Trends and Challenges of Hybrid Renewable Energy Systems (Solar–Wind–Biomass): A Bibliometric Analysis

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Abstract. Hybrid Renewable Energy Systems (HRES), particularly those integrating solar, wind, and biomass energy sources, have emerged as a key solution for advancing the global energy transition. Their role is crucial in supporting SDGs, particularly SDG 7 on affordable and clean energy and SDG 13 on climate action. This study aims to map the global research landscape of solar-wind-biomass HRES through bibliometric and content analysis. Data were retrieved from the Scopus database, the Bibliometrix R package, and CiteSpace were employed to explore research distribution, leading countries and institutions, influential authors, collaboration networks, high-impact publications, trending topics, and persistent challenges. The findings reveal a significant increase in research output over the past two decades, with India, China, and the United States leading in publications and collaborations. High-impact studies emphasize optimization models, techno-economic feasibility, and life cycle assessment frameworks. Despite these advances, recurring issues such as system reliability, resource intermittency, and integration with existing electricity grids persist. The implications highlight the need for international collaboration (SDG 17), innovation in energy management, and policy support to promote sustainable, resilient, and inclusive energy systems. This study provides evidence-based insights to accelerate global progress towards the SDGs through hybrid renewable energy integration.

1 Introduction

The growing global demand for energy and the urgent need to mitigate climate change have positioned renewable energy as a crucial pillar in the transition towards a sustainable energy future. The energy sector remains the largest emitter of greenhouse gases globally, accounting for over two-thirds of the world's emissions [1]. Fossil fuel dependence has led

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to rampant environmental degradation, economic instability, and energy security risk. Hybrid Renewable Energy Systems (HRES), which utilize more than one renewable source, such as solar, wind, and biomass, have emerged as viable alternatives to address the limitations of stand-alone systems, reduce energy dependence, and minimize carbon footprint [2]. Hybrid systems can balance intermittency, reduce resource waste, and provide decentralized solutions most suitable for remote and off-grid locations by combining complementary renewable resources.

Solar, wind, and biomass energy are the best-developed and applied renewable technologies, with each having its own specific advantages and limitations. Solar energy has clean and abundant supplies but suffers from intermittency at night or in cloudy weather. Wind energy is the leading force in global deployment of renewables, but is extremely site-specific and intermittent [3]. Whereas biomass offers secure energy production and opportunities for waste-to-energy conversion, it also has land use, feedstock availability, and sustainability challenges. Their combination in hybrid systems forms not only enhances energy security but also endorses environmental as well as socio-economic resilience. Despite having such wonderful biomass potential, the large-scale application of solar–wind–biomass hybrid systems is still constrained by several barriers, including initial investment expenses, technological complexity, policy loopholes, and environmental conditions [4].

In the last decades, research culture on hybrid renewable energy systems has progressed very dynamically, from system optimization and efficiency to environmental impacts, and socio-economic viability. Researchers have proposed alternative means of enhancing integration, improving efficiency, and minimizing ecological trade-offs, albeit at the expense of being cost-effective [5]. The literature, nonetheless, also portrays ongoing concerns regarding system scale-up, technology standardization, and policy alignment with sustainability objectives.

Given these dynamics, it becomes essential to identify how research on hybrid renewable energy systems, specifically solar–wind–biomass integration, has developed over time. In order to meet this demand, this study performs a bibliometric review of solar–wind–biomass hybrid energy systems in terms of their sustainability concerns and applicability towards the United Nations Sustainable Development Goals (SDGs). CiteSpace and Bibliometrix in R-Studio are used to visualize publication activity, determine key authors, institutions, and journals, and examine collaboration networks, and emerging themes in the area of the topic [6]. Publication and citation timelines, and keyword co-occurrence are used to track the evolution of associated ideas and distinguish key areas for future research in technology, policy, and practice. There are six particular goals of this bibliometric analysis:

(1) Analysis the distribution of hybrid renewable energy systems (Solar–Wind–Biomass) research
(2) Analysis the leading countries and institutions in hybrid renewable energy systems (Solar–Wind–Biomass) research
(3) Analysis the prominent researchers and collaboration networks in hybrid renewable energy systems (Solar–Wind–Biomass) research
(4) Analysis of high-impact publications of hybrid renewable energy systems (Solar–Wind–Biomass) research
(5) Analysis the trend topic of hybrid renewable energy systems (Solar–Wind–Biomass)
(6) Analysis the challenges of hybrid renewable energy systems (Solar–Wind–Biomass)

2 Method

This study used a descriptive bibliometric method to track research challenges and trends in HRES, specifically the integration of solar–wind–biomass systems. Bibliometric analysis is otherwise known to be the working method of analysis in knowledge growth evaluation, identifying important contributions, and thematic development in a research area [6]. The data used for this study were obtained from the Scopus database because of its extensive coverage of peer-review studies in energy, engineering, environmental sciences, and multidisciplinary fields. The search query was conducted on the keyword "Hybrid Renewable Energy System" and it returned 29,458 documents. Advanced search queries were employed to filter down the dataset for this research: Hybrid Renewable Energy System AND (solar OR photovoltaic) AND wind AND biomass, yielding 669 documents (as showed in Fig. 1).

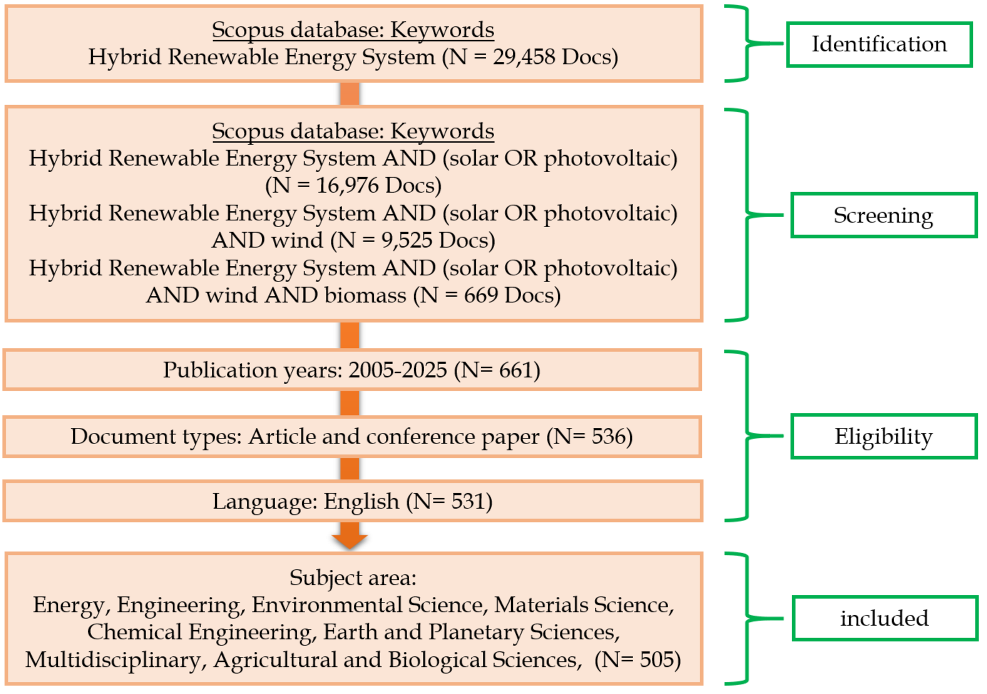

Fig. 1. Research stages of bibliometric analysis

To ensure relevance and quality, several inclusion and exclusion criteria were utilized. The articles were restricted to the time frame of 2005–2025, which left us with 661 records. Articles and conference papers alone were utilized, leaving us with 536 records. The publications were also required to be English language, which left us with 531 records for analysis. Lastly, for emphasis on disciplinary relevance, only articles that were categorized under energy, engineering, environmental sciences, materials science, chemical engineering, earth and planetary sciences, multidisciplinary sciences, agricultural and biological sciences were selected, yielding a final dataset of 505 articles.

After data collection, the records were exported in CSV and RIS formats for preprocessing. Data cleaning was performed to ensure conformity in authors' names, institution affiliation, and keyword usage variations. Bibliometrix R package and CiteSpace were employed in the analysis. Utilization of Bibliometrix helped in the calculation of publication indicators such as annual trend in publications, most cited journals, and productivity of authors. CiteSpace was utilized to create visualization networks, such as co-citation maps, collaboration networks, and keyword clusters for co-occurrences [7]. The integration of these tools gave a holistic picture of hybrid renewable energy system intellectual structure and knowledge development. This approach enabled identification of main contributors, partnership trends, most prominent research themes, and leading up-andcoming research fronts, resulting in valuable insights for future solar–wind–biomass hybrid system study and policy development.

3 Result and discussion

3.1 The distribution of hybrid renewable energy systems (Solar–Wind–Biomass) research

According to Scopus data, trends in publications on hybrid renewable energy systems (HRES) integrating solar, wind, and biomass have been increasingly rising between the years 2005 and 2025 (Fig. 2). During the first era (2005–2011), the volume of production in the form of research was not high, with less than 10 publications per annum, indicating the conceptual phase of the subject and the enormity of the technologies. Between the years 2012–2016, papers slowly built up to around 10–20 annually, with increasing world focus on sustainable energy transition. There was a sudden surge after the year 2017 when papers breached the 30 per annum mark and nearly touched 40 in the year 2019, validating the fact that HRES was turning into a permanent field of research. The most significant growth was between 2021 and 2023 with over 60 publications per year, reaching a record high of over 70 papers in 2025. This indicates that solar–wind–biomass hybrid system research has moved from initial discovery to increasingly practical and transdisciplinary research, prompted by advances in technology, system efficiency improvement, and policy support for clean energy highly congruent with the Sustainable Development Goals (SDGs).

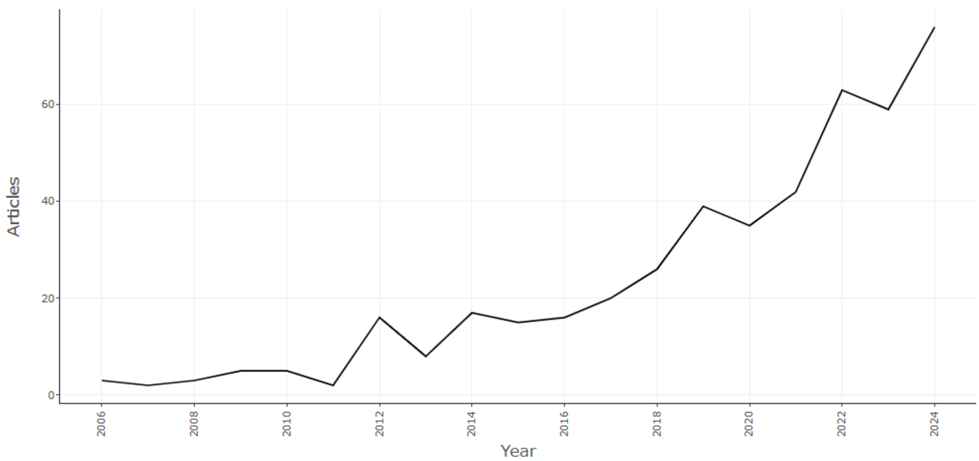

Fig. 2. Publication overtime years

3.2 Leading countries and institutions in hybrid renewable energy systems (Solar–Wind–Biomass) research

Based on the distribution of publications illustrated in Fig. 3 and the global mapping visualization, the study landscape of HRES with solar/photovoltaic, wind, and biomass exhibits high geographical disparity. India is the most prolific source, as indicated by the darkest blue cluster on the map, with a cumulative count of 426 publications. Bangladesh (140) and China (135) are closely followed by significant contributions, followed by Spain (89), Malaysia (54), Iran (51), Egypt (48), Turkey (43), the United States (42), and Australia (34). The denseness of the colors over the map serves to illustrate the amount of research produced, and it is evident that India, China, and the USA are hotspots for the production of HRES scholarship. This spread across geography indicates that future global collaboration must be with these leading nations since they have a pivotal role to play in defining the evolution of hybrid renewable technology and alignment of research with world sustainability goals [8].

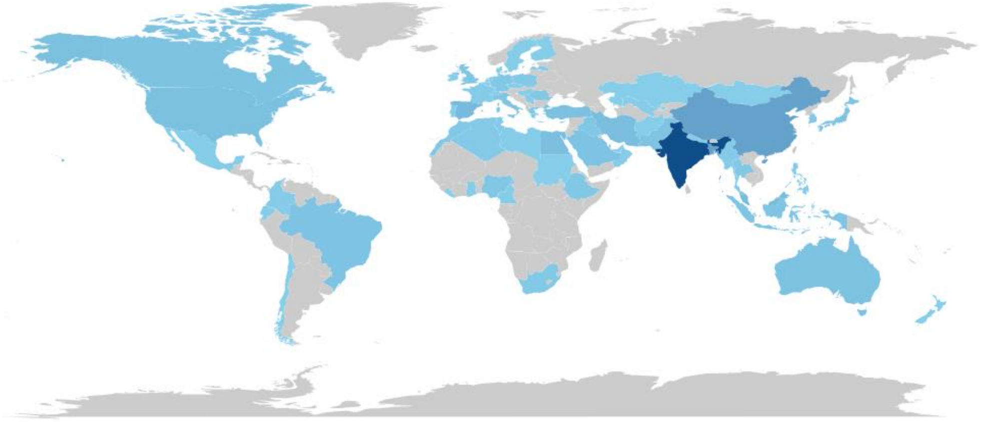

Fig. 3. Country production overtime of HRES research

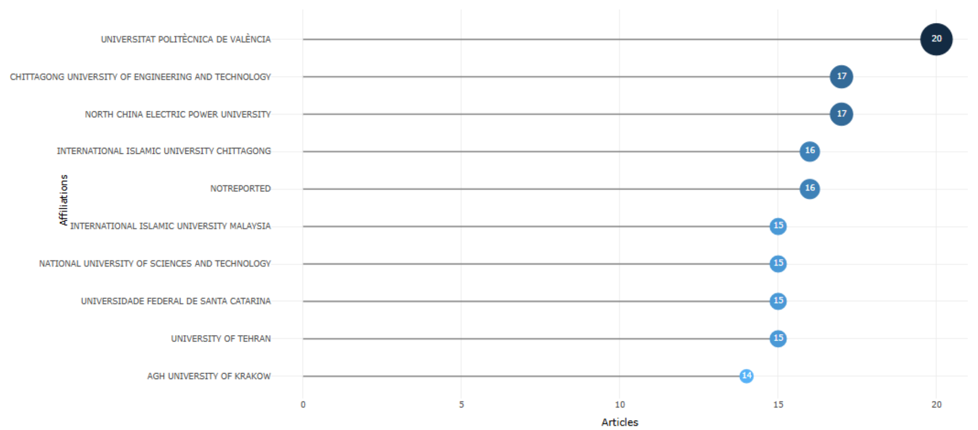

Fig. 4. Affiliation production overtime of HRES research

The strongest affiliations for HRES research covering solar/photovoltaic, wind, and biomass are shown in Fig. 4. Universitat Politècnica de València is ahead of the list with 20 publications, highlighting its research-intensive strength as well as regular contribution towards this field. Following close behind these were North China Electric Power University and Chittagong University of Engineering and Technology with 17 published papers each, and International Islamic University Chittagong and an unreported group of authors ("Not Reported") with 16 papers each. Other top contributors to the research include International Islamic University Malaysia, National University of Sciences and Technology, Universidade Federal de Santa Catarina, and University of Tehran, all with 15 publications, while AGH University of Krakow published 14. All these observations point towards European, Asian, and Latin American universities being very active in constructing HRES research. Hence, future collaboration prospects should especially focus on institutions like Universitat Politècnica de València that have shown the highest productivity, as recommended by previous research that shows collaboration at the international level is essential in order to enhance knowledge sharing and the pace of innovation in sustainable hybrid energy systems.

3.3 Prominent researchers and collaboration networks in hybrid renewable energy systems (Solar–Wind–Biomass) research

As depicted in Fig. 5, the keyword co-occurrence analysis reveals major areas of research focused on HRES, which combine solar/photovoltaic, wind, and biomass. A strong interconnection between the leading keywords like biomass, wind power, solar energy, hybrid systems, and renewable energies is evident through the Sankey diagram. These words continually emerge in varying levels of indexing (ID=Keyword plus; DE=Keyword; KW=All keyword), implying they are at the core of existing research jargon in this area. In addition, facilitating keywords such as optimization, renewable energy sources, and solar power generation capture the technical emphasis of existing research, particularly in system planning, efficiency improvement, and integration of energy. The repeated clustering of these keywords is an affirmation that the research field has progressed from standalone renewable technologies to hybrid integrated ones. This transition is an aspect of international cooperation, as collaborative learning between regions and disciplines is crucial in establishing innovative and responsive HRES models to be used globally against varied resource conditions and sustainability issues.

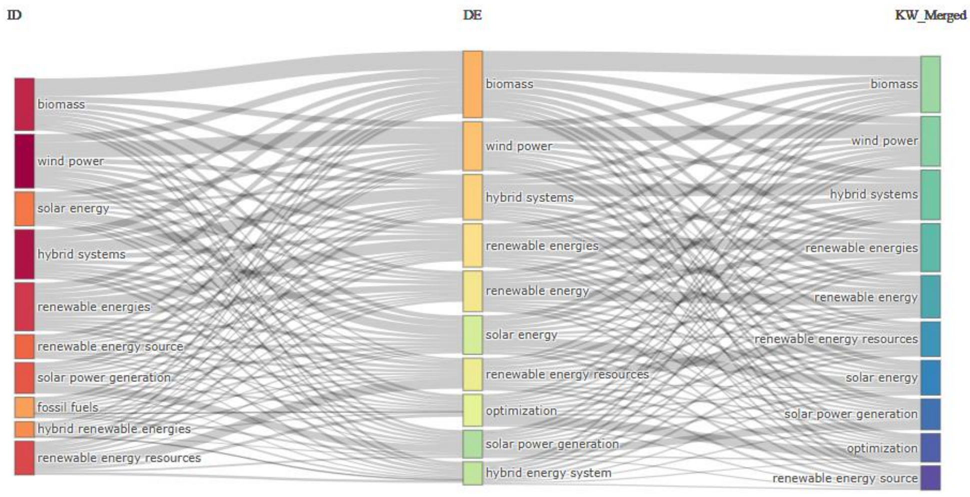

Fig. 5. Three-field plot diagram between keywords of HRES

Fig. 6 illustrates the global collaboration network in hybrid renewable energy systems (HRES) research, integrating solar/photovoltaic, wind, and biomass technologies. The visualization reveals both regional and transcontinental patterns of cooperation. Notably, India emerges as the most active node, forming extensive collaborations with countries across Asia, Europe, and North America. This reflects the country's strategic emphasis on renewable integration and its growing research infrastructure supported by both governmental and industrial initiatives.

The figure also highlights several North–South collaborations, particularly between developed economies (such as the United States, Germany, and the United Kingdom) and emerging nations (notably India, China, and Malaysia). These partnerships often aim to bridge technological capabilities and local resource potentials—where advanced nations contribute expertise and funding, while developing regions offer diverse renewable resources and implementation contexts. In addition, regional clusters are evident, such as intra-European cooperation and Asia-Pacific linkages, suggesting that geographic proximity and shared policy frameworks (e.g., EU energy transition agendas or ASEAN sustainability initiatives) facilitate collaboration.

Such global and regional partnerships not only foster knowledge exchange and technology transfer but also shape the research focus of HRES studies. For instance, collaborations involving Northern partners tend to emphasize system optimization and policy frameworks, while Southern-led studies often prioritize resource assessment and local adaptation. Consequently, these collaborations accelerate innovation, ensure contextual relevance, and strengthen the global pursuit of sustainable hybrid energy systems.

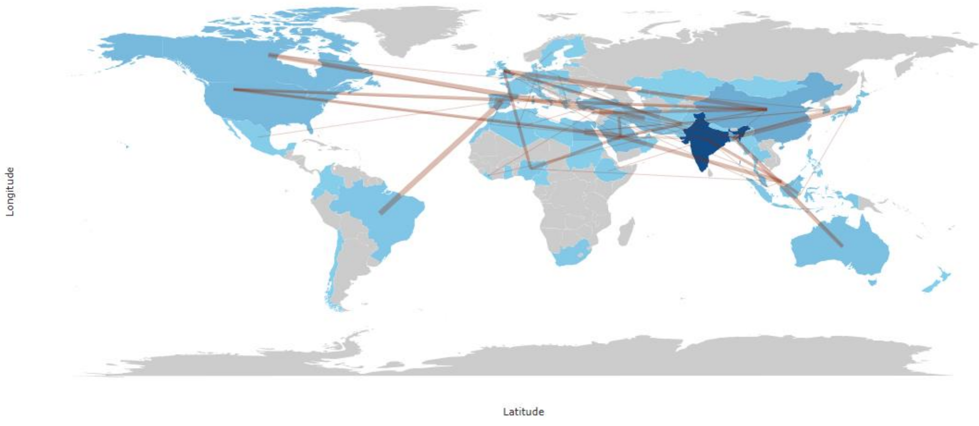

Fig. 6. Research networking country

3.4 The high-impact publications of hybrid renewable energy systems (Solar–Wind–Biomass) research

Table 1 lists the most cited papers in HRES research, categorized by solar/photovoltaic, wind, and biomass, ranked by citation counts. The most highly cited article is Shakti Singh et al. (2016) with 427 citations and an annual average of 42.57 citations, reflecting its significant and long-lasting impact in research. Getachew Bekele & Getnet Tadesse (2012) also contributed significantly, with 375 citations, testifying to the pioneering nature of their work, which appeared so prematurely. In terms of citation intensity per annum, Vendoti Suresh et al. (2020) (48.83 TC/year) and Jinze Li et al. (2020) (48.67 TC/year) top the list, attesting that new work is rapidly being recognized and utilized to inform new debate in the field. In addition to that, Jameel Ahmad et al. (2018) depict balanced influence via high total citations (326) and high normalized citation rate (10.15), indicating widespread adoption from various years of publication. Even newer publications, such as Aykut Fatih Güven & Mohamed Mahmoud Samy (2022) and Loiy Al-Ghussain et al. (2021), are performing well in year-to-year citations, as they reflect higher use despite being relatively new publications. Overall, insights here provide an introduction to the role of both early-year foundation research and contemporary literature in hybrid renewable energy development. The exponential growth in annual citation numbers of more recent publications indicates the rapid development of the sector and growing global interest in integrated and sustainable energy systems.

Table 1. Top 10 cited publications on HRES research.

Sources	Total Citation	TC per Year	Normalized TC
Shakti Singh et al., 2016	427	42.57	7.91
Getachew Bekele & Getnet Tadesse, 2012	375	26.79	7.01
Jameel Ahmad et al., 2018	326	40.75	10.15
Vendoti Suresh et al., 2020	293	48.83	5.35
Jinze Li et al., 2020	292	48.67	5.33
Nahar Alshammari & Johnson Asumadu, 2020	211	35.17	3.85
Tathagata Sarkar et al., 2019	207	29.57	5.75
Loiy Al-Ghussain et al., 2021	192	38.40	4.92
Aykut Fatih Güven & Mohamed Mahmoud Samy 2022	163	40.75	6.31
Gourav Kumar Suman et al., 2021	161	32.20	4.13

3.5 Trend topic of hybrid renewable energy systems (Solar–Wind–Biomass)

Fig. 7 depicts the yearly trend of research themes in accordance with the HRES research under solar/photovoltaic, wind, and biomass. The timeline illustrates how research trends have evolved year after year, with specific sets of keywords emerging during particular periods. For example, in 2022, the popular trending keywords were cost-effectiveness, biomass, and renewable energy, which indicate increasing interest in assessing the financial viability of integration based on renewable sources while moving towards the issue of climate change and global warming. In 2020, popular trending keywords were wind energy, hybrid systems, and solar energy. This has aligned with the COVID-19 pandemic economic crisis globally, where affordable and long-lasting energy solutions were in the limelight. Being reliant on renewable resources further projected the necessity of sustainable energy transitions to promote economic and environmental stability.

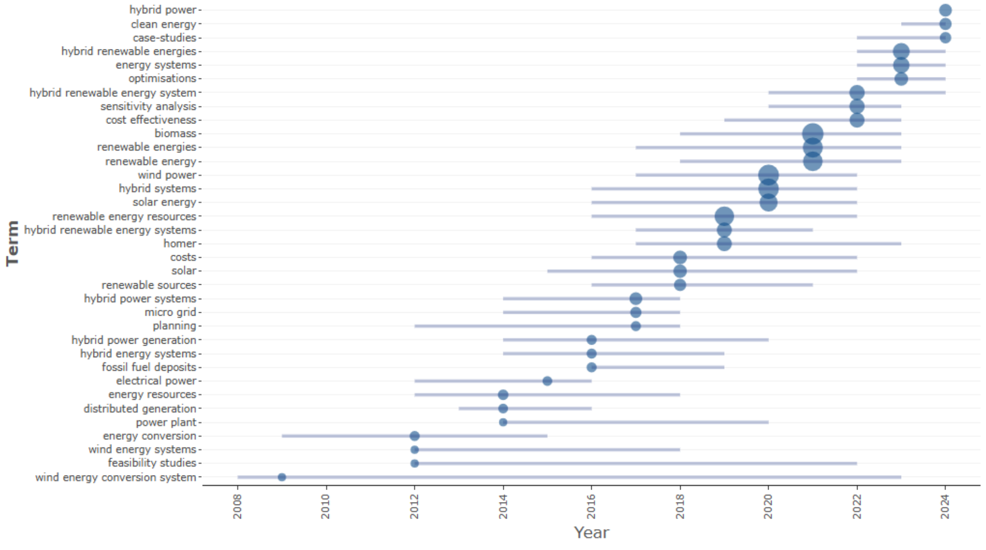

Fig. 7. Trend topics of HRES research

The trends indicated are consistent with findings of earlier bibliometric research on renewable and hybrid energy systems. Earlier studies have emphasized technical feasibility and hybrid system optimization, with unit sizing, energy modeling, and resource integration as top priorities. Later studies emphasize socio-economic factors like cost-effectiveness and sustainability. This change marks a departure from exclusive technical optimization to holistic strategies taking into account economic, social, and environmental requirements. Further, the wave of research interest in biomass and renewables throughout 2021 indicates a global common agenda that aligns renewable energy systems with climate action and Sustainable Development Goals (SDGs).

In general, keyword trend analysis indicates that hybrid renewable energy research is becoming increasingly interdisciplinary, more and more divorcing from system design and technical modeling to examine economic feasibility, environmental concerns, and world sustainability issues. The trend predicts that future research will increasingly focus on scalable innovations that can address both global crises and local energy needs.

This study utilizes the Scopus database from 2005 to 2025, presenting a research evolution from 2006 to 2024 (Fig. 8). Between 2006 and 2021, the following seven main keywords were identified: alternative energy, biomass, geothermal energy, hybrid power systems, optimization, renewable energy sources, and rural areas. From 2022 to 2024, the eight main keywords were: battery power, biomass, cost of energy, decarbonization, electric power system control, hybrid renewable energies, hydrogen production, and solar energy. The decimal point in thematic evolution indicates the evolution of the keywords studied. For example, the keyword biomass can evolve into research with the keyword hydrogen production. This suggests that the development and evaluation of biomass research has changed to hydrogen production [9].

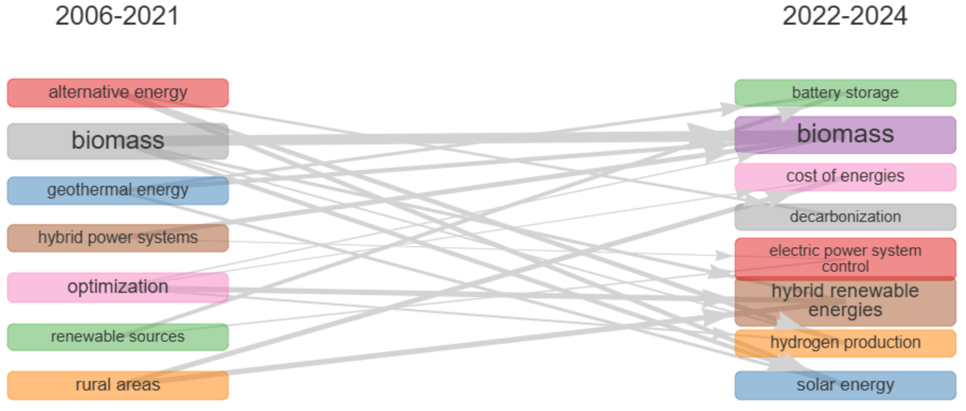

Fig. 8. Thematic evolution of HRES research

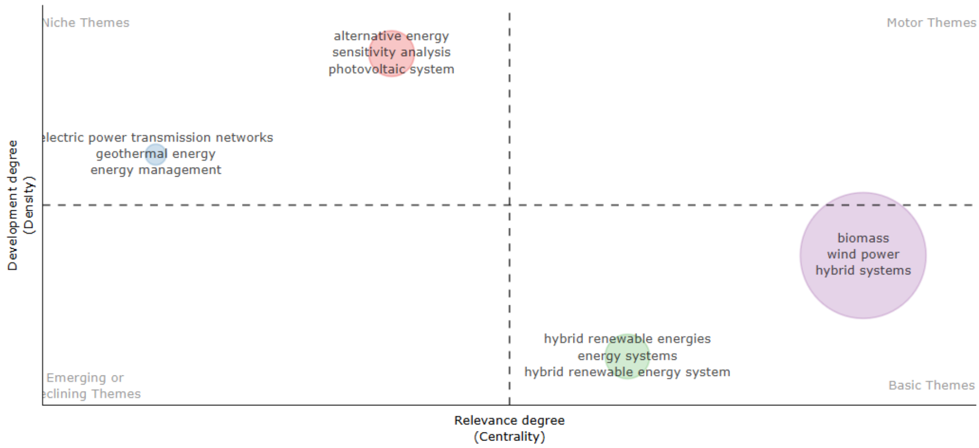

Fig. 9. Thematic map research of HRES

The thematic map locates research themes in four quadrants according to centrality and development (density) in Fig. 9. Curiously, biomass, wind power, and hybrid systems are all situated in the lower-right quadrant "Basic Themes", suggesting that they are basic yet less developed in internal unification. Their greater centrality indicates that they are core themes in the area of study, especially as major constituents of hybrid renewable schemes. On the other hand, specialist but immature subjects like alternative energy, photovoltaic systems, and sensitivity analysis are in the top-left "Niche Themes" quadrant, i.e., specialist but mature themes that have few external associations.

Surprisingly, hybrid renewable energies, energy systems, and hybrid renewable energy systems are located in the bottom-right quadrant, but closer to the origin, indicating that despite these subject matters being increasingly important, they are relatively immature in terms of theory and method development. This finding aligns with the conclusion from earlier research, which identified an increased interest in hybrid energy systems but emphasized the need for more effective system modelling and integration approaches. Compared to earlier studies, the present results indicate a clear thematic shift from expansive renewable energy research to more system-centered, integrated research, with a greater interest in controlling systems, hydrogen production, and energy storage. The shift in themes is in consonance with the overall trend of the world towards smart, more secure energy systems that can address both environmental and energy security objectives [10].

3.6 Challenges of hybrid renewable energy systems (Solar–Wind–Biomass)

The analysis of selected studies reveals that HRES, like solar, wind, and biomass, faces a series of interdependent issues, as shown in Table 2. Spatial and sustainability issues in hybrid plant siting are among the most salient, as geographical suitability and environmental trade-offs directly influence system viability [11]. In addition, the engineering sophistication of planning multi-source energy systems, especially in isolated settings like islands, is still a powerful deterrent. Rural and remote location power supply remains unpredictable and unstable, and off-grid communities frequently have limited access to reliable electricity. Technical issues also include addressing environmental effects and lifecycle performance, pointed out by Al-Rubaye et al. [12]. Meanwhile, increased energy demand and the global burden of climate change are other limiting factors on which innovative strategies need to be formulated in order to accomplish energy system integration.

Other long-standing issues are economic and reliability issues, wherein cost balancing with guaranteed supply has been a long-standing issue. Overall, the transition of mature energy industries, for example, natural gas, to renewables integrations also gives rise to structural issues of system accommodation and flexibility. Energy security during times of crisis is a further dimension, in which vulnerabilities will have high costs and low capacity in times of crisis [13]. Moreover, the intermittent nature of renewable power generation is a conventional problem towards grid equilibrium, with generation and demand imbalance making energy management complex [14]. While these challenges present substantial obstacles, the reviewed studies also demonstrate that advances in optimization tools, life cycle frameworks, and energy management strategies can play a significant role in mitigating these difficulties, by demonstrating pathways through which solar-wind-biomass hybrid systems can evolve into more reliable and sustainable energy solutions.

Table 2. Challenges and alternative solutions of HRES.

Author(s)	Challenge	Alternative Solution
Ahmet Şekeroğlu & Demet Erol, 2023	Spatial and sustainability problems in hybrid renewable facility siting.	Developed a fuzzy logic–GIS model for optimal solar–wind–biomass site selection.
Cheng-Liang Chen et al., 2016	Complex hybrid power system design for remote islands.	Applied MILP-based optimization to balance wind, diesel, and hydro storage capacities.
Haytham El-Houari et al., 2020	Energy supply challenge in isolated rural areas.	Proposed an off-grid PV–Wind–Biomass hybrid system optimized for cost and sustainability.
Haider Al-Rubaye et al., 2022	Technical challenges in microgrid design and lifecycle analysis.	Built a comprehensive LCA framework for evaluating hybrid microgrid performance.
Mohammad Khalid Saifullah et al., 2023	Lack of energy access in remote regions.	Designed a solar–wind–biogas hybrid system using HOMER for lower cost and emissions.
Lanyu Li et al., 2019	Rising energy demand and climate change constraints.	Developed a multi-objective optimization framework combining renewables with biochar capture.
Prosenjit Barua & Bikram Ghosh, 2020	Ensuring uninterrupted and economic power supply.	Used HOMER simulation to determine the most cost-efficient hybrid configuration.
Jan Willem Turkstra & Frits W. Bliek, 2008	Gas sector adaptation to renewable energy transition.	Implemented a bottom-up intelligent network model to improve reliability and flexibility.
Francesco Fuso Nerini et al., 2015	Low energy security and high costs during emergencies.	Introduced a modular "Energy & Water Emergency Module" utilizing local renewable sources.
Samrat Chakraborty et al., 2022	Managing fluctuating renewable generation and grid stability.	Created an EMS for solar–wind–biomass hybrids to control energy flow and storage efficiently.

4 Conclusions

This study presents a comprehensive bibliometric and content analysis of research on Hybrid Renewable Energy Systems (HRES), with a specific focus on solar–wind–biomass integrations. The following are the conclusions of this study:

- The analysis of distribution indicates an increase in publications in the last twenty years as an indicator of greater interest in hybrid technology on a worldwide scale.
- High-end contributions are made by only those states with robust renewable energy policies, such as India, China, and the United States, with several of the top-ranked institutions serving as innovation foci and centers for knowledge transfer.
- Top scholars and collaborative networks indicate that HRES research is becoming increasingly multidisciplinary, although collaboration primarily occurs within agglomerated regional clusters.
- High-impact papers emphasize optimization frameworks, techno-economic analysis, and sustainability assessment, in response to the urgent need for implementable and scalable solutions.
- Future research topics include energy management strategies, life cycle assessments, and smart-grid integration, in line with the global agenda of carbon neutrality and sustainable development.
- The challenge analysis reveals significant challenges, including ongoing problems such as siting and space limitations, technical intricacy, economic viability, system reliability, and variability in renewability.

Even though there are valuable contributions made in this research, there are some limitations. Bibliometric analysis is constrained by the fact that it relies on a single database, which may potentially miss significant publications and collaborations. Secondly, although the research identifies research trends and gaps, it does not provide a broad comparative analysis of technological performance indicators across case studies.

Future research should therefore expand the scope of bibliometric mapping by incorporating multiple databases, strengthening comparative studies across countries, and developing combined models that relate technical, economic, and environmental aspects. Moreover, policy regimes, social acceptance, and demonstration projects within the field in remote and rural settings must be addressed more intensively, as these are crucial in transforming hybrid renewable energy systems into sustainable, reliable, and adoptable energy systems.

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