Hybrid Renewable Energy Systems: An Analysis from the State-of-the-Art Review

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This state-of-the-art review investigates the literature on Hybrid Renewable Energy Systems (HRES) in response to growing global energy demands and climate change concerns. Solar photovoltaic (PV) and wind turbine (WT) systems are pivotal components of HRES, which, when complemented by Battery Energy Storage Systems (BESS), enhance system efficiency by storing and dispatching surplus energy during low-generation periods. An analysis of literature trends reveals a notable surge in HRES research publications, peaking in 2022. Researchers primarily focus on optimizing hybrid systems, emphasizing modeling, sizing, and feasibility assessments. The dominance of Asian countries in HRES research highlights potential applications in off-grid settings within densely populated, remote, and isolated regions. A review of the ten most cited articles from 2019 to 2023 reveals that these publications predominantly discuss the state-of-the-art in HRES. The analysis identifies knowledge gaps, emphasizing the importance of research addressing control strategies, simulation tools, and the feasibility of large-scale hybrid power plants across diverse geographies, particularly in areas with high solar and wind generation potential. This review not only highlights the rapid growth and global relevance of HRES but also serves as an incentive for ongoing exploration, innovation, and collaboration in areas concerning the future of energy.

Keywords: HRES. Hybrid Renewable Energy Systems. Literature Review.

The worldwide energy demand has expanded in recent decades, a trend attributed to socio-economic developments. Energy generation is pivotal in ensuring electricity accessibility and availability to meet this growing demand [1].

Conversely, sustainability concerns have sparked discussions about reducing fossil fuel use for energy generation. Climate change has been a significant driver in adopting renewable energy sources (RES) as the most suitable solution for meeting energy requirements [2].

In 2020, renewable energy accounted for one-third of total power generation worldwide. Notably, RES were the only energy resources that experienced increased demand during the pandemic period [3]

Annual renewable capacity additions increased by 45%, reaching almost 280 GW in 2020. This high-capacity growth became the norm in 2021 and 2022, with RES representing 90% of new power capacity expansion globally [4]. Renewable energies account for approximately 80% of the national energy matrix in Brazil, reflecting the country's significant hydropower, solar, and wind potential [5].

Solar photovoltaic (PV) and wind turbine (WT) systems stand out as the primary RES for practical implementation. These technologies continuously improve for higher efficiency and can be assumed for large-scale applications [6]. Thus, the combined utilization of PV and WT systems represents an up-and-coming option among RES for meeting the growing load demand.

Additionally, the complementary energy generation profiles exhibited by PV, WT, and other RES allow for the construction of Hybrid Renewable Energy Systems (HRES). HRES involves the integration of two or more generation units, offering a solution to the intermittent power supply challenge and thereby increasing power system reliability, resilience, and stability [7].

Battery Energy Storage Systems (BESS) applied in Hybrid Power Plants (HPPs) complement the hybrid arrangement and maximize the energy generated. When the power generated by the

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sources exceeds the demand, the excess energy can be stored in BESS and then dispatched into the grid during periods of low generation [3]. Despite the increasing discussion around this configuration, models outside Brazil are the primary references for installing HPPs. European countries, Australia, the United States, China, and India, are highlighted as the primary market players. Table 1 show cases the main projects involving the hybridization of energy sources worldwide [6].

For example, the Kennedy Energy Park in Flinders Shire, Australia, stands as one of the pioneering large-scale hybrid power plants globally. Construction commenced in 2017, and it successfully became operational in 2019. It has an installed capacity of over 60 MW, with 43.5 MW from wind, 15 MW from solar, and 4 MWh of lithium-ion storage.

Drawing on the innovative advances of projects like the Kennedy Energy Park, which has demonstrated the capabilities of large-scale hybrid power plants, this work aims to present a state-of-the-art review of HRES research issues, emphasizing the following aspects:

- Literature publications about HRES: perspective over time;
- The main themes regarding hybrid systems presented in the literature;
- Geographical perspective on scientific content regarding HRES;
- Literature review of principal works on the feasibility assessment of HRES.

Materials and Methods

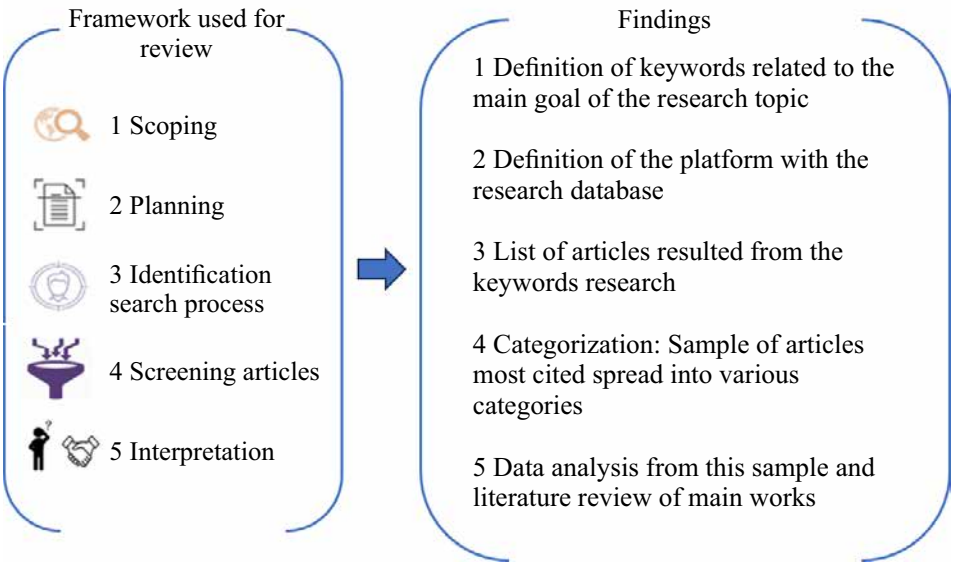
A state-of-the-art review was chosen to clarify, group, and synthesize the most relevant current knowledge about HRES. Figure 1 summarizes the schematic of the methodology approach used in this study. A framework is proposed for the state-of-the-art review, and the respective findings are presented below.

- Scoping Step: The research strategy was based on the selection of keywords and the use of Boolean operators "AND" and "OR," detailed as follows: ("HRES") AND ("HYBRID RENEWABLE ENERGY SYSTEMS") AND ("HYBRID POWER PLANT" OR "HYBRID

Table 1. Some of the main examples of hybrid power plants in the world.

Location (City - Country)	Wind Power (MW)	Solar Power (MW)	Storage (MW/MWh)	Wind/Solar PV Proportion (%/%)	Company
Parc Cynog - Wales	3.60	4.99	-	42 / 58	Vattenfal
Haringvliet - Netherlands	21.00	31.00	12 / 12	40 / 60	Vattenfall
Kavital - India	50.00	28.80	-	63 / 37	Hero Futures Enery & Siemens Gamesa
Flinders Shire - Australia	43.00	15.00	2 / 4	74 / 26	Wind Lab & Eurus Energy
Pelica Rapids (MN) - United States	5.00	0.50	-	90 / 10	Juhl Energy
Ollague - Chile	0.30	0.21	0.3 / 0.8	59 / 41	Enel Green Power
Tilos - Greece	0.80	0.16	0.8 / 2.4	83 / 17	H2020 Research Consortium
Graciosa - Portugal	4.50	1.00	6.0 / 3.2	81 / 19	Younicos
La Muela - Spain	0.85	0.25	0.4 / 0.5	78 / 22	Siemens Gamesa

Figure 1. Method approach (Adapted from Babatunde and colleagues [1])



POWER SYSTEMS"). This research aimed to identify the main general works on the theme from various nonrestrictive perspectives, such as control, modeling, simulation, feasibility, and others.

- Planning Step: Dimensions AI was chosen as the research database platform. Dimensions is an artificial intelligence platform that provides a search tool for linked research databases covering publications, grants, patents, datasets, policy documents, and technical reports [7].
- Identification Step: The number of works resulting from the keyword search was accounted for. The platform returned a list of publications that could be ordered, analyzed, and downloaded to compose a literature review on the research topic.
- Screening Articles Step: The chosen platform allowed the download of 500 works organized by ranking based on the number of citations. Therefore, this study considers the first 500 articles from the research results.
- Interpretation Step: The downloaded sample was analyzed from various perspectives: number of publications over time and by source titles, number of citations for each source, and geographical perspective of the most cited publications.

The research aimed to answer the question: What is the current literature discussing hybrid renewable systems? We proposed segregating the results into distinct categories to complement the analysis of our results (Table 2). The words related to each category were searched in the content of the title of each paper. A literature review was conducted, highlighting the ten most cited works from the last five years, from 2019 to 2023.

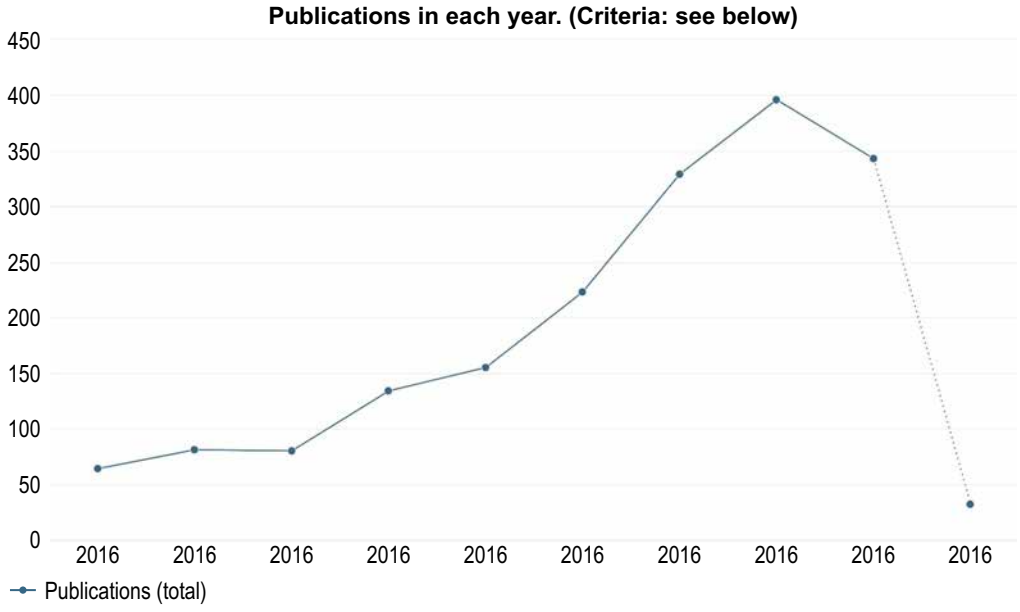
Results and Discussion

Applying this research strategy to Dimensions AI returned 1923 publications, including articles, thesis, dissertations, and technical reports, among others. As the first result of the analysis of HRES literature, Figure 2 illustrates the number of publications in each year from 2015 until 2023. This graph shows an expressive rise in the literature discussion about hybrid systems after 2019, reaching a peak in 2022. The results for 2024 are still non-expressive because these data were taken in January of this same year. In addition to understanding when the topic began to gain volume in publications, it is essential to understand the primary source titles discussing the theme. Figure 3 demonstrates the relationship

Table 2. List of categories chosen to represent the main themes regarding HRES.

Categories (CAT)							
1	2	3	4	5	6	7	8
Optimize	Sustainability	Assesment	Control	Sizing	Review	Simulation	Management
Optmization	Sustainable	Feasibility		Design	State-of-the-art		Operation
Optimization		Assessing		Size	Overview		
Optimal		Techno-economic		Model			
		HOMER					
		Cost analysis					
		Techno-economic					

Figure 2. Number of publications in each year within the scope of HRES [7].



between source titles and citations about hybrid renewable energy systems. Publication citations are the number of times other publications in the database have cited a publication. Citing publications can be of any type, such as articles, chapters, preprints, or monographs. The results show that the journal Energies from MDPI has the most publications about HRES from the Dimensions database. However, the most cited journal regarding hybrid technologies and applications is the Renewable and Sustainable Energy Reviews from Elsevier. Moreover, from the total number of publications, the following analysis considered only the number of articles produced, which totaled 1,383 registers, excluding other types of scientific productions.

The sample of 500 works exported from Dimensions AI was categorized into different themes, presented in Table 2, returning the number of articles for each category, as shown in Table 3 for each category

Figure 3. Source titles and citations related to the top 10 journals obtained from the search.

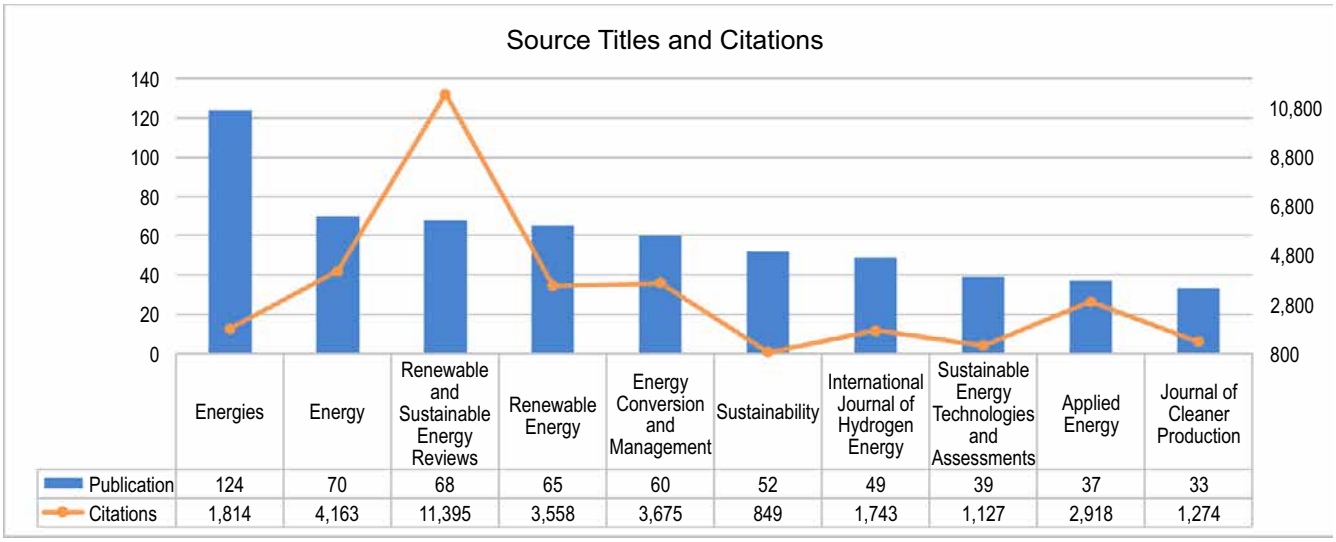


Table 3. Number of articles found about HRES.

Results by categories	
CAT 1	241
CAT 2	22
CAT 3	115
CAT 4	45
CAT 5	182
CAT 6	83
CAT 7	7
CAT 8	66

We concluded that researchers are prioritizing studies about the optimization of hybrid systems, followed by sizing and modeling the design of the plant and its equipment. The feasibility assessment is also an essential study in understanding the techno-economic aspects of the project. There is a lack of studies about simulation tools, and the results for control strategies suggest that this theme can be explored more. Although these works explore renewable energy sources, researchers do not associate the title of their works with sustainability. This shows that authors prioritize technical aspects over environmental approaches when discussing hybrid systems. Despite HRES being affordable for any country, especially the ones with high solar and wind potential, it is evident that Asian countries have more scientific production about the theme. Table 4 lists the ranking of the 10 countries with the most articles produced, of which the first 5 are from Asia.

The expressive participation from Asian countries can be explained by the fact that 60% of the world population is from Asia, and more than half of them live in rural and remote areas. In this case, HRES projects can be applied in an off-grid arrangement to supply the population's energy needs without the necessary infrastructure investment to connect the HPP to the electrical grid [8]. Understanding the financial resources applied to this type of project is fundamental to evaluating

Table 4. Number of publications about HRES for each country.

Country	Publications
India	79
China	58
Iran	37
Malaysia	31
Saudi Arabia	28
Spain	21
Egypt	18
Australia	17
Morocco	14
United States of America	14

the feasibility of the HPP implementation. When solar and wind generation are applied separately, it is usually necessary to increase the installation size when compared to using a hybrid combination of both to supply the same demand. Thus, the HRES can improve reliability and performance, and decrease generation fluctuation and investment costs [9].

To better understand the principal topics of study about HRES that contributed to the increase in publications after 2020, Table 5 presents a list of the 10 most cited articles of the last 5 years, from 2019 to 2023.

With the analysis of Table 5, it is possible to observe a certain balance among categories 1, 3, 5, and 6, with CAT6 containing four of the top five most cited articles. This is explained by the need for access to the literature review and state-of-the-art references in developing large projects involving various themes of HRES. Among these CAT6 articles within the top five, it is worth noting some that review methodologies for sizing and optimization of HRES, which are the main themes of CAT1 and CAT5, respectively.

For CAT3, different evaluations and case studies involving various software tools such as HOMER and MATLAB were conducted among the articles in the table. As for CAT1, different optimization methodologies (e.g., PSO, genetic algorithms) were applied and reviewed.

Conclusion

This state-of-the-art review has comprehensively explored the scientific scenario of HRES studies. Notably, 2020 represented a significant milestone, with renewable energy contributing one-third of total power generation worldwide. This rise in implemented generation projects is reflected in a substantial increase in HRES research publications, achieving a peak in 2022 until now.

Solar and wind technologies' complementary energy generation profiles make them an ideal pair within hybrid renewable systems. Integrating a BESS further enhances the efficiency and reliability of HRES, allowing for the storage and dispatch of excess energy during periods of low generation.

The analysis of literature trends shows that researchers predominantly focus on optimizing hybrid systems, followed by sizing and modeling, with feasibility assessments playing a crucial role in understanding the techno-economic aspects. The top countries contributing to HRES research are predominantly from Asia, emphasizing the potential for off-grid applications in populous regions.

The literature review of the ten most cited articles from 2019 to 2023 encompasses studies of state-of-the-art, the use of tools such as HOMER

Table 5. List of the 10 most cited articles from 2019 to 2023.

Title	Year	Authors	Keywords	Source	DOI	Study Type	Categories
A review on recent sizing methodologies of hybrid renewable energy systems [10]	2019	Lian, Jijian; Zhang, Yusheng; Ma, Chao; Yang, Yang; Chaima, Evance	Hybrid renewable energy system; Renewable energy source; Classification Evaluation indicator; Sizing methodology; Sofware tool	Energy Conversion and Management	10.1016/j.enconman.2019.112027	Literature review; mathematical approach	CAT5, CAT6
Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources [11]	2019	Adefarati, T.; Banasal, R.C.	Economic; Emission; Environment; Microgrid; Reliability	Applied energy	10.1016/j.apenergy.2018.12.050	Literature review; Case Study; mathematical approach	CAT3
Uncertainty models for stochastic optimization in renewable energy applications [12]	2020	Zakaria, A.; Ismail, Firas B.; Lipu, M.S. Hossain; Hannan, M.A.	Stochastic optimizations; Uncertainty model; Scenario generations; Renewable energy applications	Renewable Energy	10.1016/j.renene.2019.07.081	Literature Review; Optimization models for renewable energy applications	CAT1, CAT6
Solar and wind power generation systems with pumped hydro storage: Review and future perspectives [13]	2020	Javed, Muhammad Shahzad; Ma, Tao; Jurasz, Jakub; Amin, Muhammad Yasir	Pumped hydro storage; Solar-hydro energy storage; Wind-hydro energy storage; Hybrid renewable energy systems; Hybrid storage	Renewable Energy	10.2016/j.renene.2019.11.157	Literature review; Future perspectives	CAT6
Battery energy-storage system: A review of techologies, optimization objectives, constraints, approaches, and outstanding issues [14]	2021	Hannan, M.A.; Wali, S.B.; Ker, P.J.; Rahman, M.S. Abd; Mansor, M.; Ramachandar amurthy, V.K.; Muttaqi, K.M,; Mahlia, T.M.I.; Dong, Z.Y.	Battery energy-storage system; Sizing; Optimization algorithm; Objective functions; Constraints	Journal of Energy Storage	10.1016/j.est.2021.103023	Literature review; Optimization of BESS	CAT1, CAT6
Environmental and economic multi-objective optimization of a household level hybrid renewable energy system by genetic algorithm [15]	2020	Mayer, Martin János; Szilágyi, Artúr; Gróf, Gyula	Renewable energy production; Hybrid energy system; Life-cycle assessment; Multi-objective optimization; Genetic algorithm	Applied Energy	10.1016/j.apenergy.2020.115058	Optimization of HRES; MATLAB simulation; Literature review	CAT1, CAT6
Integrated sizing of hybrid PV-wind-battery system for remote island considering the saturation of each renewable energy resource [16]	2019	Ma, Tao; Javed, Muhammad Shahzad	Solar-wind-battery system; Renewable energy saturation; Cost of energy Energy balance; Net present cost; Hybrid Renewable system reliability	Energy Conversion and Management	10.2016/j.enconman.2018.12.059	Case study; Mathematical approach	CAT3, CAT5
Techno-economic analysis of a hybrid renewable energy system for an energy poor rural community [17]	2019	Krishan, Om; Suhag, Sathans	Wind energy conversion system (WECS); Photovoltaic (PV) system; Battery energy storage system (BESS); Techno-economic analysis; Hybrid renewable energy system (HRES)	Journal of Energy Storage	10.2016/j.est.2019.04.002	Case Study; Homer and MATLAB simulation;	CAT3
Feasibility analysis and techo-economic design of grid-isolated hybrid renewable energy system for electrification of agriculture and irrigation area: A case study in Dongola, Sudan [18]	2019	Elkadeem, M.R.; Wang, Shaorong; Sharshir, Swellam W.; Atia, Eman G.	Hybrid renewable energy; Techno-economic optimization; Carbon emissions; Net present cost; Sensitivity analysis; HOMER Pro®	Energy Conversion and Management	10.1016/j.enconman.2019.06.085	Case Study; Literature review of existing HRES; HOMER simulation;	CAT3, CAT5
Potential, optimization and sensitivity analysis of photovoltaic-diesel-battery hybrid energy system for rural electrification in Algeria [19]	2019	Fodhil, F.; Hamidat, A.; Nadjemi, O.	Hybrid renewable energy system; Photovoltaic; Diesel; PSO optimization; Rural electrification	Energy	10.1016/j.energy.2018.12.049	Case study; HOMER simulation; literature review of optimization methods	CAT1, CAT3, CAT5

to optimize strategies, and the relevance of sizing methodologies to implement hybrid systems. In this work, it is noteworthy that many literature reviews and state-of-the-art articles suggest the necessity of such materials for research and development involving HRES.

Furthermore, it is fundamental to recognize the global significance of HRES and bridge the knowledge gaps identified in this review. Future research investigations should explore control strategies and simulation tools and address the feasibility of large-scale hybrid power plants in diverse geographical contexts.

In essence, this review not only underscores the rapid growth and global relevance of HRES but also motivates continued exploration, innovation, and collaboration in pursuing a sustainable and resilient energy future.

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