or countries while employing fixed and predetermined values for system parameters. However, since these absolute values are subject to change and lack predictability, sensitivity analysis, as demonstrated in the aforementioned studies [130], [131], proves relevant in accounting for the uncertainty during optimization. By systematically examining the impact of variations in input variables on the objective function or constraints, sensitivity analysis facilitates a comprehensive understanding of the optimization model's responsiveness and sensitivity.

It is crucial to acknowledge that the selection of essential sensitivity parameters in HRES studies depends on the specific objectives, system configuration, and operational considerations. When the focus is primarily on technical aspects such as system sizing, performance, and operation, certain parameters like carbon emission costs, interest rates, inflation rates, tax incentives, and energy prices may have a diminished impact. However, it is important to note that carbon emission costs play a significant role in evaluating the environmental impact and social values within HRES studies. Similarly, while interest rates play a significant role in financial analysis and investment decision-making, their direct influence on the technical performance and economic feasibility of the system is relatively less influential compared to other parameters. Likewise, the impact of tax incentives, such as investment tax credits or renewable energy subsidies, depends on the specific policies and regulations in different regions. Changes in power demand proportion, although affecting the utilization of different energy sources, may not substantially alter the technical characteristics and operation of the system. Considering these factors, conducting a comprehensive sensitivity analysis that aligns with the specific objectives and requirements of the HRES study is essential. Such an analysis should incorporate parameters that have a significant impact on the technical and economic feasibility, such as solar radiation, wind speed, energy consumption, component costs, battery storage capacity, H2 tank capacity, grid electricity prices, operation and maintenance costs of the components, efficiency of energy conversions and storages, capacity factors, and weather patterns. By focusing on these essential parameters and potentially omitting less influential ones, computational load and time in HRES studies can be reduced.

Table 6: Cost indices studied in recent HRES study

Cost	***Definition***	
TSC	Total system costs (TSC) within the system lifetime include the initial price of the components, total capital costs, installation costs, replacement costs, fuel costs, operation and maintenance costs throughout the lifetime	[24], [58], [63], [65], [69], [73], [87], [124]
NPC	Net present costs (NPC) during the lifetime of the project includes all costs associated with installing and operating the component deduced from all revenues that the component earned	[15], [22], [66], [68], [85]
TAC	Total annual costs (TAC) include capital cost (Capex), operational cost (Opex), maintenance costs, and replacement costs of all the system components	[9], [13], [18], [25], [26], [70], [89], [115]
LCOE	Levelized cost of energy (LCOE) is the ratio of the total annual cost to the total annual energy generation	[10], [11], [14], [23], [64], [79], [84]
LCC	Life cycle cost (LCC) is the sum of all the costs during the lifetime of the system	[88]

LCOH	Levelized cost of hydrogen (LCOH) is the capital and operating costs of hydrogen production without H2 storage and transport	[16], [90]
TOC	Total operation cost (TOC) is the sum of bought power from the upstream network grid and gas utility differencing the selling of the power and gas to the upstream utility	[82]

Table 7: Reliability indices studied in recent HRES study

Power Reliability	***Definition***	
LPSP	Load power supply probability (LPSP) is the load not supplied by the system, the ratio of power deficit to the load demand for some time	[58], [64], [66], [73], [89]
EENS	Expected energy not supplied (EENS) is the expected energy that is not going to be supplied when the system load exceeds the available generation capacity. When the demand increases suddenly, the generated energy is not enough to fulfill the load demand	[65]
LOLE	Loss of load expected (LOLE) is the average number of hours for which the system load is not expected to exceed the available generation capacity	[65]
LA	Level of autonomy(LA) is the percentage of time when the renewables are solely and sufficiently meeting the load demand	[61]
SSR	Self-sufficiency ratio (SSR) is the percentage of the load that is met by the system, It indicates the renewable energy penetration level	[85]
SCR	Self-consumption ratio (SCR) is the ratio of onsite renewable energy consumption to total energy generation.	[132]
DPSP	Deficiency of power supply probability (DPSP) is the ratio of the total energy deficit to the total consumption for a considered time	[59]
LOLP	Loss of load probability (LOLP) is the ratio of the total loss of energy supply to total load demand.	[18]
LOEE	Loss of energy expected (LOEE) is the total loss of energy in time intervals	[15]
GD	Grid dependency (GD) is the ratio between the total energy imported from the grid and the total energy demanded by users	[13]
LDP	Load deficit probability (LDP) is the reliability index, owing to the insufficient supply of load demand	[22]

Table 8: Recent Optimization framework in different HRES studies

	Decision Variables	***Objective Functions***	***Goals***	***Constraints***
[13]	The efficiency of the system, lifetime of components Capital, Operation, and Maintenance costs of components	Minimize TAC, CO2, GD	Sizing, Satisfy Demand	Bt and HS capacity, BM availability, Power balance
[17]	Power production by renewables, SOC of Bt, Elz power, mass of H2 produced, FC power, mass of H2 in FC, Level of H2 in HS	Maximize Power Production	Energy Management, Satisfy Demand	Bt and HS level, FC Power, Elz Power
[20]	Area PV, Inverter, Bt, Elz, Compressor, HS, FC capacity, energy lost during charge and discharge of Bt, Annual cost of Bt, and HS	Minimize energy resource use and TSC	Satisfy Demand, Sizing	NA
[21]	Component power, Component Costs, Component numbers	Minimize Opex	Energy Management, Economic Analysis, Sizing	SOC HS, Power balance, NPV
[90]	Number WT, Bt capacity, Bt cycle spent, HS capacity, Initial Bt SOC, Elz power and operation hour	Minimize total H2 deficit, energy dump possibility, CO2 emission, LCOH	Energy Management, Prolong Component Life, Sizing	Bt SOC, Elz operation time and power, HS SOC
[80]	Deviation between actual and forecasted value, Uncertain energy demand, wind intermittency, Power market uncertainty	Minimize TSC, CO2	Improve System Performance, Satisfy Demand	Load and energy price forecast, Energy and Power balance, Bt charge and discharge, Elz performance, Demand response of load (heating and electrical)
[24]	Inlet pressure of steam turbine, Pinch point temperature difference at the evaporator, Collector outlet temperature, Figure of merit coefficient (used to determine the thermal efficiency)	Minimize TSC, Maximize exergy efficiency	Economic Analysis, Improve System Performance, Peak Shaving, Load Leveling, Sizing	Ranges of values for inlet pressure of steam turbine, Pinch point temperature difference at the evaporator, collector outlet temperature, Value range for Figure of merit coefficient from 0.3-1.5 (used to determine the thermal efficiency)

[10]	Power PV, WT, Steam Turbine, Gn (D), Thermal storage, Bt capacity, Area solar thermal collector	Minimize LCOE	Economic Analysis, Sizing	Renewable energy fraction (REF)
[25]	Number of PV, Bt, Annual amount of electrical energy generated	Minimize TAC	Improve System Performance, Satisfy demand, Sizing	Power balance, Bt energy capacity, Charge and discharge of Bt, Components stop time
[12]	H2 generation, consumption	Minimize H2 consumption, Maximize H2 generation	Satisfy demand, Energy Management, Improve System Performance	Power balance, Bt energy capacity, Power FC, Elz, Bt SOC, HS level
[16]	Capacity PV, Elz, Bt	Minimize LCOH	Sizing, Satisfy demand, Energy Management	H2 production
[132]	PV area, WT number, Bt capacity, HS volume	Optimal energy management and decision making	Energy Management, Satisfy demand	NA
[73]	Capacity of PV, Bt, HS	Minimize TSC	Sizing, Satisfy Demand, Energy Management	Bt SOC, SOC HS, LPSP
[22]	Power PV, WT, Tidal, Elz, FC, Inverter, Mass and energy capacity of HS	Minimize NPC	Sizing, Satisfy Demand, Economic Analysis	Power balance, Load deficit Probability (LDP), Water flow speed in tidal power plant, Wind speed, Power PV, WT, Tidal, Elz, FC, Inverter, Mass, and energy capacity of HST
[68]	COE, Components power	Minimize NPC, CO2 emission, Unmet load	Sizing, Economic Analysis, Satisfy Demand	NA
[63]	Reference Temperature, Solar radiation Wind Speed, Collector area, Sea water mass flow rate, Organic Rankine cycle isentropic efficiency, Warm sea water temperature	Maximize exergy efficiency, Minimize TSC, Maximize H2 Production	Sizing, Improve System Performance	Range of values for all the decision variables i.e. Reference temperature, Irradiation intensity, Wind speed, Sea water mass flow rate, Isentropic efficiency of the turbine, pump, Flat plate collector area, Warm sea water temperature

7. Optimization Methods and Solvers

The nature of the hybrid renewable energy system (HRES) is highly stochastic since the prediction of the load demands and energy production from PV, and WT is not precise. Load demands, solar irradiation, wind speed, etc. do have random probability patterns that can be analyzed statistically though. Similarly, the nature of HRES is non-linear most of the time as it deals with the non-linearities present in various HRES components that lie on energy generation units, storage units, distribution units, and their automation and control. The solution to these problems turns the optimization problem into a combinatorial constrained optimization problem with a large number of linear and non-linear constraints, single and multi-objective functions, as well as discrete or continuous variables [9], [13], [17], [18], [90], [133]. To find the most appropriate solution, it is necessary to select an optimization algorithm to arrive at the best local or global solution. The system can be optimized using exact methods, such as iterative [23], [90], linear programming [21], [61], [63], [124], analytical [134] or by using metaheuristics and hybrid algorithms [10], [11], [15], [16], [22], [79] or such methods can be implemented in varieties of commercial software such as HOMER or HOMER pro [19], [57], [72] i-HOGA [68] etc. It is imperative to note the selection of optimization methods depending on their accuracy to reach the near-optimal solution.

7.1 Metaheuristics

In hybrid renewable energy system (HRES) research, metaheuristics are widely used. This method has advantages in search landscapes, with a high probability of finding the approximated solutions close to the global optimal value. Table 10 presents various HRES research analyses based on this method. In metaheuristics, Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) have been found popular among researchers. A large number of HRES bibliography consists of PSO and GA as a primary optimization algorithm. This is the reason why this article presents in brief PSO and GA algorithms studied in recent works of literature with or without the combination of other metaheuristics algorithms.

7.1.1 PSO in recent HRES studies

Many optimization problems involving single and multi-objective hybrid renewable energy systems (HRES) can be solved using the swarm algorithm. In 1995, Kennedy and Eberhart proposed PSO [135]. Since then, it has gained popularity among researchers. PSO algorithm is a population-based intelligent stochastic method that functions on the swarm techniques, which is finding out the optimal solutions from the search space based on the search for foods by the flock of birds. Authors presented PSO as an optimal sizing tool for PV-Bt-H2-grid-based HRES in [9]. Authors of [73] attempted to resolve the supply and demand mismatch resulting from renewable energy's intermittent nature through optimal sizing of microgrid components such as PV, inverter, Bt, FC, Elz, compressor, and hydrogen storage by PSO algorithm. It is also not uncommon for PSO to be coupled with other optimization algorithms to obtain the optimal solution in HRES. In [16], authors highlighted the use of both GA and PSO for PV-Bt-H2-based HRES to minimize H2 costs and ensure better system control. To verify the result obtained from PSO, GA was computed only in one simulation case.

7.1.2 GA in recent HRES studies

Another popular algorithm in HRES is the genetic algorithm (GA). GA is founded on the principle of survival of the fittest. In this algorithm, selection, crossover, and mutation operators are applied for improving the quality of the population in the next generation [136]. GA is characterized by its robustness in the handling of multi-model problems and non-differentiable objective functions. NAGA-II is an improved version of the non-dominated sorting genetic algorithm [136]. Dufo-Lopez and Bernal-Agustin also developed a hybrid optimization algorithm based on genetic algorithms (HOGA), which was considered to solve complex constrained non-linear optimization problems. Authors of [77] applied GA to optimize a poly-generation system that consists of several components by implementing multi-criteria optimization. Poly-generation systems are generally termed as systems that are designed for multi-energy vectors such as power, space heating, process heating, space cooling, process cooling, etc. including different energy carriers such as hydrogen, biogas, steam, methanol, etc. As well, [85] utilized GA to optimize PV-H2-Bt grid-connected systems. To investigate PV-WT-Bt-DGn-based HRES [68], inbuilt i-HOGA system parameters were used to formulate the problem to minimize unmet load, CO2 emissions, and Net Present Costs (NPC) under different economic, technical, and environmental constraints. [89] presented NAGA-II as an optimization algorithm for off-grid applications involving WT, FC, Elz, Bt, and supercapacitors. Similarly, [132] used NAGA-II in their study due to its versatility and robustness. In this study, the objective was to study the robust energy planning approach for PV-WT-Bt-H2 systems integrated with hydrogen vehicles and high-rise residential buildings.

In recent HRES studies, other metaheuristics algorithms besides GA and PSO are also examined, as shown in Table 10. However, it was observed that other algorithms were either compared or combined with GA or PSO in large numbers. Only a small number of research works are found to use other metaheuristics algorithms without combination with GA, PSO, or with other algorithms even if their number increases. A study conducted in [74] investigated three new algorithms based on Global Dynamic Harmony Search (GDHS-I, GDHS-II, and GDHS-III) to determine the optimal number of each component within the given constraints. Similarly, [79] presented their study considering Grey Wolf Optimization (GWO) to investigate how various types of load input data (such as real load, monthly adjusted typical load, and typical daily load) affect energy costs provided by off-grid PV-Bt systems supplying varying loads with varying reliability levels. GWO [137], is the nature-based algorithm that mimics the hunting and leadership quality of the wolf. In this study, GWO was found to be reliable for obtaining the near-optimal solution. Different nature and human-based optimization algorithms are presented in Table 9.

Table 9: Nature and Human-based optimization algorithms

Nature-Based	***Year***	
Particle Swarm Optimization (PSO)	1995	[135]
CLONAL Selection Algorithm (CLONALG)	2002	[138]
Ant Colony Optimization Algorithm (ACO)	2006	[139]
Monkey Search (MS)	2007	[140]
Biogeography Based Optimization (BBO)	2008	[126]
Cuckoo Search (CS)	2009	[141]
Grey Wolf Algorithm (GWA)	2014	[137]
Flower Pollination Algorithm (FPA)	2014	[142]
Whale Optimization Algorithm (WOA)	2016	[143]
Human-Based	***Year***	
Tabu (Taboo) Search (TaS)	1998	[144]
Harmony Search (HaS)	2001	[145]
Teaching Learning Based Optimization(TLBO)	2011	[146]
Mine Blast Algorithm (MBA)	2013	[147]
Simulated Annealing (SiA)	1983	[148]

7.1.3 Comparison of different metaheuristics

Other metaheuristics are also noticed to be compared with PSO in recent HRES studies. In the study [15], authors compared the nature-inspired flower pollination algorithm (FPA) with PSO and the teaching learning-based algorithm (TLBO) for hybrid PV-WT-FC systems. FPA is based on the pollination of flowering plants [142] whereas the TLBO is based on the influence of a teacher on the output of learners in a class in terms of grades or results [146]. In comparison with PSO and TLBO, FPA was concluded to solve the optimal sizing problem easily with fast convergence, lower NPC, and better reliability indices. The Whale Optimization Algorithm (WOA) was also introduced by [22]. It mimics the behavior and hunting methods of whales [143]. To obtain the optimal design of seven hybrid systems that were based on tidal, WT, and FC costs and reliability, they concluded that WOA provided superior convergence and precision. In [58], the clonal selection algorithm (CLONALG) was compared to a GA and a Fuzzy Adaptive Algorithm to find the optimal sizing for PV-WT-Bt HRES. GA with Fuzzy algorithms was found to reduce the cost of WT. The authors of [65] proposed Cuckoo Search (CS) as an optimization algorithm and compared the optimal solutions obtained by CS with GA and PSO simultaneously in 3 system configurations i.e. PV-Bt, WT-Bt, and PV-WT-Bt. In comparison to GA and PSO, CS was able to provide the best solution for cost with fast convergence however, GA and PSO were able to find optimal design parameters. It has also been noticed that PSO and GA are combined and compared with other evolution-based algorithms, however, swarm-based algorithms have been found advantageous in preserving search space information over a subsequent iteration [143]. Additionally, authors also concluded that PSO is faster and more reliable than other algorithms for optimizing PV-WT-H2 HRES system sizing [66]. Several papers have presented HRES studies that take into account the numerous metaheuristic algorithms and compared their results; however, it is still unclear which metaheuristic performs the best and which one outperforms to solve the HRES optimization problem. It is also not clear why the particular metaheuristic algorithm is best suited for solving the problem.

7.2 Hybrid methods

In regards to fast convergence and computational time, single stochastic optimization algorithms provide an accurate set of near-optimal solutions. Hybrid algorithms, which combine several metaheuristic algorithms, have been extensively considered for the sizing optimization of standalone PV-WT HRES. Researchers presented a hybrid Genetic-Annealing Algorithm consisting of hybrid GA and Simulated Annealing (SiA) algorithms in [11] for developing code for generation islands using renewable energy with an H2 system to determine the optimal configuration and energy mix for reducing electricity consumption unit costs. [24] also presented a hybrid algorithm based on GWO-Artificial Neural Network (ANN) to develop an eco-friendly system using solar parabolic concentration panels, Elz, FC, and HS. ANN in HRES studies is usually used to reduce computational time and to forecast the load demand and weather conditions. In this study, five types of thermal oil were compared as the operating fluid in the solar unit and the most economical option was selected. To begin with, GWO was used for optimization, and ANN was used to reduce the optimization time. GWO algorithm was prioritized because of their easy implementation, low storage, and computational requirement, fast convergence, and high stability [137] However, the optimization process was time-consuming which was why the simulation results were trained by using ANN to reduce simulation time from few hours to a few minutes. Experiments were also conducted to validate the calculated model. For six different schemes viz. WT-H2, PV-H2, PV-WT-H2, WT-Bt, PV-Bt, PV-WT-Bt, authors combined Chaotic search (ChS), Harmony search (HaS), Simulated Annealing (SiA) to obtain the optimal configuration in [88]. According to the study, hybrid ChS-HaS-SiA achieved the best results. In [62], authors developed a combined Quadratic Programming (QP) and PSO algorithm to determine the type and capacity of distributed generation sources as well as storage devices. In this study, PSO provided insight into future EMS and assured that the microgrid installation was profitable. Table 9 presents different hybrid algorithm research works.

HRES studies have considered different metaheuristics or hybrid algorithms to solve optimization problems. However, it has been difficult to determine which one is the most effective. This is because the choice of an algorithm is largely influenced by HRES configuration, constraints, objectives, parameters, defined search space, and solution types. Fast convergence and near-optimal solutions can be found with hybrid approaches while the global optimum solution is not sure to be obtained. Exact methods of optimization can be the option to reach the optimal global solution but, exact algorithms are complex and need more computational time.

Table 9 Recent optimization methods and solvers

	Analysis	***Optimization***	***Tools***	***Load time interval (hours)***
[17]	Technical	Polynomial time algorithm, Binary Search compared with MILP algorithm	NA	72 (three days), 1h step interval
[20]	Technical, Economic	P graph (B&B) compared with Electric System Cascade Analysis (ESCA)	NA	24 (one day) and 8760 (one year), 1h step interval
[21]	Technical, Economic	MILP	E-OPT	8760 (one year), 1h step intervals
[27]	Technical, Economic	MILP (B&B)	Gurobi™ (Python),	24
[82]	Technical, Economic, Reliability	ε-constraint and fuzzy decision method	CPLEX® (GAMS)	24 (one day), 1h step interval
[90]	Technical, Economic, Reliability, Environmental	Iterative algorithm	NA	8760 (one year), 1h step intervals
[80]	Technical, Economic, Reliability, Environmental	ε-constraint and fuzzy decision method	SCENRED (GAMS)	24 (one day)
[13]	Technical, Economic, Environmental, Social	Sequential Quadratic Algorithm (SQP)	MATLAB	8760 (one year), 12h step interval
[24]	Technical (Thermodynamics), Economic, Environmental	GWO, ANN	MATLAB	NA
[96]	Technical (Thermodynamics), Economic, Environmental, Social	GA, Fuzzy LINMAP (Linear Programming)	Pareto front Solver (Not specified)	NA
[10]	Technical, Economic, Reliability	PSO, Hooke and Jeeves algorithm	GenOpt®, TRNSYS	8760 (one year), 1h step intervals
[79]	Economic, Reliability,	GWO	NA	8760 (one year)

[12]	Technical	BBO	NA	NA
[25]	Technical, Economic	Scenario-based optimization algorithm	Gurobi™(Python), Pyomo	365 days based on various weekly, monthly, and daily profile
[68]	Technical, Economic	GA	i-HOGA	24 (one day), 720 (one month), and 8760 (one year), 1h step intervals
[16]	Technical, Economic,	GA, PSO	MATLAB	8760 (one year), 300 s step intervals
[19]	Technical, Economic,	Best Worst approach	HOMER	8760 (one year)
[73]	Technical, Economic, Reliability	PSO	MATLAB	8760 (one year), 1h step intervals
[22]	Technical, Economic, Reliability	WOA compared to PSO	NA	8760 (one year), 1h step intervals
[132]	Technical, Economic, Reliability, Environmental	NSGA-II	TRNSYS, jEplus+EA	NA
[81]	Technical, Economic, Reliability, Environmental	HOMER	HOMER	24 (one day), 1h step interval

7.3 Exact methods

In recent years, there has been a slight increase in the study of HRES considering exact methods however, it is difficult to find an optimal global solution using exact methods because of the presence of computational complexities. Exact methods include iterative methods, linear programming, analytical methods, etc. Exact methods which deal with linear programming (LP), Mixed integer linear programming (MILP) implements most often Branch & Bound (B&B) algorithms in HRES optimization. B&B methods partition the problem into independent subproblems, solve the subproblems, and find the best optimal solutions in the defined search space [149]. B&B algorithms are solved using CPLEX®, and Gurobi™ solvers in open-source programming interfaces like GAMS, Python, MATLAB, etc. In [20], authors presented an accelerated B&B algorithm embedded in a graph-theoretic algorithm known as P-graph to resolve the supply-demand mismatch caused by the intermittent nature of renewable energy sources in the PV-Bt-H2-grid HRES system. Furthermore, using the Gurobi™ solver in the Python Pyomo module, the authors presented B&B's algorithm to solve the MILP problems for maximizing profit by selling electricity and H2 to BEVs and FCVs in [27]. Similarly, [115] presented MILP formulation to size the off-grid PV-powered charging station for BEVs and FCVs. The problem was solved using the CPLEX® solver in GAMS. Differently, authors solved the Mixed integer nonlinear programming (MINLP) problem to maximize the volume of energy from PV and HP reducing energy deficit and surplus below 5% using the generalized reduced gradient (GRG) method [150]. Generally, GRG is famous to solve non-linear problems dealing with non-linear inequalities. Besides LP, MILP, and MINLP, in [90], authors presented an iterative algorithm to solve multi-objective optimization problems that involved mathematical modeling and energy management of WT-Elz-Bt systems. Based on the multi-objective optimization, total hydrogen deficit, energy dump possibility, LCOH, and CO2 emission were minimized. The iterative algorithm executes in steps to find a solution by successive approximation, and it repeats the step until the approximated value is determined in the evaluation of the objective function [151]. In [152], authors also used an iterative method to optimize standalone PV-WT-FC HRES for a desalination system. Table 9 also presents HRES studies based on exact methods.

There is a tendency for HRES studies to find local solutions due to the fast convergence and little computational time of metaheuristics and hybrid algorithms, however, they do not guarantee the optimal solution. Therefore, besides the computational complexities in exact methods, MILP, and MINLP algorithms can be still used carefully to obtain the optimal global solutions.

7.4 Optimization software tools

MATLAB Simulink is a multi-physics modeling tool embedded in MATLAB which includes modeling, simulation, and optimization of various systems used in telecommunications, power electronics, control systems, signal processing, etc. MATLAB is widely used as an interface to solve various linear and non-linear optimization problems in HRES studies [13], [15], [16], [24], [58], [59], [88], [89]. MATLAB Simulink has been considered a favorable language to model the power system components and control system which provides the graphical environment, a set of libraries with modeling blocks. It is mostly preferred because of its feasibility of integrating the component and because of its sound optimization facilities. [13], [15], [16], [24], [58], [59], [88], [89] studied different HRES sizing and energy management optimization problems based on the MATLAB Simulink environment. Except for the wide acceptance of MATLAB as an optimization tool in the HRES system, other tools can be found utilized to solve the optimization problems as well. Among them, some commercial tools like HOMER, and i-HOGA have been found in the application. Likewise, Python-based optimization solving modules like PyPSA, and FINE are also found in applications with a wide range of scope to solve linear and non-linear optimization problems.

7.4.1 HOMER, HOMER Pro

HRES has been optimized using a variety of software tools. HOMER and i-HOGA are two well-known tools. These are primarily used for sizing the HRES system. In HOMER, a variety of energy generation units and energy storage units can be sized in both a grid-connected and a standalone configuration. The HOMER database contains information regarding load profiles and location. By calculating the energy balance for 8760 hours in a year, HOMER simulates the operation of the system. In addition, it calculates energy flows for each hour to and from each component. As part of this study, researchers used HOMER to size the different PV-WT-H2 HRES to decrease the LCOE. Accordingly, [57] examined an off-grid PV-WT-FC hybrid system utilizing HOMER optimization to reduce the LCOE. [76] investigated a standalone PV-WT-Bt-H2-grid HRES to reduce the NPC, cost of energy (COE), and cost of hydrogen (COH) in West China. For the electrical and hydrogen load data, the authors relied on HOMER in the study [73]. It can be used to size different HRES with a wide range of component selections, but it needs quality input data to run black box simulations and optimizations.

7.4.2 i-HOGA

The i-HOGA software tool is an improved software tool used in the size optimization of single and multi-objective optimization problems. To determine the optimal solutions, GA is used. The i-HOGA software provides multi-objective optimization capabilities. An accurate solution is obtained by using detailed models of the components. HRES that are connected to the grid or isolated are included in the control strategies. Battery charge and discharge management and accurate battery life estimation are also included. [68] studies multi-objective WT-PV-Bt- DGn HRES to size the system. i-HOGA pre-sized the components for this study. From the i-HOGA database, suitable Bt, PV, WT, inverters, and DGn were selected based on previous component information.

Except for HOMER, and i-HOGA, other tools have also been used to size and manage hybrid power plants. In [10], authors used the GenOpt® software tool to calculate the optimal energy mix of hybrid power plants and TRNSYS for the simulation of the model whereas, [21] employed E-OPT© to determine the most cost-effective dispatch of PV-Bt-H2-grid storage facilities. They are both commercial software tools used to solve optimization problems. In addition, authors in [132] presented the multi-objective optimization problems for the sizing of HRES in zero energy building applications based on an integrated simulation platform of jEplus + EA and TRNSYS. jEplus + EA is the new version of jEPlus which is used for parametric analysis and optimization through JEA web platforms. It is free of charge and used for non-commercial purposes.

7.4.3 PYTHON-based optimization solvers

Table 10: Recent Python-based optimization solvers

	Optimization Algorithm	***Modeling languages and solvers***
[25]	Linear algorithm	Pyomo, Gurobi™ Solver
[153]	Nonlinear Algorithm	Pyomo, IPOPT Solver
[26]	MILP	FINE, MILP Solver
[154]	MILP	Pyomo, Gurobi™ Solver
[155]	MILP	Pyomo, Gurobi™ Solver

Several research papers have demonstrated their interest in solving energy system optimization problems with Python-based solvers. Python can be used to size and optimize HRES in various linear, nonlinear, single, and multi-objective optimization problems. Open-source Python software packages provide a wide range of optimization capabilities for the formulation and solution of optimization problems. Programming problems that are linear or nonlinear, quadratic, MILP and MINLP, stochastic, disjunctive, differential algebraic, equilibrium constraint, etc. can be solved by utilizing the optimization packages that are available in Python. These days, it is widely used in different research and engineering applications due to its simplicity.

One of the most popular Python-based open-source toolboxes for the simulation and optimization of modern power systems is PyPSA. This package includes variable solar and wind generator units, as well as storage units and other control units designed to handle large networks and long time series. PyPSA has a high potential for optimization of power systems, e.g. power to gas, power to power, or gas to power with heat couplings, etc. In PyPSA, the optimization problem is modeled and solved by Pyomo and Linopy optimization packages. Linopy incorporates optimization solvers such as GLPK, Gurobi™, and CPLEX®. Furthermore, Pyomo integrates several well-known solvers, including Gurobi™, IPOPT, and GLPK as well. The advantage of PyPSA in power system modeling and optimization is that it is designed well to function with large networks consisting of different components. Optimization of the linear power flow equations with mixed AC and DC networks is fully supported. It can optimize the dispatch, storage, and transmission of power. The Pyomo optimization package has been used in several recent studies, as shown in Table 10. In [25], authors proposed a linear formulation of the optimization problem that is solved by a Pyomo-integrated Gurobi™ solver for sizing PV-Bt-DGn systems under uncertain solar irradiation scenarios. In [153], authors proposed a non-linear optimization problem to determine the best flexibility for multiple energy sources, including multiple power-to-gas options. To formulate and analyze the techno-economic analysis of hydrogen production and demand in Texas, USA, CPLEX® solvers integrated into the Pyomo modeling language were used [156]. Gurobi™ solver interfaced on Pyomo was used by [154], [155], [157] for solving linear and nonlinear power system problems. Another Python-based framework for optimizing energy systems is FINE (A Framework for Integrated Energy System Assessment). This is an open-source package that facilitates the modeling, optimizing, and assessment of energy systems. Generally, MILP problems are solved using the FINE package, which includes well-known optimization solvers such as Gurobi™ and GLPK [158]. For an energy-self-sufficient family house, [26] used the FINE framework to solve the MILP.

While Python-interfaced optimization algorithms are popular and widely applicable, few research articles have been published about the sizing and energy management of HRES for transportation and stationary applications. This opens the door to a more comprehensive study involving Python-interfaced optimization modules and solvers in HRES in the future.

8. Critical findings and discussions

- Hybrid renewable energy systems (HRESs) are found to be reliable, environmentally friendly, and cost-effective solutions for meeting stationary and transportation energy demands. Grid-integrated HRES is found to be more economical in terms of energy cost and the grid ensures that load demand is met during energy shortages. Nevertheless, people in remote villages and islands rely on standalone HRES due to a lack of utility grids. There are several factors to consider while selecting an HRES, including the location, size, and energy requirements. Figure 1 depicts that the grid-integrated HRES study has been increasing recently, out of 60 research studies from the past and recent years.
- Several microgrids in distributed energy systems can feed power to the grid, which can result in grid congestion or even blackouts in case of ill-management of the flow of power. It may also require proper control methods for turning on and off the microgrids in distributed energy systems to relieve grid stress. One of the objectives of this kind of study can be shaving the peak power demand on the grid by the utilization of many distributed energy systems and microgrids with power flow management.
- Microgrids can also utilize grid power as a backup source when other energy sources are unavailable during peak times. In this case, the grid might get stressed as well if the inflow and outflow of power are not properly managed. In studies, the stress in grids was overlooked which opens door to the future study of HRES systems including grid stress and grid power management.

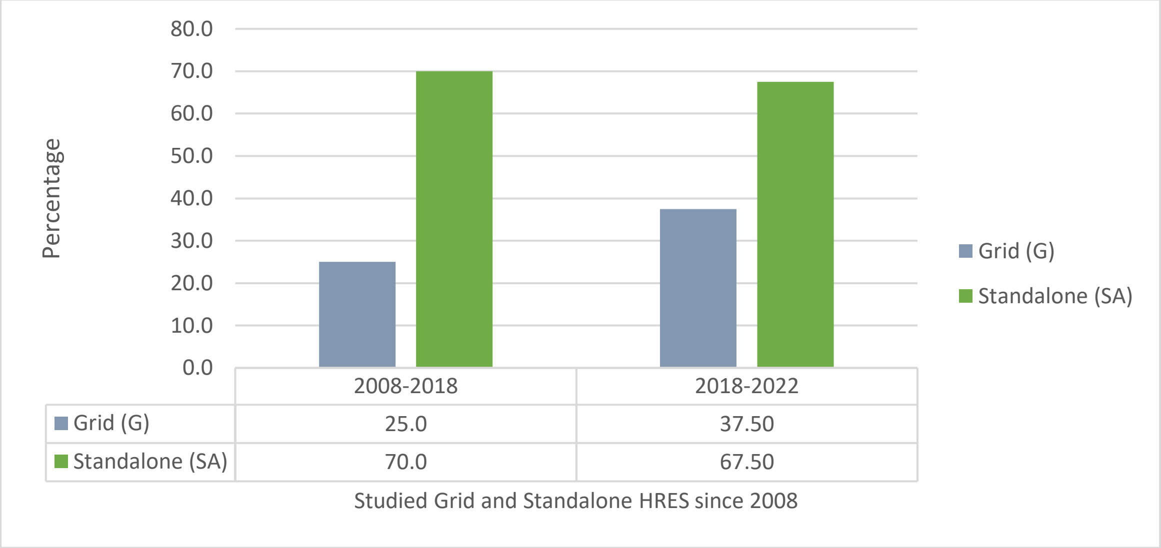
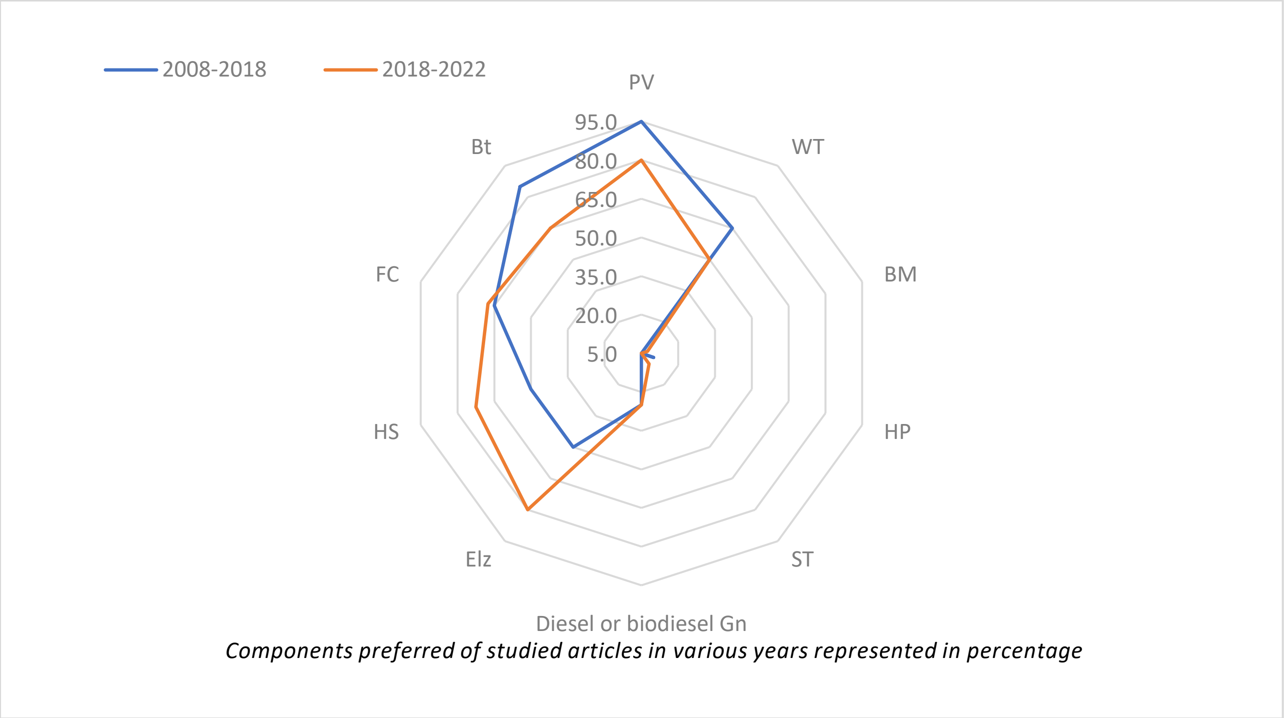


Figure 2 Percentage of studied Grid/Standalone HRES in different years

- Out of 60 HRES studies, it can be noticed that the most preferred renewable generators are solar photovoltaic and wind turbines as shown in figure 2, while the most preferred storages are battery and hydrogen storage. Figure 2 also illustrates that, from 2008-2018, PV-WT-Bt HRES was focused on by most of the studies, however, after 2018, the PV-WT-H2 system with Elz, FC, and HS has attracted a great deal of attention. Despite these, the choice of storage depends on the EMS and load demand, whether seasonal, monthly, or daily. The PV-WT-Bt-H2 HRES is found not economically viable at present due to the high costs of Elz and FC, whereas it is more reliable because it can satisfy daily and seasonal loads reliably.



Components preferred of studied articles in various years represented in percentage

Figure 3 HRES components preference in different years

- Most of the time, HRES systems are used in remote villages and islands. There is difficulty in obtaining load profile data, making optimal sizing and energy management more difficult. To predict the load profile more accurately, a more accurate technique is needed. To determine the optimal system size, it is also necessary to obtain more accurate solar and wind data.
- Solar, wind, and load demand data directly influence the sizing of a system. Thus, it is better to use hourly solar, wind, and load data on an annual basis. With solar, wind, and load demand data provided every 1, 5, or 10 minutes on an annual basis, HRES sizing will be more precise. However, it increases simulation complexity due to the need for processing large amounts of data and the requirement for fast and reliable computer processing units. Therefore, in terms of processing and technical suitability, hourly solar, wind, and load demand data are well suited to be considered on an annual basis.
- There are very few research works that consider PV tilt angle adjustment as a constraint. To determine the optimal system size, considering tilt angle is always a better option. Most research considers the height and swept area of WT to be fixed. As a result, the optimal sizing of the system may not be accurate. Therefore, different wind heights and swept areas should be taken into account.
- There are very few research works that consider intermittency lying on the electrolyzer for the constant production of hydrogen. It has not been explained clearly about maintaining the rated power of the electrolyzer for the production of hydrogen, shut down conditions of the electrolyzer in case of intermittency, and degradation of electrolyzers. This can be the possible prospective future HRES study.
- Most of the HRES studies focused their goals on technical and economic aspects. There is also an increased tendency to consider reliability and environmental studies along with technical and economic aspects as shown in figure 3. Despite the importance of

social aspects in HRES, very few studies have taken this into account. Social factors influence the economy and power consumption of end users. Consequently, it is better to include social aspects in HRES studies.

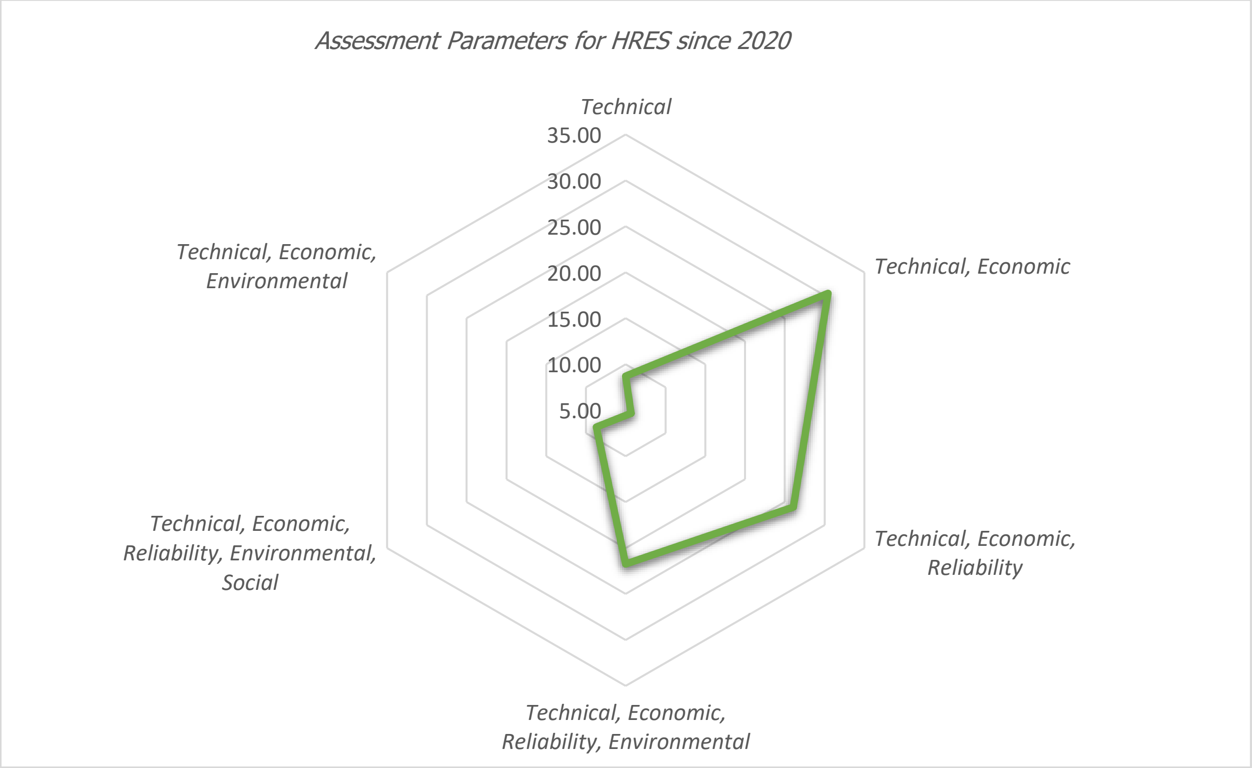


Figure 4 Different aspects considered in recent HRES studies expressed in percentage

- A lot of research has considered the integration of diesel generators in HRESs to improve power flow. However, the environmental footprint should be accurately evaluated on the life cycle of the system for each HRES solution, even with renewable energy sources.
- Several sources of energy, such as hydropower, biomass, PV, and wind power, were able to produce enough power to meet the energy demands of highly populated areas. However, only a few research articles examined HRES storage options for storing large amounts of excess power produced by these generators.
- There has been a limited amount of research focused on the simultaneous production of electricity from renewable sources and hydrogen from electrolysis on a large scale, as well as the challenges related to large-scale H2 production and maintaining the electrolyzer-rated power.
- The integration of renewable energy sources into the energy mix has significant implications for expansion planning across various sectors of the energy infrastructure. Generation expansion planning needs to consider the complementarity of different renewable sources, advanced forecasting techniques, and factors like resource availability and intermittency patterns.
- Distribution expansion planning must address challenges related to network capacity, voltage regulation, and bidirectional power flows from distributed generation. Storage expansion planning becomes crucial to balance supply and demand, enable load shifting, and ensure system stability.
- Transmission expansion planning requires investments in infrastructure to facilitate the integration of renewable energy and the exchange of clean power across regions. By considering these factors, policymakers and energy planners can effectively incorporate renewable energy sources while ensuring a reliable and sustainable energy system for the future.

- There are very few research articles that examine how HRESs can be implemented in agriculture, data centers, telecommunication centers, and weather stations.
- PV-WT HRES integrating H2 system including electrolyzer, fuel cell, and hydrogen storage is found well suited in the regions with high solar irradiation and wind, such as Iran and India where very case studies are considered.
- In Europe and the Middle East, HRESs are more widely studied. An interesting option would be to study islands and small villages where there is no grid electricity in Asian, African, and South American regions.
- In the review pieces of literature, most researchers viewed cost and reliability as objective functions. Lots of studies are based on the reduction of total annual costs, net present costs, and the Levelized cost of energy, however, the Levelized cost of hydrogen and life cycle cost is encountered rarely. When it comes to reliability, load power supply probability and loss of load expected are most often encountered. In future studies, other reliability indices such as level of autonomy, self-sufficiency ratio, etc. can be considered.
- Very few research articles addressed peak shaving energy management strategy including demand response programs. Peak shaving can be included in a future study since it enables consumers to shift their consumption from peak to other periods, reducing expenses to the greatest extent possible.
- Given that the sizing and energy management strategy of Hybrid Renewable Energy Systems (HRES) is greatly influenced by a multitude of local factors, such as meteorological conditions and load demands, it becomes imperative to employ site-specific modeling or a comprehensive global sensitivity analysis. These approaches aid in gaining deeper insights into the key factors that exert a substantial impact on the HRES scheme. Moreover, it is equally crucial to enhance the sensitivity analysis within the economic and reliability models, ensuring that the obtained results align as closely as possible with real-world scenarios. By doing so, the outcomes of the analysis become more accurate and reflective of the practical implications and considerations involved.
- In energy management and HRES sizing, metaheuristics are mostly used due to their advantages in fast convergence and reaching near-optimal solutions. In HRES, hybrid algorithms can also be found in most of the studies since they provide even better convergence and optimal results.
- For sizing the HRES, nature-based and human-based optimization algorithms have been favored most of the time. In comparison with other metaheuristics, PSO proved to be a fast and reliable method for finding the optimal size of HRES by preserving search space information over subsequent iterations which means in every iteration, PSO is recording and preserving the information of the generated solutions.
- A Large number of metaheuristics are presented and compared concerning HRES studies however, it is not very clear which metaheuristic algorithm is the best and which outperforms the other.
- Due to the availability of large amounts of components and databases, Blackbox computer tools like HOMER and i-HOGA have been used more frequently recently.
- Several studies preferred MATLAB-based platforms to solve the optimization problem, while very few deal with Python-based modules such as PyPSA, FINE, etc. Researchers can therefore study HRES systems in Python-based modules.

9. Conclusion

This article presents a comprehensive review, along with a description of a recent stand-alone and grid-integrated HRES. It presents a variety of HRES that are composed of different renewable energy generation and storage units: PV-WT-Bt-DGn, PV-WT-Bt-DGn-H2, PV-WT-Bt-H2, and PV-WT-H2. Renewable energy sources and storage are analyzed along with their optimization and energy management strategies. In addition, the application and studied locations are discussed based on recent HRES studies. In HRES, an optimization formulation framework that includes various optimization design variables, constraints, and objective functions is introduced and discussed. We also tried to provide insight into the various optimization solvers such as Gurobi™, GLPK, IPOPT, and other MILP and MINLP solvers, etc. based on different programming platforms such as MATLAB, Python, GAMS, etc. Similarly, commercial software tools such as i-HOGA, TRNSYS, and HOMER or HOMER pro that can be used in the solution of HRES modeling and optimization problems are presented. Additionally, several cases from the literature are presented regarding EMSs in HRES studies. Finally, in this article, we tried to propose a discussion that may lead to follow for future studies.

10. Acknowledgements

This work has been supported by the EIPHI Graduate School (contract ANR-17-EURE-0002), by the Region Bourgogne Franche-Comté, and by the ISITE BFC (contract ANR-15-IDEX-003). Authors are also grateful for the support provided by the department énergie and DISC under UMR6174 FEMTO-ST, laboratories FCLAB, and DRIVE (ISAT), France.

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