


Trends and Knowledge Structures on Hybrid Energy Systems: Literature Analysis and Mapping

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Abstract- Strategies to avoid the variability effects in energy resources have become an essential study field. In order to avoid electricity shortages, particular types of power plants employ power storage or have two or more sources, the so-called hybrid plant. This article combines bibliometric analysis and literature mapping aiming to assist researchers in understanding the trend, structure, and latest development in research focused on hybrid energy systems. It was analyzed 7,183 scientific publications indexed in the Scopus and Web of Science databases. The mapping performed presents the critical aspects through publications, journals, authors, institutional affiliations, and geographic diversity of countries that collaborate in publications in the study's research line. The most relevant keywords, their conceptual construction, and the research's thematic evolution were analyzed to identify what evolved and how the research flows evolved. Through the bibliographic map, it was possible to identify a rapid increase in the number of publications, and this context explains the importance of hybrid energy systems by the academic community. The evidence is that the newest research has been evolving towards greater efficiency and optimization of energy production in hybrid systems.

Keywords Hybrid Energy Systems, Energy Resources, Bibliometric Analysis, Literature Mapping.

1. Introduction

Authors should any word processing software that is The continuous increase in world population and negative environmental impacts directs attention to alternative renewable energy sources. However, the intermittent nature of renewable energy can lead to problems of variability in demand-supply. Therefore, strategies to avoid variability in these resources have become an important field of study [1]–[4]. Particular types of power plants are built to avoid power shortages and use all available energy. There are at least two ways to achieve this goal: electrical energy storage or power plants with two or more sources, which are called hybrid plants [5], [6].

The hybrid approach serves different purposes, such as biomass solar thermal systems [7]–[9]. In addition, hybridization can also refer to the combination of renewable

energy sources such as solar and wind [5], [10]–[13], solar and geothermal [14]–[16], fuel cell and gas turbine [17]–[19], and solar-coal [20]–[22]. Seminal studies in the area of hybrid energy systems proposed innovative solutions at the time of their publications, such as Wang and Nehrir [23], which projected an alternative wind energy hybrid system with photovoltaic and fuel cells for autonomous applications, followed by Li, Hui and Lai [24], which presented the results of simulation analysis of a hybrid wind, photovoltaic, and battery power system performed to improve the smoothing performance of hybrid power generation. Many of these solutions are seen in practice over the years, showing that scientific publications are at the frontier of knowledge.

Based on this context, this study combines two approaches: bibliometric analysis and literature mapping. Bibliometric analysis or performance analysis aims to evaluate the study of countries, universities, researchers and

the impact of activities based on bibliographic data [25]. On the other hand, literature mapping or scientific mapping provides scientific research's structural and dynamic aspects [26]. Compared to other literature review methods, such as narrative and systematic literature reviews, bibliometric analysis is a methodical and reproducible process that reduces intrinsic subjectivity [27]. Furthermore, the method maps the overview of a given area based on indicators [28]. Moreover, by organizing the data available in the databases, it is possible to transform it into understandable information to help expand knowledge in a given study area about articles, journals, authors, institutions, and countries [29], [30].

In the literature, some studies provided an overview through bibliometric analysis or literature mapping. Thus, it is possible to highlight some areas and studies such as management [31]–[33], statistics [34]–[36], environmental and ecological economics [37]–[39], energy emissions [40]–[42], mapping global trends in research on energy poverty [43]–[45] and study on trends of future research on solar energy management [46]–[48]. However, articles with an overview of "hybrid energy systems" were not found. Some authors study the energy efficiency analysis of a hybrid system [49]–[51], potential evaluation and performance evaluation of hybrid systems, such as the study of Wang et al. [52] that evaluated the potential of hydro-photovoltaic-wind systems on a large scale on a global scale, Ding et al., (2016) [53] analyzed large-scale photovoltaic integration in China and the study of Guo and Sepanta [54] that evaluated the performance of a new combined energy system to produce electricity and hydrogen with an energy storage option. Other studies such as Guo and Sepanta [54] also analyzed a combined energy system with hybrid energy systems and the storage option such as Lin; Wang; Rezazadeh (2021) [55] who analyzed electrical energy storage for a combined energy process based on solid oxide fuel cell and waste heat use. Also, there is the study by Dong et al. (2021)[56] who presents and investigates a new hybrid energy system for energy production and storage, this hybrid energy system is composed of a solar thermal collector, Stirling engine, and thermoelectric generator.

Thus, to gain insight into the concentration of existing research in the literature and identify potential areas to explore about hybrid energy systems, the study aims to answer the following questions: What are the bibliographic characteristics of articles related to hybrid power systems? What other topics are related to research on hybrid energy systems? What are the leading journals and universities that publish on hybrid energy systems?

As a result, this study makes it possible to identify the main trends in scientific production in the analyzed study area. It also allows viewing the countries that actively collaborate with publications on the topic. In addition, it contributes to the analysis of how the themes have evolved, enabling the understanding of future perspectives related to the theme.

This study has four sections. The second section presents the method. The third section presents the results, including the discussion and the main bibliographic indicators for

understanding the scientific production. Finally, the fourth section concludes the study and directs readers to final considerations and future research areas.

2. Method

Bibliometric methods have been used in the literature to analyze publications. This type of analysis identifies publications' broadest sense, focused on a particular thematic area [57]. The goal is to transform something intangible (scientific quality) into something manageable. Furthermore, compared to peer review, which has a limited area of investigation, bibliometric methods examine unlimited amounts of publications [58].

Bibliometric analysis and literature mapping of research on hybrid energy systems were carried out in June 2021, using two databases: Scopus and Web of Science (WoS). The terms used to search the titles, abstracts, and keywords were: "hybrid power plant*," "hybrid energy system*," "hybrid power system*," "energy source integration*" and "complementary energy system*." There was no restriction on language and year of publication. Table 1 shows how the search was performed in the databases.

Table 1. Description of searched databases and options

| Investigation Process | | |
|-----------------------|--|--|
| Database | Scopus | Web of Science |
| Search Type | Advanced search | Advanced search |
| Search fields | Article title, abstract, keywords | Topic |
| Search string | "hybrid power plant*" OR "hybrid energy system*" OR "hybrid power system*" OR "energy source integration*" OR "complementary energy system*" | "hybrid power plant*" OR "hybrid energy system*" OR "hybrid power system*" OR "energy source integration*" OR "complementary energy system*" |
| Stipulated period | Every year until June 2021 | Every year until June 2021 |
| Document type | Article, Conference Paper e Review | Article, Proceedings Paper e Review |

The analysis and mapping used the R software, an open-source statistical application, particularly the "Bibliometrix" package [59], to analyze the data obtained through research queries in the Scopus and WoS databases. In addition, the 'Biblioshiny' extension was used to tabulate and visualize the search results. This tool contributed to the analyzes carried out, mainly with the bibliographic map of the topic of interest. This makes it possible to understand the intellectual and structural origins of literature over time [60]. The following section presents the results and discussion of this study.

3. Results and discussion

This section presents the results obtained from the analysis and mapping of literature. The search in the Scopus resulted in 6,601 articles, and in the WoS, the result obtained was 4,672 articles. By joining the databases, 3,985 duplicate documents were removed, resulting in 7,183 articles. Annual publications on hybrid plants increased throughout the year. The result is in Figure 1.

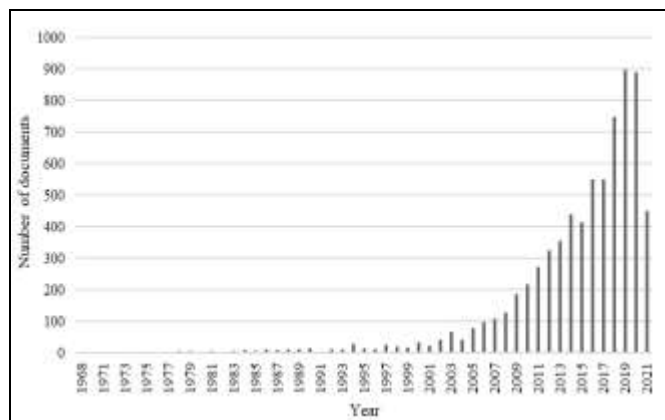


Figure 1. Annual scientific production.

The annual growth rate of scientific production on hybrid plants is 12.47%. This growth may be related to energy scarcity issues. There are at least two ways to control scarcity: electrical energy storage or hybrid systems using two (or more) energy generation sources to balance the strengths and weaknesses of each [5]. Changes in scientific production may also be related to the COVID-19 pandemic, which significantly affects energy demand. While many effects result from a rapidly changing economic situation, other non-macroeconomic factors in the energy sector are also changing. Since the first quarter of 2020, when cases of COVID-19 spread globally and governments began designing mitigation efforts to contain the pandemic, responses to the pandemic have impacted global economic activity [61]. Given the growth in publications, other results permeate the leading newspapers and publications that contribute to the theme, such as "hybrid energy systems", the conceptual structure of literature, the research thematic mapping, and the thematic evolution of research on "hybrid energy systems".

3.1. Journals, Universities and Countries

This section features information on publications and publication sites that contribute the most to research related to hybrid energy systems. Citation impact analysis has been used to assess research performance and can be applied at all organizational levels such as author, institution, country/region, the field of research, or journal [62]. Figure 2 contains the top fifteen journals that published the highest number of articles on hybrid plants.

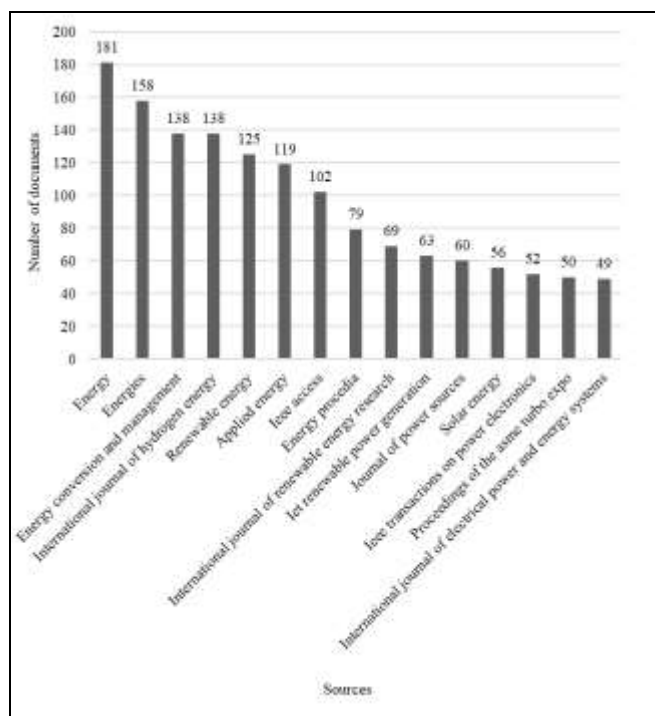


Figure 2. Most relevant sources.

Among the fifteen journals that published the most, the ones that stood out, respectively, were Energy, Energies, Energy Conversion and Management, International Journal of Hydrogen Energy, and Renewable Energy. Based on the number of global citations received, it was also possible to identify the fifteen most impactful publications within the theme addressed in this study. First, the article entitled Power Management of a Stand-Alone Wind/Photovoltaic/Fuel Cell Energy System is the most cited publication. This publication is from Wang and Nehrir [23], published in IEEE Transactions on Energy Conversion. Second is a more recent article, titled Battery Energy Storage Station (BESS)-Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations, by Li, Hui and Lai [24] published in IEEE Transactions on Sustainable Energy.

In addition, the five universities that publish the most on the subject were evaluated, in particular, the North China Electric Power University, followed by the Islamic Azad University, Department of Electrical Engineering, Tsinghua University and National Institute of Technology. Regarding the collaboration among countries, Figure 3 shows in blue the existence of scientific production in each country. The darker the blue, the more productive the country is in the theme of hybrid plants. The red lines indicate the collaborative networks of the publishing countries.

Countries that actively collaborate with others are China, Canada, the USA, and South Africa. The map indicates that there is strong collaboration between China and the USA. China is one of the countries that most collaborate with others, which may justify the highlight of the North China Electric Power University among the five universities that publish the most on the subject.

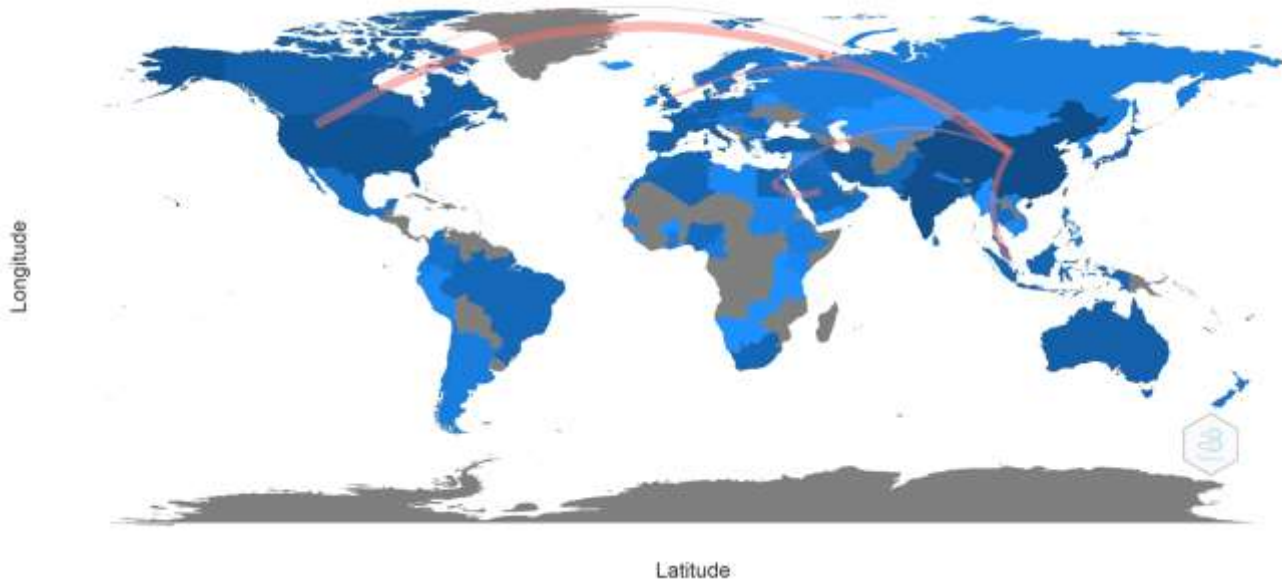


Figure 3. Country collaboration map.

3.2. Conceptual Structure of Literature

Through the conceptual structure of the literature, it is possible to discover the hidden and dynamic pattern of a research field to identify the main themes addressed in the literature [63]. Table 2 presents the twenty keywords most used by the authors of the analyzed database, that is, the list of terms that the authors believe best represent the content of the article [64]. Thus, it is possible to identify research trends in several scientific fields [65].

As expected, the four most recurring keywords are "hybrid power systems", "hybrid systems" "hybrid energy system" and "renewable energy". From these four main keywords, other associated topics were observed, such as: systems optimization, fuel cell, homer analysis, energy management, microgrids, batteries and storage systems.

In addition to a return focused on hybrid plants, it also focuses on renewable energy, emphasizing words or phrases such as: "renewable energy sources" and "renewable energies". Using hybrid renewable energy systems helps to reduce the carbon emitted by power plants. Another aspect relates to climate change mitigation and global warming, which provides better health for human beings and the environment [66]. Among the terms presented there are also solar energy and wind energy. This presence may be related to the capacity to generate renewable energy, which increased by 261 GW (+10.3%) in 2020, while solar energy had an increase of 127 GW (+22%), followed by wind power with 111 GW (+18%) [67]. Evidencing that hybrid energy systems are more explored in conjunction with storage systems and with solar and wind sources. This is also proven when analyzing the literature, it is possible to find studies that integrate solar and wind energy, such as Liao, Mathieson and Finney, (2021) [68] which deals with a hybrid system of photovoltaic solar energy, wind energy and fuel cell in ship power systems. The results of this study show that the hybrid

energy system can reduce the emission of 151,467 kg of CO₂. Other studies discuss modeling, hybrid power system techniques, and battery storage system sizing to smooth power fluctuations of a hybrid system composed of renewable energy such as solar and wind power [69], [70], [11], [71], [72].

Table 2. Author’s keywords.

| Terms | Frequency | |
|--------------------------|-----------|-----|
| Hybrid Power System | 705 | 12% |
| Renewable Energy | 577 | 10% |
| Hybrid Energy System | 538 | 9% |
| Hybrid Power Systems | 519 | 9% |
| Optimization | 378 | 6% |
| Fuel Cell | 342 | 6% |
| Hybrid System | 305 | 5% |
| Homer | 252 | 4% |
| Photovoltaic | 248 | 4% |
| Wind Energy | 240 | 4% |
| Battery | 234 | 4% |
| Hybrid Energy Systems | 221 | 4% |
| Solar Energy | 214 | 4% |
| Energy Management | 211 | 4% |
| Wind | 192 | 3% |
| Energy Storage | 180 | 3% |
| Renewable Energy Sources | 177 | 3% |
| Hybrid | 174 | 3% |
| Wind Turbine | 170 | 3% |
| Microgrid | 151 | 3% |

3.3. Thematic Mapping of Research on Hybrid Energy Systems

Thematic mapping enables the analysis of the themes according to the quadrant in which they are inserted [73].

The distribution of keyword groups is in Figure 4. The upper right quadrant represents the motor themes, the lower right quadrant represents the basic themes, the lower left quadrant contains emerging or disappearing themes, and the upper left quadrant indicates very specialized, niche themes [74].

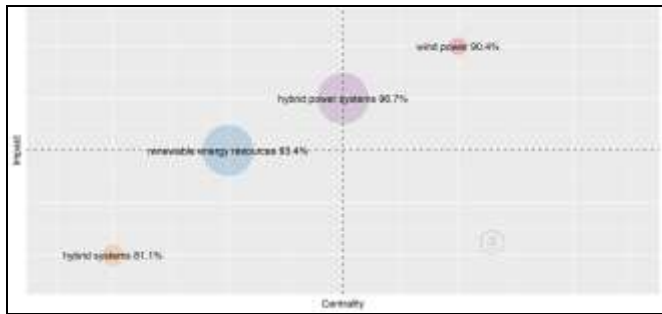


Figure 4. Clusters by documents coupling.

Figure 4 presents about four major areas. The upper right quadrant representing the engine theme of a search area shows the domain of the "wind power" theme, and apparently, the "hybrid power systems" theme is also in this quadrant. The theme "hybrid power systems" is also placed in the upper left quadrant, representing very specialized themes. It indicates that the theme represents essential and critical research areas, presenting association with additional research. In addition to the "hybrid power systems" theme, the "renewable energy resources" theme is likewise located in the top left quadrant. However, this theme is also presented in the lower-left quadrant that represents emerging or disappeared themes. It can be said that it is an emerging theme in this specific case because it is in the quadrant of specialized themes, niches with additional research. The lower left quadrant also has the theme "hybrid systems," representing possibly an emerging theme, as it is a variation of the word hybrid power systems.

It was noted again that renewable energy resources are strongly related to hybrid energy systems. This case highlights wind power as well. Wind expansion practically doubled in 2020 (111 GW) compared to 2019 (59 GW) [67], [75]. China introduced a new wind power capacity of 72.4 GW, followed by the United States (+14.2 GW). Ten other countries increased their wind capacity by more than 1 GW in 2020 [67]. Therefore, strategies to avoid or mitigate the effects of the variability of energy resources are an essential field of study, which justifies the fact that wind power is an area in the thematic mapping of research on hybrid plants.

3.4. Thematic Mapping of Research on Hybrid Energy Systems

In addition to verifying the general composition of the research areas, it analyzed changes in themes in different periods. Helps identify what and how research flows have evolved [63]. A weighted inclusion index was used by the occurrence of words in each cluster containing more than 250 keywords. Figure 5 illustrates a Sankey diagram [76], [77] two periods, encompassing the development of the research in these periods.

The analysis made it possible to verify the most recent issues related to hybrid plants. In the first period (1968-2016), the focus of the research was on the terms "hybrid plants". The term "hydrogen" did not receive prominence in this period. One justification may be that it has lost favor since the oil shocks of the 1970s. Thus, one can observe the transition from the term "hydrogen" to "fuel cells". Although there is this transition, the two are not synonymous. Hydrogen and fuel cells can be deployed in combination or separately. When used together, hydrogen fuel cells have zero-emission at the point of use, depending on the fuel production method, as in the case of electricity [78].

In the second period (2017-2021), the predominance of the term hybrid power plants was again verified, however, together with other terms such as "optimization" and "fuel cells". The term "optimization" may be related to the optimization of the use of the transmission system (association or hybridization with the addition of a source to take advantage of idle capacity in specific periods), along with the adoption of hybridism. As a result, the expectation is a reduction in variability of power injection into the electrical network due to the complementarity of generation between the sources [79].

Regarding the term 'fuel cells', some studies such as that by Brouwer [80] state that hybrid gas turbine systems with fuel cells can significantly increase the efficiency of fuel-to-electricity conversion and reduce greenhouse gas emissions. Furthermore, another study claims that fuel cells are experiencing a resurgence of interest due to the large-scale production of fuel cell vehicles and homes being heated and powered by fuel cells [78]. Consequently, it is possible to observe that future research is around climate change and emissions, considering the use of renewable energies and optimization of energy systems to implement hybrid energy plants.

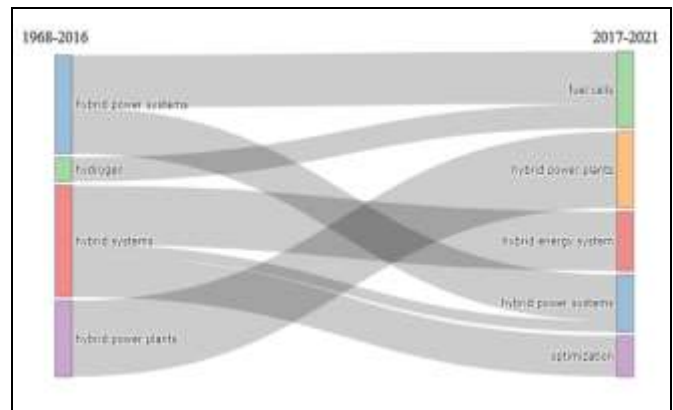


Figure 5. Thematic evolution of research on hybrid energy systems.

3.5. Conceptual Structure of Literature

The results of this study show the characteristics of the articles published in the Scopus and WoS databases about hybrid energy systems. Table 3 contains the analysis with the

top results. It is possible to observe that researches related to hybrid plants present an excellent consolidation in the literature. The growth in publications reached a peak in 2019. In 2006 there were 98 publications, and as of 2016, it is possible to observe that the number of publications increased significantly, reaching 549. The growth trend shows that the accumulated number of publications reached 897 in 2019. This demonstrates a tendency for research in this area of hybrid plants to continue to grow in the coming years, which can serve as a strategy to avoid or mitigate the effects of the variability of energy resources. Furthermore, Tilahun et al. [81] state that regardless of the measures taken by the electricity sector to improve the efficiency of electricity supply, the use of alternative local energy resources, such as solar and biomass, for heat and energy cogeneration, can help to reduce energy supply problems.

Regarding the number of articles per country, China is the country with the most publicity on the subject and concentrates most of the most productive institutions. According to Pu and Yang [82], improving energy efficiency is one of the main issues in China to decrease energy consumption and achieve a carbon-neutral society. Furthermore, to effectively reduce coal capacity, the Chinese government has included a policy of cutting coal capacity that should promote a revolution in energy supply [83]. These issues demonstrate China's concern with energy efficiency, which may justify its position in ranking countries that publish more on the subject.

The keywords analysis showed that terms such as hybrid power systems and renewable energy resources direct the focus of research to the topic. Energy consumption is increasing, and there is an increased cost and the worsening of the global environment, which creates greater interest in green energy generation systems (renewable energy sources and/or based on fuel cells) [23]. However, natural restrictions allied to the stability of the electric network, the difficulty of energy storage, and the relatively low benefits cause a series of challenges in the development of renewable energies. In contrast, fossil energy generation is relatively stable and inexpensive, but it generates environmental pollution and climate change. This creates a complementary relationship between fossil energy generation and renewable energy generation [84].

According to Wang and Nehrir [23], in their article "Power Management of a Stand-Alone Wind/Photovoltaic/Fuel Cell Energy System", presented as the publication with the most citations related to the topic, hybrid energy systems have a great potential to supply higher quality power than a system based on a single resource. This article presented 610 citations in the impact analysis. However, the most productive authors are not the most cited. Furthermore, it was observed that the most cited articles had the main objectives of identifying control strategies, energy management, and a search for improvements in energy performance.

Table 3. Description of the characteristics of the articles dealing with the topic of hybrid energy systems

| Analysis performed | Main results | Preliminary conclusions |
|--|--|--|
| Description of the most cited scientific productions | The most cited scientific productions are articles that are primarily published in journals in the energy area in the publishers IEEE and Elsevier | The main topics discussed in scientific productions deal with control strategies, energy management, and energy performance improvement |
| Number of publications by type of document | 55% of the articles are research, 41% are conference paper, and only 4% proceedings paper | Research articles and conference paper present a more significant number than proceedings paper |
| Quantity of articles per year of Publication | The theme was consolidated in literature after the year 2016 and reached its peak in 2019 | The theme is consolidated in the literature, but it still has a growth perspective in studies related to the area of interest |
| Quantity of articles by country | China, India, and USA represent the most productive countries | Different countries have similar productivities related to hybrid energy systems |
| Quantity of articles by institution | The University of China leads the ranking with more articles related to the subject | China concentrates most of the most productive institutions on the subject |
| Keywords most used to represent the articles | The keywords show a relationship between hybrid power systems and renewable energy resources | There is an evolution in research related to hybrid energy systems and linked terms in order to improve the efficiency of the electricity supply |
| Quantity of citations per article | The most cited article had 610 citations | The most productive authors are not necessarily the most cited |

Most infrastructure in developing countries has grid-connected systems, making it difficult for areas far from the grid to access power supplies. Therefore, even with

improvements in power generation, countries like in Africa continue to have poor access to electricity [85]. Access to energy is a challenge for the African continent,

where more than 55% of the rural population does not have access to electricity [86], [87]. A low-cost hybrid plant can be a solution in these cases, and it can be built using various wind optimization methodologies or even photovoltaic generation and non-linear features of the hydroelectric plant. Thus, it can be said that there are motivations for designing a hybrid system, such as reducing peak load (load reduction), providing energy security, and minimizing problems related to uncertainty in renewable generation systems.

This article demonstrates how literature analysis and mapping can be valuable tools for the business, government, and academic communities as it presents an overview related to hybrid energy systems. What contributes to the identification of countries, researchers, and institutions at the forefront of research in the area and thus serve as a reference in improvement processes related to energy efficiency.

4. Conclusion

The results show a rapid increase in publications concerning hybrid energy systems, and this context explains the academic community's importance to the theme. China is the top country in collaborative publications. There is strong collaboration between China and the USA. North China Electric Power University ranks first among universities that publish the most on hybrid power systems. Moreover, in terms of publication sources, "Energy" has been the most productive journal in publishing research on the field of study.

The main contribution of this article is the evidence that hybrid systems are being more studied and associated with two specific renewable energy sources: solar and wind. Both sources are intermittent in nature. Storage systems and the combination with non-intermittent sources, such as biomass, should receive greater efforts from the academic community. The evidence is that hybrid energy systems have already been modeled and proposed in the older literature (1968-2016). The newest research has been evolving towards greater efficiency and optimization of energy production in hybrid systems (2017-2021). Then, researchers are looking for the evolution of these systems' technical and economic feasibility. These viabilities will permit the diffusion in the countries.

In addition, the electricity sector around the world is transforming the bulk grid model into the distributed generation and storage model. However, studies involving the distributed generation of hybrid systems are not so recurrent. Hybrid systems with storage reduce the need for a network connection. However, in free energy markets, being connected to the grid will allow the sale of this energy. Therefore, inserting hybrid systems into profitable business models is as important for their diffusion as their technical capacity.

Thus, the analyses carried out in this research can help researchers understand the trend, structure, and latest development of research related to hybrid energy systems, which contributes to gaining insight into the concentration of existing research in the literature and enables the identification of potential areas to explore. Future research

may be related to climate change and emissions, emphasizing the use of renewable energies and optimization of energy systems for the implementation of plants with complementary sources.

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