

The emerging hybrid renewable energy systems in the global domain: A bibliometric approach to the study

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ABSTRACT - Hybrid renewable energy systems (HRES), particularly those integrating solar photovoltaic (PV) and wind technologies, have emerged as vital solutions for enhancing energy security and sustainability. This study aims to examine the evolution, thematic focus, and global collaboration trends in HRES research by applying a comprehensive bibliometric analysis. Using Scopus data spanning 2009 to 24 May 2024, the study evaluates 162 carefully selected documents out of 1,023 initial records. Analytical tools such as Lotka's Law, co-occurrence networks, keyword frequency analysis, and cluster mapping are employed to explore publication patterns, author productivity, and dominant research themes. The field demonstrates a notable annual growth rate of 21.69% and an international co-authorship rate of 35.14%, indicating expanding global engagement. A significant portion of contributions comes from single-publication authors (93%), suggesting a wide range of interdisciplinary interests. Iran and India lead global research output, followed by Malaysia, Turkey, and China. Key themes identified include system optimisation, economic analysis, energy storage, and environmental sustainability. Influential authors' contributions were identified to showcase the foundational development of the field. Cluster analysis reveals prominent areas, including rural electrification, techno-economic evaluation, and power converter control, underscoring the diversity of applications. The results affirm HRES as a rapidly advancing, multidisciplinary domain. Future research should prioritise region-specific system design, affordable storage technologies, grid integration, life cycle assessment, and stronger international collaboration. These focus areas are essential to accelerate the deployment of cost-effective and environmentally resilient hybrid systems across varied geographical contexts.

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1. INTRODUCTION

The global energy landscape confronts unprecedented transformation pressures, compelling nations to reconsider their fundamental energy strategies. Climate change mitigation imperatives, coupled with greenhouse gas reduction targets, have catalysed an extraordinary shift from conventional fossil fuel dependencies toward renewable energy alternatives [1]. This transition manifests profound complexities, particularly as renewable sources must simultaneously address environmental concerns whilst ensuring robust energy security frameworks [2]. Recent statistical evidence underscores this transformation's momentum. The BP Statistical Review of World Energy 2021 documented a remarkable 45% surge in global renewable capacity between 2019 and 2020, occurring despite COVID-19's economic disruptions [1]. Furthermore, the International Energy Agency projects that renewable sources will dominate over 90% of forthcoming global electricity capacity expansions [3]. Such projections illuminate renewable energy's emerging centrality within contemporary energy discourse.

However, conventional single-source renewable technologies encounter inherent limitations that constrain their widespread adoption. Solar photovoltaic systems experience diurnal variability, whilst wind energy demonstrates temporal inconsistencies that challenge grid stability requirements. Consequently, Hybrid Renewable Energy Systems (HRES) have emerged as sophisticated solutions addressing these fundamental constraints [4]. These systems, particularly those integrating solar PV and wind technologies, exploit complementary resource characteristics to enhance reliability, reduce storage dependencies, and deliver consistent power output [5, 6]. The strategic significance of HRES transcends technical considerations, encompassing broader socio-economic dimensions. Hassan *et al.* [4] emphasise HRES deployment's direct contribution to Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Additionally, these systems offer viable electrification solutions for remote communities where grid extension proves economically prohibitive [22]. This relevance intensifies considering that approximately 733 million people remain without electricity access, predominantly in sub-Saharan Africa and South Asia [7].

HRES scholarship has expanded considerably over recent decades, reflecting intensified academic and industrial interest. Research has evolved across interconnected streams: system design optimisation, economic feasibility

assessment, energy management strategies, and technological innovations. System design optimisation represents a fundamental research pillar. Bekele and Palm introduced comprehensive frameworks for assessing standalone solar-wind hybrid systems in Ethiopia [8], whilst Merei *et al.* [9] employed genetic algorithms optimising off-grid hybrid configurations with diverse battery technologies. Yang *et al.* [10] subsequently proposed multi-objective optimisation approaches for Chinese solar-wind systems, integrating capacity configuration with operational feasibility considerations. These investigations underscore the criticality of appropriate system sizing for achieving technical reliability whilst minimising economic expenditures. Economic feasibility analyses constitute another significant research strand. Turkey and Telli conducted comparative assessments demonstrating hybrid configurations' substantial cost advantages over single-source alternatives [11]. Similarly, Shezan *et al.* [12] evaluated off-grid wind-PV-diesel-battery systems, identifying operational cost reductions alongside carbon emission decreases. Naderipour *et al.* [13] advanced this work by incorporating battery storage optimisation, analysing energy loss probability and economic factors for remote applications.

Technological advancement trajectories have expanded HRES application potentials significantly. T. Luz and P. Moura [14] examined hydrogen energy storage integration with batteries and supercapacitors, whilst Ayodele *et al.* investigated off-grid systems with hydrogen storage for South African rural health clinics [17]. These studies highlight the importance of advanced storage technologies for enhancing hybrid system reliability and operational flexibility. Energy management strategies represent another dynamic research area. Suresh *et al.* modelled off-grid systems incorporating sophisticated control algorithms for enhanced performance [16], whilst Bravo *et al.* [18] proposed multi-objective operational optimisation frameworks for hybrid plants with thermochemical storage. These investigations demonstrate the potential for effective energy management to significantly improve overall system efficiency.

Recent research increasingly incorporates advanced computational methods and artificial intelligence techniques. Jamshidi and Askarzadeh [19] employed techno-economic analysis for sizing off-grid hybrid systems, whilst Sanajaoba and Fernandez [20] applied Cuckoo Search algorithms for optimal remote system sizing. Optimal sizing for wind-photovoltaic-hydrogen systems was examined by considering levelised storage costs and source-load interactions [21, 22]. Regional case studies provide valuable context-specific insights. Adaramola *et al.* [23] analysed systems for southern Ghana applications, whilst Ahmad *et al.* conducted techno-economic analyses for Pakistani rural electrification [24]. Razmjoo and Davarpanah [25] investigated residential applications in southern Iran. These studies emphasise local resource availability, load profiles, and the importance of socio-economic factors in HRES design.

Innovative applications have emerged beyond conventional electricity generation. Ma and Yuan [26] examine techno-economic optimisation for green building energy independence [27], whilst Konneh *et al.* [28] developed multi-criteria decision-making frameworks using particle swarm optimisation. Such studies demonstrate HRES's versatility across diverse application contexts. Despite substantial HRES research, systematic analysis of publication trends, research themes, and collaborative networks remains notably absent. Whilst numerous primary studies investigate technical, economic, and environmental aspects, comprehensive bibliometric analyses examining HRES research's intellectual structure and evolution, particularly solar PV-wind systems, are scarce. Bibliometric analysis offers powerful methodological approaches for mapping scientific landscapes, identifying influential contributors, tracking research theme development, and revealing collaboration patterns [29]. Such analyses provide valuable insights for researchers, policymakers, and industry stakeholders by illuminating knowledge gaps, emerging trends, and future investigation opportunities [30].

Previous bibliometric studies in related fields demonstrate this approach's utility. Tan *et al.* [31] examined global green energy and environmental technology research evolution, whilst Qin *et al.* [32] conducted green energy adoption bibliometric analyses. However, these studies did not specifically focus on hybrid systems, particularly solar PV-wind integration. This study's rationale stems from recognising that comprehensive HRES bibliometric analysis can make several important contributions. Firstly, it provides macro-level perspectives on research trends, complementing micro-level primary study insights. Secondly, it identifies key research clusters, influential publications, and collaborative networks, facilitating knowledge exchange and potential partnerships. Thirdly, it reveals emerging research frontiers and underexplored areas, guiding future efforts. Finally, it offers historical perspectives on field development, contextualising current research within broader evolutionary trends.

This study makes several novel contributions to existing literature. Firstly, it presents the first comprehensive bibliometric analysis specifically focused on hybrid renewable energy systems, emphasising solar PV-wind integration. Whilst previous studies examined broader renewable energy domains or specific technologies, none specifically targeted these technologies' intersection within hybrid systems. Secondly, the study employs multi-faceted bibliometric approaches, combining publication growth analysis, author productivity assessment using Lotka's law, co-occurrence network analysis, and word cloud visualisation. This methodological triangulation enables a more comprehensive HRES research landscape understanding than single analytical approaches permit. Thirdly, the study provides timely insights into rapidly evolving field trends and patterns. Given accelerating global renewable energy deployment and growing hybrid system interest, the current bibliometric analysis offers valuable guidance for researchers, policymakers, and industry stakeholders navigating this dynamic domain. Finally, the study identifies emerging research frontiers, knowledge gaps, and potential future investigation areas, contributing to strategic HRES research agenda development. By mapping HRES research's intellectual terrain, this study facilitates more targeted and impactful future investigations.

Through addressing these objectives, this study aims to provide researchers, policymakers, and industry stakeholders with a clear understanding of the current state of hybrid solar PV-wind research and reveal future exploration opportunities. The findings will contribute to more strategic HRES research and development approaches, ultimately supporting broader sustainable energy system transitions.

2. MATERIALS AND METHODS

2.1 Bibliometric Approach

Bibliometrics constitutes a quantitative analytical framework employing bibliographic data from publication units and citation networks [33-35]. These methodologies have proliferated remarkably, with publications averaging 1,021 annually over the preceding decade [35-37]. Such approaches effectively evaluate historical research trajectories, trace evolutionary patterns, examine knowledge architectures, and forecast emerging paradigms across diverse scientific disciplines [38-40]. Subsequently, this investigation utilises seven fundamental bibliometric analytical techniques to accomplish the specified research objectives.

2.2 Annual Publication Growth in HRES Research

Bibliometric examination demonstrates consistent escalation in HRES research throughout the preceding decade, predominantly propelled by solar photovoltaic and wind energy integration [41-43]. Scopus and Web of Science databases reveal robust annual growth trajectories in energy-related scholarly publications, exemplifying intensified global sustainable energy endeavours [44-46].

2.3 Local Citation Analysis in HRES Research

Local citation analysis elucidates influential publications shaping contemporary HRES research by quantifying citations within specialised databases or research communities [35, 36, 47]. Identifying locally cited articles enables researchers to discern fundamental literature propelling sector-specific innovations, whilst supporting systematic reviews that guide future hybrid system developments [48, 49].

2.4 Author Productivity Through Lotka's Law in HRES Research

Lotka's Law elucidates the inverse correlation between author quantities and publication volumes, whereby few scholars generate numerous manuscripts, whilst most contribute singularly [50].

2.5 Leading Countries by Citation Impact in HRES

An analysis of citation impact reveals that the global HRES research landscape is shaped by a diverse group of countries, reflecting variations in institutional collaboration and research focus [3, 51]. The United States focuses on smart-grid integration and advanced system modelling, while China prioritises large-scale deployment and optimisation. Germany drives policy-oriented research and financing mechanisms. India shows growing strength in decentralised hybrid microgrids, and the United Kingdom contributes to theoretical frameworks and comprehensive policy analyses [47, 52, 53].

2.6 The Frequent Word Cloud

Word cloud visualisation is a widely adopted bibliometric tool that offers intuitive insight into dominant themes in HRES research [54]. By extracting high-frequency keywords from titles, abstracts, and author-designated terms, it highlights key areas such as hybrid energy systems, solar-wind integration, optimisation models, energy storage, microgrids, techno-economic assessments, and sustainability metrics [43, 51]. While limited in analytical depth, word clouds remain effective for rapidly identifying emerging trends and thematic gaps [55]. This approach supports understanding of interdisciplinary linkages and research evolution, guiding future investigations and informing policy development within the sustainable energy sector [51, 56].

2.7 Co-occurrence Network Analysis in HRES Research

Co-occurrence network analysis is a powerful bibliometric method that maps relationships among frequently appearing keywords in the scientific literature, offering insight into thematic structures and evolving research directions in HRES [56]. By analysing terms from titles, abstracts, and author keywords, tools like VOSviewer and CiteSpace reveal conceptual linkages and highlight core themes such as solar-wind hybrid systems, optimisation algorithms, and energy storage technologies [35, 57]. This approach also uncovers interdisciplinary trends, including applications in microgrids and artificial intelligence [39, 58]. Co-word analysis identifies emerging and influential topics while tracking thematic shifts over time [59]. Ultimately, these networks provide a robust foundation for understanding HRES research landscapes and guiding future innovation and policy.

2.8 Data Collection and Search Strategy

This methodological framework outlines the systematic approach adopted for a comprehensive bibliometric analysis of HRES, with a focus on the integration of solar photovoltaic and wind technologies. Data were exclusively retrieved from the Scopus database, selected for its broad coverage and reliable indexing of peer-reviewed scientific literature [38,

60]. The search was conducted on 24 May 2024, covering publications from January 2009 to May 2024. The search strategy targeted key subject areas, Environmental Sciences, Energy, and Engineering, yielding an initial set of 1,023 documents [35].

A structured search protocol employed combinations of relevant terms, including "hybrid PV-wind energy system," "solar energy," "photovoltaic array," "wind turbine generator," "cost of energy," and "net present value" [51]. Boolean operators such as AND and OR enhanced precision and selectivity, ensuring targeted retrieval of literature explicitly related to hybrid solar PV-wind systems. To maintain academic quality and relevance, the inclusion criteria were strictly applied. Only peer-reviewed journal articles published in English were considered. The study excluded conference proceedings, book chapters, and magazine articles. The selection was further refined to include only documents within the Energy, Engineering, and Environmental Sciences domains [38]. This rigorous filtering ensured a focused and high-quality dataset suitable for bibliometric evaluation. The methodology was designed to capture the evolution, trends, and key research contributions within the hybrid solar PV-wind energy landscape, forming a robust foundation for further analysis and academic insight.

2.9 Data Processing and Analysis

From an initial pool of 1,023 documents, 350 articles were selected and exported in CSV format for further analysis. Two duplicate entries were identified and removed during the screening to preserve data integrity. The refined dataset, retrieved from Scopus, was converted into plain text to facilitate detailed examination. VOSviewer (v1.6.18) was employed as the primary tool for mapping bibliometric networks, offering advanced visualisation and clustering functions to illustrate thematic relationships across the literature [29, 61]. In parallel, the bibliometrix package enabled in-depth visualisation and interpretation of co-authorship, citation, and keyword networks. Scopus was chosen for its broad coverage and recognised quality, making it highly suitable for bibliometric research [62]. This method complements both meta-analytical and systematic review approaches, enhancing understanding of emerging trends [63, 64]. A doctoral researcher, in collaboration with co-authors, screened the documents and identified 162 relevant publications focused on hybrid solar PV–wind systems. Manual content verification, including abstract and full-text review, ensured that selected entries aligned with the study’s specific objectives. Bibliographic accuracy was verified and validated systematically.

2.10 Data Visualisation and Interpretation

This study employed bibliometrix software to visualise and analyse the research landscape of HRES, with a focus on solar photovoltaic and wind integration as shown in Figure 1. The resulting network maps revealed thematic interconnections, emerging technologies, and distinct research clusters, offering valuable insight into the structural and dynamic evolution of the field [38]. The analysis identified leading researchers, influential publications, and prominent institutions while highlighting key research areas, technological advances, and knowledge gaps requiring further investigation [35]. Although Scopus was used as the primary data source due to its breadth and reliability, relevant studies indexed in other databases may have been excluded.

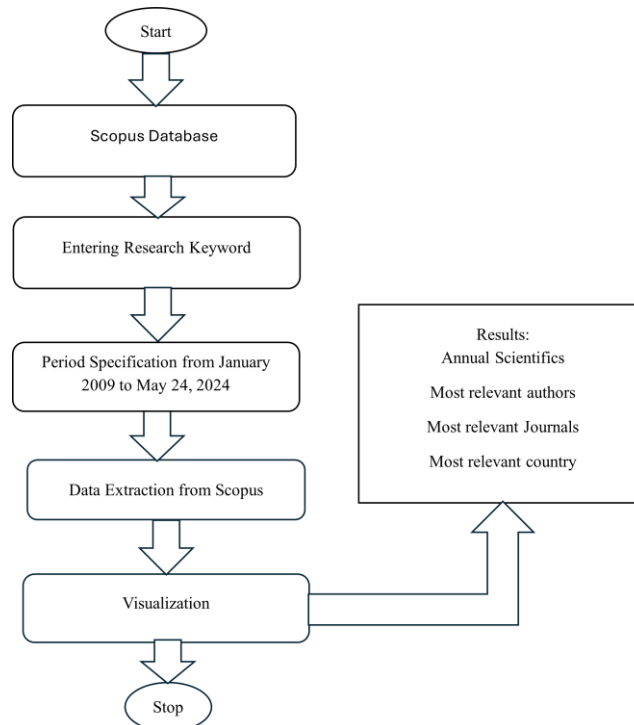


Figure 1. Flowchart for the bibliometric framework using the Scopus database

Additionally, the keyword-driven search strategy could have overlooked relevant works not explicitly labelled with selected terms [60]. Nevertheless, the methodology ensured a systematic and focused review within clearly defined parameters. This bibliometric investigation provides a rigorous and data-driven overview of HRES research. By applying advanced analytical tools [29], the study uncovers collaboration networks, developmental trends, and strategic directions, providing a robust foundation for future academic research and policy development aimed at advancing hybrid energy technologies and supporting global sustainability transitions.

3. RESULTS AND DISCUSSION

3.1 Main Information

This bibliometric analysis examines the evolving landscape of HRES, with a focus on the integration of solar PV and wind technologies, as illustrated in Figure 2. Based on 162 selected documents drawn from 112 sources between 2009 and 24 May 2024, the field demonstrates rapid expansion, with an impressive annual growth rate of 21.69%. The dataset reflects a highly collaborative research environment. A total of 1155 authors contributed to the literature, with only 21 single-authored papers. International collaboration accounts for 35.14% of co-authorships, highlighting strong cross-border academic engagement. On average, each paper involved nearly four authors, pointing to the multidisciplinary and cooperative nature of HRES research.

Keyword analysis identified 944 unique terms (including Keywords Plus and indexed terms), revealing both thematic diversity and conceptual depth. The citation pool includes 14,011 references, demonstrating a solid intellectual foundation and strong continuity with past research. The average document age of just over four years shows the field's relevance to current technological and environmental challenges. Notably, an average of 32.28 citations per document based on the final analysed dataset reflects substantial academic impact, indicating that these studies fill critical knowledge gaps and guide both theory and practice. Three major trends emerge. First, the field has reached a critical point of maturity, supported by sustained research interest. Second, the high level of international collaboration confirms that HRES challenges demand global responses. Third, the dense citation network reflects both the cumulative nature of the research and its forward-looking orientation. In summary, the rapid growth, strong international partnerships, and significant academic influence suggest that HRES, particularly systems integrating solar PV and wind, will remain central to global energy research. This field is well-positioned to shape future sustainable energy solutions and contribute to climate change mitigation worldwide.



Figure 2. Main information about the data in the bibliometric analysis

3.2 Annual Publication Growth

This analysis examines publication trends in HRES, with a focus on the integration of solar PV and wind technologies from 2009 to 2024, as shown in Figure 3. The data reveal a clear upward trajectory, reflecting a sustained increase in research activity and growing scholarly interest in this field. The early years (2009–2011) marked the inception of HRES research, beginning with a single publication in 2009. This phase reflects an exploratory period in which researchers were primarily investigating the theoretical potential and feasibility of hybrid configurations [65]. Between 2012 and 2015, publication output fluctuated, likely due to shifting research priorities or inconsistent funding streams. Nevertheless, the publication of seven articles in both 2013 and 2014 signifies an important turning point, indicating increasing academic recognition of hybrid systems as viable solutions to global energy challenges. During this consolidation period, foundational methodologies and conceptual frameworks began to take shape. This outcome is consistent with findings from previous studies [66, 67].

From 2016 onwards, the field entered a phase of consistent growth. The number of publications rose steadily, peaking at 13 in 2020. This acceleration coincided with heightened global attention to renewable energy, driven by environmental imperatives, policy reforms, and the urgency of climate change mitigation. The alignment of these drivers created fertile ground for HRES research to expand and mature [68, 69]. The most dramatic growth occurred between 2021 and 2024, with publication numbers nearly tripling. This expansion can be attributed to several converging developments: technological advances in PV and wind systems, increased research funding, and the growing commercial deployment of hybrid technologies. These real-world applications have yielded empirical data and operational insights, further

energising academic inquiry. Although 2024 saw a slight dip to 28 publications, the volume remains significantly high, suggesting that interest in HRES research is far from waning. This minor decline may reflect a brief period of thematic consolidation or strategic redirection rather than a downward trend. Three distinct developmental phases emerge from this temporal analysis. The exploratory phase (2009–2015) focused on conceptual foundations and proof-of-concept studies. The establishment phase (2016–2020) brought methodological refinement and system modelling. The expansion phase (2021–2024) now marks a shift towards practical implementation, integration challenges, and performance optimisation. In conclusion, this evolving publication pattern underscores the field’s growing maturity and significance. The sustained increase in output highlights the academic community’s commitment to advancing hybrid PV-wind systems as a critical pathway towards a low-carbon, resilient global energy future.

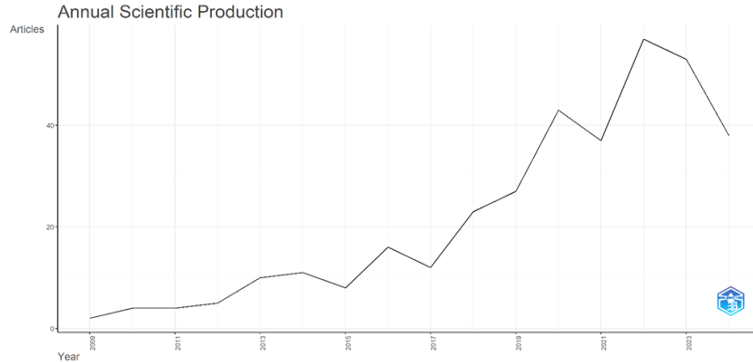


Figure 3. Annual scientific production from 2009 to 24 May 2024

3.3 The Locally Cited Articles

In energy research, particularly within the domain of HRES, citation frequency remains a key indicator of a publication’s intellectual impact and relevance. Local citation counts, representing influence within a specific research domain, offer insight into how individual studies shape the trajectory of the field [36, 70-72]. As illustrated in Figure 4, this bibliometric analysis highlights several pivotal works that have influenced the scholarly discourse on HRES. Among the most cited is the study by Maleki, A. (2017), published in Sustainability, which stands out with 15 local citations. Its high citation count suggests foundational significance, positioning it as a core reference for subsequent research in HRES design and optimisation. Not far behind are the works of Ahmad, J. (2018) in Energy (7 citations) and Shezan, S.A. (2016) in the Journal of Cleaner Production (6 citations), both of which have significantly advanced understanding of the technical and implementation challenges associated with hybrid systems. Other influential contributions include those by Adaramola, M.S. (2014) in Energy for Sustainable Development and Energy Conversion and Management, as well as Zhang, W. (2018) in Energy, each receiving between 4 and 6 citations. These studies have provided valuable frameworks and analytical models adopted by researchers investigating system performance, resource assessment, and integration strategies.

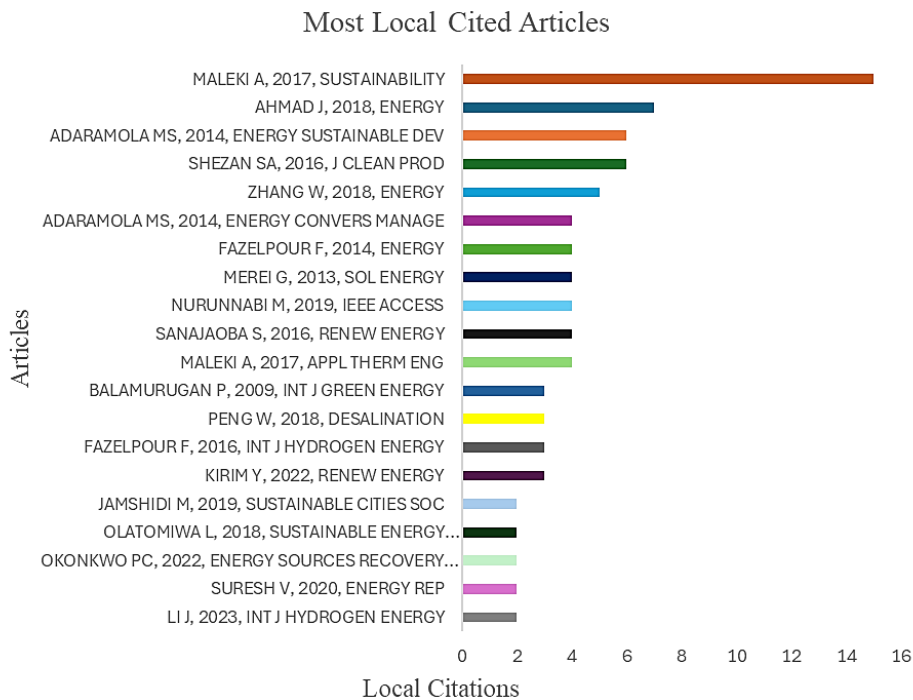


Figure 4. The top 20 locally cited documents in HRES

More recent works, such as those by Kirim, Y. (2022) in *Renewable Energy* and Fazelpour, F. (2016) in the *International Journal of Hydrogen Energy*, have garnered three citations each, highlighting growing interest in hydrogen's role within hybrid configurations. This trend reflects the sector's transition towards exploring complementary energy vectors alongside traditional PV-wind combinations. Even publications with fewer citations, such as Li, J. (2023) and Suresh, V. (2020) (each with two citations), hold significance. These articles often represent emerging subfields or niche applications that are still gaining momentum. As academic and industrial attention expands, these works may see increased recognition and impact. Notably, a handful of researchers have consistently contributed highly cited publications. Maleki, A., for instance, appears as a central figure in the field, with multiple influential works shaping debates on system sizing, optimisation algorithms, and techno-economic assessments. These individuals act as intellectual anchors, often affiliated with leading institutions or research groups. The journals housing these impactful studies, *Energy*, *Renewable Energy*, and *Sustainability*, are prominent platforms in the energy field. Their role in disseminating key findings enhances the visibility and credibility of HRES research, reinforcing their status as go-to sources for new developments. Temporal trends in citation patterns also reveal the field's maturation. Earlier publications (2014–2017) laid foundational methodologies and theoretical frameworks, while more recent studies (post-2018) have shifted focus towards applied optimisation, grid integration, and techno-environmental assessments. This evolution marks a progression from conceptual models to real-world implementation.

Finally, the geographical and institutional diversity of cited works reflects the global nature of hybrid renewable energy challenges. Contributions originate from across Asia, Europe, Africa, and the Americas, suggesting a well-established international research network. This diversity promotes cross-border collaboration and strengthens the field's capacity to develop solutions adaptable to varied socio-economic and climatic contexts [43]. In conclusion, citation patterns in HRES research highlight both established foundational studies and emerging scholarly directions. The interplay between highly cited works, early contributions, and newer specialised studies indicates a dynamic, expanding field. These trends point to a promising future for HRES research, underpinned by a robust body of knowledge and driven by international collaboration, innovation, and the pressing global need for sustainable energy systems.

3.4 Author Productivity Through Lotka's Law

This study applies Lotka's Law to examine author productivity in the domain of HRES. Lotka's Law predicts that the number of authors contributing "n" papers is proportional to $1/n^2$, resulting in a small group of prolific researchers and many occasional contributors [50, 56]. This analysis reveals patterns characteristic of rapidly developing, interdisciplinary fields such as renewable energy. As shown in Figure 5, the empirical data closely conform to Lotka's theoretical distribution, which is in line with earlier research, specifically that done by Nicholls [73]. An overwhelming 93% of authors in HRES literature have contributed only a single publication. This strong skew suggests a broad influx of new or occasional participants, reflecting the field's interdisciplinary and socially relevant nature. Renewable energy research draws on expertise from engineering, physics, economics, and environmental science, fields whose practitioners may contribute briefly before returning to their primary specialisations.

As publication count increases, the proportion of contributing authors declines sharply: 5.6% have authored two documents, while only 0.7% have produced three. Beyond this, the percentage continues to drop dramatically. This pattern points to a small, highly productive cohort of researchers who drive much of the field's intellectual and theoretical development. These authors are likely embedded in dedicated research groups or academic centres with long-term commitments to hybrid energy system research. The observed distribution aligns with the theoretical beta coefficient of 2, confirming the validity of Lotka's model in this context [74]. Such mathematical conformity lends confidence to the bibliometric approach and underscores that HRES research shares core features with other fast-evolving scientific disciplines. Unlike highly specialised fields, where barriers to entry limit participation to a concentrated community, HRES invites diverse contributions due to its practical urgency, interdisciplinary openness, and wide-ranging application. Several factors explain this distinctive authorship pattern. First, the applied nature of the field encourages contributions from researchers who bring insights from their core disciplines without necessarily establishing long-term research programmes. Second, the technological dynamism of the sector offers frequent entry points for new participants, enabling fresh perspectives and innovative methods. Third, the global relevance of energy transition draws interest from policymakers, engineers, and academics alike, fostering cross-sector collaboration.

The presence of prolific contributors is particularly noteworthy. These authors play a central role in shaping the research agenda, mentoring early-career scholars, and ensuring theoretical coherence. Their sustained efforts offer a stabilising force in a field characterised by rapid expansion and diversity. It is also important to consider the temporal dimension of author productivity. The dominance of single-publication authors may partly reflect the field's relative youth and accelerating growth. As hybrid systems become further institutionalised within academic and policy frameworks, more researchers will likely transition from occasional to sustained engagement, thereby reshaping future productivity distributions. In view of the above, the application of Lotka's Law reveals that hybrid renewable energy systems research is supported by a vibrant, evolving authorship structure. The coexistence of many one-time contributors with a committed core of domain experts reflects a healthy balance between intellectual diversity and scholarly depth. This pattern supports innovation while ensuring continuity, positioning the field for sustained academic and practical impact.

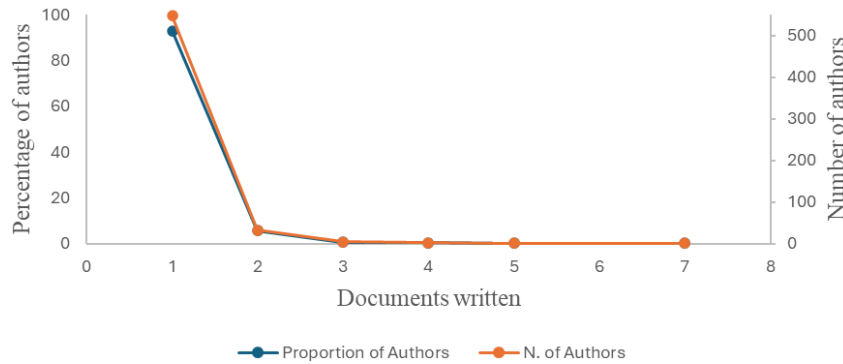


Figure 5. Author productivity analysis based on Lotka's Law

3.5 Leading Countries by Citation Impact in HRES

Figure 6 offers a citation-based evaluation of the 20 most influential countries contributing to HRES research, particularly focusing on solar PV–wind integration. This analysis quantitatively captures the scholarly impact and leadership of nations in this rapidly evolving field. Iran emerges as the global leader with 1,505 citations, demonstrating sustained output and high-quality research that resonates across the international academic community. This citation strength highlights both the volume and scientific depth of Iranian contributions, underscoring its scholars' commitment to innovation in hybrid energy systems.

India ranks second with 903 citations, reaffirming its strong presence in renewable energy research, especially in the areas of system design, optimisation, and integration. Despite the considerable gap with Iran, India's output signifies a robust and growing research culture aligned with national energy priorities. Malaysia (375 citations) and Turkey (373 citations) also feature prominently. Their nearly equivalent citation counts, despite differing economic contexts, highlight the increasing global dispersion of research excellence. Both countries are advancing the hybrid energy agenda through targeted policies and strategic collaborations. China (288 citations) and Germany (271 citations) maintain their long-standing influence, benefiting from consistent investments in research infrastructure and renewable energy innovation. Germany's output reflects its leadership in energy transition frameworks, while China's rising profile is fuelled by its broader energy strategy and scientific ambitions. Countries such as Pakistan (258 citations) and South Africa (254 citations) show commendable engagement despite socio-economic and infrastructural challenges. Their growing academic presence in HRES research reflects a commitment to overcoming energy security issues through technological advancement and international cooperation. Italy and the United States (each with 193 citations), along with the United Kingdom (173 citations), remain vital contributors within the Western research sphere. These figures reflect their continued involvement in renewable energy innovation, supported by long-established academic networks and institutional frameworks.

Norway (161 citations), Bangladesh (138), and South Korea (126) exhibit substantial research activity. Norway's progress marks a shift from its traditional hydrocarbon dependency towards renewable diversification. Bangladesh's presence is significant for the Global South, while South Korea's contributions reflect its emphasis on high-tech solutions. Sweden (118 citations) and Japan (108) maintain consistent outputs aligned with their national sustainability agendas. Sweden's performance mirrors its environmental leadership, while Japan's research aligns with its strategic focus on energy security and resilience. Emerging contributors such as Morocco (89 citations), Egypt (86), Colombia (78), and Saudi Arabia (72) are gradually asserting themselves in the global landscape.

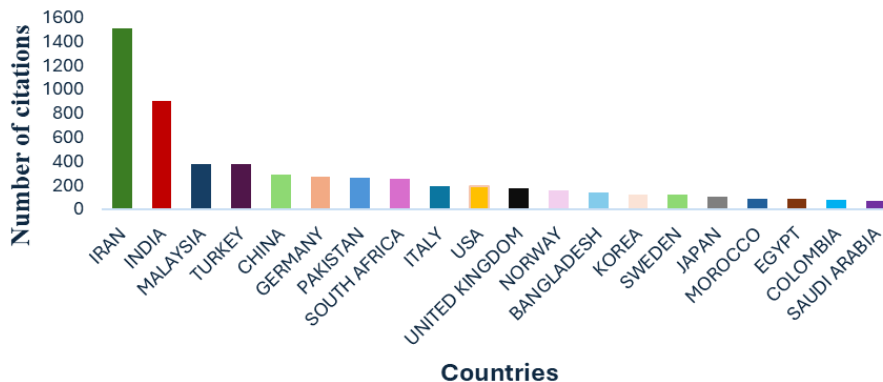


Figure 6. The top-cited countries in the HRES worldwide

While their citation counts remain modest, their trajectory suggests increasing involvement, particularly considering policy shifts towards knowledge-based economies. Saudi Arabia's position is especially notable, signalling a move away from fossil-fuel dependence towards renewable energy development. Overall, this citation analysis reveals a dynamic, inclusive, and multi-polar research environment. High-impact contributions now emerge from both traditional academic

powers and newer participants across the Global South. The diminishing North–South divide, driven by international partnerships and policy reform, reflects a maturing field. As hybrid solar–wind systems become central to global decarbonisation and energy resilience strategies, the widening geographic distribution of scholarly influence bodes well for sustainable energy transitions.

3.6 The Bibliographic Coupling of HRES

Of 350 documents analysed, 79 met the 38-citation threshold necessary for bibliographic coupling. The most cited works were by Merei *et al.* [9] with 271 citations, followed by Bekele *et al.* [8] with 269, and Zhang *et al.* [75] with 261. Based on shared references and total link strength (TLS), the strongest links were identified in [75] (73 TLS), [76] (68 TLS), and [11] (23 TLS). The bibliographic network generates four thematic clusters. These clusters represent emerging directions in HRES research. Multiple thresholds were tested (30–38) to ensure robustness, with 38 yielding the most stable structure, as Figure 7 illustrates. This methodological rigour avoided both over- and under-filtering, ensuring thematic clarity [56], [77]. Table 1 summarises each cluster’s features, reinforcing the field’s intellectual diversity and guiding future research trajectories.

Cluster 1 (Red): Cluster 1 highlights advanced optimisation in off-grid HRES design. Suresh *et al.* [16] compared Genetic Algorithm and HOMER Pro for system sizing, control, and component selection across four hybrid configurations, including sensitivity analyses on wind speed and biomass costs. Zhang *et al.* [78] found that solar–wind hybrids with electrochemical storage were more reliable and cost-efficient than chemically stored systems. Similarly, Sanajaoba and Fernandez [20] reported that combining PV, wind, and battery storage produced the most economical and reliable energy mix for remote areas. Tazvinga *et al.* [79] demonstrated that solar–wind–diesel–battery systems effectively mitigate uncertainty and external disturbances. Overall, this cluster underscores the importance of multi-objective optimisation and hybrid configurations in enhancing system resilience, operational reliability, and cost-effectiveness in decentralised energy systems.

Cluster 2 (Green): Cluster 2 focuses on the techno-economic feasibility of hybrid energy systems. Bekele and Palm [8] used HOMER to identify viable solar–wind configurations for both on-grid and off-grid Ethiopian communities, accounting for diverse load profiles. Turkey and Telli [11] compared multiple renewable-based system designs, revealing optimal configurations based on technical and economic criteria. Hemeida *et al.* [80] concluded that integrated wind, solar PV, and battery energy systems offer more cost-effective solutions than standalone alternatives. Similarly, Fazelpour *et al.* [81] found that a wind–hydrogen–battery hybrid system achieved the lowest net present cost (US\$63,190) and energy cost (US\$0.783/kWh). Collectively, this cluster underscores the value of system integration, simulation-based optimisation, and hybrid configurations for delivering affordable and reliable electricity, especially in resource-constrained settings.

Cluster 3 (Blue): Cluster 3 focuses on hybrid system optimisation, integrating hydrogen and biomass technologies. Jamshidi and Askarzadeh [19] reported that incorporating hydrogen significantly reduces the total system cost. Ahmad *et al.* [24] optimised a microgrid incorporating wind, PV, and biomass, demonstrating effective load sharing and surplus energy export, with the potential to generate over 50 MW. Toopshekan *et al.* [82] assessed PV–wind–diesel systems under intermittent grid conditions, highlighting their suitability for rural electrification. Baruah *et al.* [83] evaluated a multi-source hybrid system for an academic township in Sikkim, achieving a low LCOE of \$0.095/kWh using the Analytical Hierarchy Process. This cluster collectively underscores the importance of hybrid diversification, robust techno-economic modelling, and strategic integration of emerging technologies to enhance performance and reduce costs in decentralised renewable systems.

Cluster 4 (Yellow): Cluster 4 centres on advanced hybrid configurations and algorithmic optimisation. Maleki *et al.* [76] investigated a multi-source hybrid system integrating PV, wind, fuel cell, and solar thermal technologies to meet both electrical and thermal demands. Tang *et al.* [84] assessed a grid-connected hybrid microgrid for Kallar Kahar, which proved techno-economically viable, generating over 50 MW at a peak load of 73.6 MW and an LCOE of \$0.05744/kWh. Zhang *et al.* [78] compared optimisation algorithms and found the hybrid search method outperformed both simulated annealing and chaotic algorithms, with a minimal relative error of 4.08%. Overall, this cluster highlights the critical role of multi-objective optimisation in improving performance and cost-effectiveness in hybrid renewable energy systems.

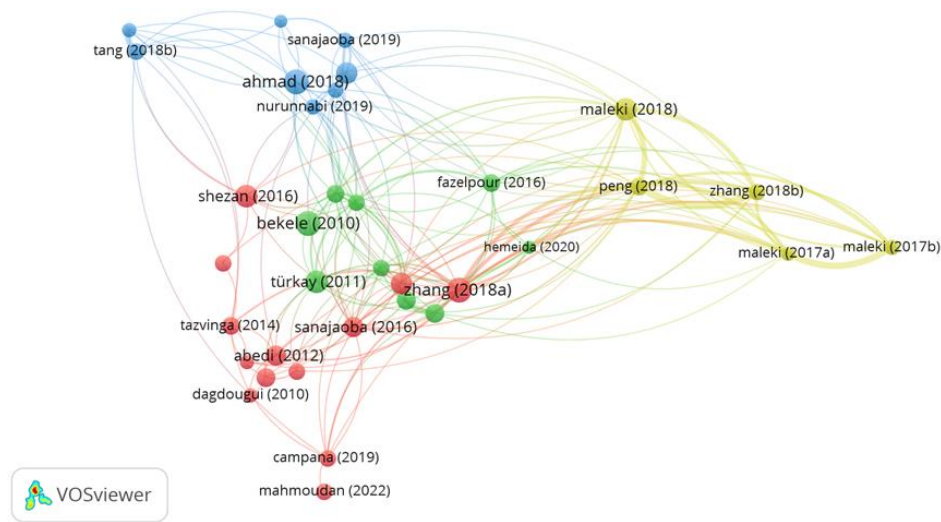


Figure 7. Bibliographic coupling analysis on HRES

Table 1. Top 10 documents in bibliographic coupling analysis

Rank	Publication	Citation	Total link strength
1	Merei, G., Berger, C., & Sauer, D. U. [9]. Optimization of an off-grid hybrid PV–Wind–Diesel system with different battery technologies using genetic algorithm. <i>Solar Energy</i> , 97, 460-473.	271	0
2	Bekele, G., & Palm, B. [8]. Feasibility study for a standalone solar–wind-based hybrid energy system for application in Ethiopia. <i>Applied energy</i> , 87(2), 487-495.	269	3
3	Zhang, G., Wu, B., Maleki, A., & Zhang, W. [75]. Simulated annealing-chaotic search algorithm-based optimization of reverse osmosis hybrid desalination system driven by wind and solar energies. <i>Solar Energy</i> , 173, 964-975.	261	73
4	Ahmad, J., Imran, M., Khalid, A., Iqbal, W., Ashraf, S. R., Adnan, M., ... & Khokhar, K. S. [24]. Techno economic analysis of a wind-photovoltaic-biomass hybrid renewable energy system for rural electrification: A case study of Kallar Kahar. <i>Energy</i> , 148, 208-234.	258	13
5	Türkay, B. E., & Telli, A. Y. [11]. Economic analysis of standalone and grid connected hybrid energy systems. <i>Renewable energy</i> , 36(7), 1931-1943.	223	23
6	Maleki, A., Rosen, M. A., & Pourfayaz, F. [76]. Optimal operation of a grid-connected hybrid renewable energy system for residential applications. <i>Sustainability</i> , 9(8), 1314.	222	68
7	Shezan, S. A., Julai, S., Kibria, M. A., Ullah, K. R., Saidur, R., Chong, W. T., & Akikur, R. K. [12]. Performance analysis of an off-grid wind-PV (photovoltaic)-diesel-battery hybrid energy system feasible for remote areas. <i>Journal of Cleaner Production</i> , 125, 121-132.	213	11
8	Suresh, V., Muralidhar, M., & Kiranmayi, R. [16]. Modelling and optimization of an off-grid hybrid renewable energy system for electrification in rural areas. <i>Energy Reports</i> , 6, 594-604.	199	19
9	Mehrpooya, M., Ghadimi, N., Marefati, M., & Ghorbanian, S. A. [4]. Numerical investigation of a new combined energy system includes parabolic dish solar collector, Stirling engine and thermoelectric device. <i>International Journal of Energy Research</i> , 45(11), 16436-16455.	198	0
10	Jamshidi, M., & Askarzadeh, A. [19]. Techno-economic analysis and size optimization of an off-grid hybrid photovoltaic, fuel cell and diesel generator system. <i>Sustainable Cities and Society</i> , 44, 310-320.	192	12

3.7 The Frequent Word Cloud

This study presents a keyword frequency analysis of existing literature on HRES, with a focus on solar and wind technologies, as shown in Figure 8. The results reveal core thematic clusters and emerging research directions. ‘Solar energy’ appears most frequently (90 mentions), underlining its central role in HRES research due to its technological maturity and global applicability. Closely following is ‘wind power’ (78 mentions), which complements solar energy in hybrid systems by mitigating diurnal and seasonal intermittency. The term ‘hybrid energy systems’ (74 mentions) reflects

the growing trend of integrating multiple renewable sources to improve system reliability and operational flexibility. This shift away from single-source installations illustrates a more sophisticated approach to energy planning, balancing generation, demand profiles, and resource availability. Optimisation and economic feasibility are increasingly dominant themes. High frequencies of keywords such as ‘optimisation’ (48), ‘economic analysis’ (39), ‘cost-benefit analysis’ (27), and ‘cost-effectiveness’ (29) signal the field’s transition from theoretical modelling to real-world system design. These findings highlight the drive to ensure HRES configurations are both technically sound and financially sustainable. Similarly, the notable presence of ‘sensitivity analysis’ (26) reflects growing concern with how variable parameters affect performance and return on investment over time. Energy storage is another critical focus. ‘Electric batteries’ (30) and ‘hydrogen storage’ (16) underscore efforts to stabilise energy supply and match demand fluctuations. While batteries remain the dominant storage solution, rising interest in hydrogen points to diversification, particularly for long-duration and grid-scale applications.

Environmental considerations feature prominently in the evolving discourse. Keywords such as ‘greenhouse gases’ (23), ‘sustainable development’ (14), and ‘environmental impact’ (13) align HRES research with broader global imperatives, including the UN Sustainable Development Goals and decarbonisation targets. The integration of environmental metrics alongside technical and financial parameters reflects the maturing of HRES as a pillar of sustainable energy systems. Keywords related to ‘grid integration’, ‘system reliability’, and ‘performance monitoring’, though less frequent, indicate growing attention to operational challenges. These aspects are vital for translating models into deployable, efficient, and resilient systems. The shift suggests increased interest in smart grid compatibility, real-time control, and long-term performance tracking. Technological focus within the literature is skewed towards solar and wind, owing to their maturity and market availability. The relative absence of terms linked to hydro, geothermal, or marine energy may reflect technological or regional limitations. This presents a research gap, an opportunity to diversify hybrid configurations based on locally abundant, underutilised resources. Although temporal trends are not explicitly tracked, the evolution from feasibility studies and component modelling towards system integration, cost optimisation, and sustainability indicates a field edging closer to deployment. The intersection of economic, environmental, and technical concerns signals a holistic shift in research priorities. In conclusion, the keyword analysis reveals a multidisciplinary and increasingly practical research landscape. The prominence of solar-wind integration, storage strategies, and economic optimisation reflects both the maturity and forward momentum of HRES research. As global energy systems decarbonise, hybrid solutions grounded in robust, interdisciplinary research will be essential in achieving sustainable, resilient, and scalable energy futures.



Figure 8. Word cloud based on Keyword Plus in HRES research

3.8 Co-occurrence Network

This investigation employs sophisticated cluster analysis techniques applied to 50 nodes, as visualised in Figure 9, to present the network of co-occurrence, systematically identifying distinct thematic domains within the HRES research corpus, with comprehensive data presented in Table 2. Through meticulous examination of the key terminologies associated with each cluster, we obtain invaluable insights into the research foci and contemporary trends that fundamentally shape this dynamic and rapidly evolving field.

Cluster 1: This comprises 16 interrelated keywords and focuses on the application of HRES in rural electrification and distributed generation systems. Central terms such as “wind,” “hybrid energy system,” “wind turbines,” and “photovoltaic cells” indicate a strong emphasis on combining solar and wind technologies to supply electricity to remote, underserved areas [85-87]. The presence of analytical tools like “sensitivity analysis” and “multi-objective optimisation” reflects the systematic use of advanced methods to tailor system performance to local conditions. These approaches are essential for addressing the inherent design complexities and ensuring cost-effective, reliable operation. Environmental concerns are also prominent in this cluster [88, 89]. Keywords such as “renewable energy resources” and “greenhouse gases” affirm the environmental motivations underpinning this research. These studies align closely with global climate targets and the UN Sustainable Development Goals, particularly in advancing low-carbon energy solutions for marginalised communities [90-92]. However, the concurrent presence of “fossil fuels” and “diesel engines” indicates that many HRES configurations are currently designed as transitional systems. In such contexts, renewables are often integrated with existing diesel

generators to improve fuel efficiency and reduce emissions, thereby enabling a gradual shift toward fully renewable operations [93, 94]. This reflects a pragmatic approach that acknowledges the logistical and financial constraints of immediate, full-scale decarbonisation. The inclusion of “computer software” and “genetic algorithms” highlights the growing role of computational intelligence in system modelling and optimisation. These tools enable real-time control and enhance performance under dynamic conditions. Overall, Cluster 1 encapsulates the critical intersection of energy access, sustainability, and technological innovation, underscoring HRES’s transformative potential in bridging energy equity and environmental responsibility.

Cluster 2: It encompasses 20 thematically grouped keywords in “Techno-Economic Analysis and System Design Optimisation”, reflecting a focused inquiry into the techno-economic optimisation of HRES. Core terms such as “solar power generation,” “wind power,” “hybrid systems,” and “digital storage” underscore an integrated approach that balances technical performance with economic viability, which is in line with earlier research [93, 95, 96]. This cluster reflects a growing emphasis on designing HRES that are not only functionally robust but also financially sustainable. The prevalence of keywords such as “optimisation,” “economic analysis,” and “net present cost” points to the centrality of financial evaluation in system planning. These frameworks are essential for assessing feasibility, enabling decision-makers to weigh cost-effectiveness against operational efficiency. This outcome is consistent with the study [53, 97, 98]. The presence of “electric batteries” and “cost-benefit analysis” highlights the increasing role of energy storage in enhancing reliability and economic returns.

The inclusion of “particle swarm optimisation (PSO)” signifies the adoption of advanced metaheuristic algorithms to manage the complex, multi-objective challenges in HRES design. These computational methods are pivotal for refining system configurations under diverse operational conditions. Notably, the keyword “environmental impact” indicates a holistic perspective that integrates ecological considerations into techno-economic assessments [52, 99, 100]. This shift towards comprehensive modelling aligns with global sustainability goals, reinforcing HRES as viable, low-carbon energy solutions for a decarbonising world.

Cluster 3: This cluster comprises nine strategically selected keywords, “Solar PV Integration and Multi-Source Renewable Systems”, centring on the integration of solar PV systems with other renewable energy sources [97, 101]. Keywords such as “energy systems,” “hybrid renewable energy,” and “optimisations” reflect an emphasis on combining and refining multiple technologies to enhance system performance, flexibility, and reliability. The presence of terms like “electric loads,” “electric utilities,” and “biomass” reveals a broad and diverse energy mix tailored to meet complex and context-specific demand profiles. This indicates that recent HRES research increasingly adopts multi-source approaches to account for variable energy consumption patterns and fluctuating resource availability across different regions [102, 103].

The keyword “sustainable development” underscores the environmental and socio-economic motivations driving such integration. This aligns with global climate action targets and the Sustainable Development Goals, reinforcing the role of HRES in fostering long-term, low-carbon energy access [90-92]. Moreover, the co-occurrence of “energy efficiency” alongside “hybrid renewable energy system” highlights a dual focus on optimising both the combination of resources and their utilisation [36, 104]. Overall, this cluster captures a critical shift in HRES research, towards smarter, more sustainable configurations that respond effectively to the demands of a dynamic and decentralising global energy landscape.

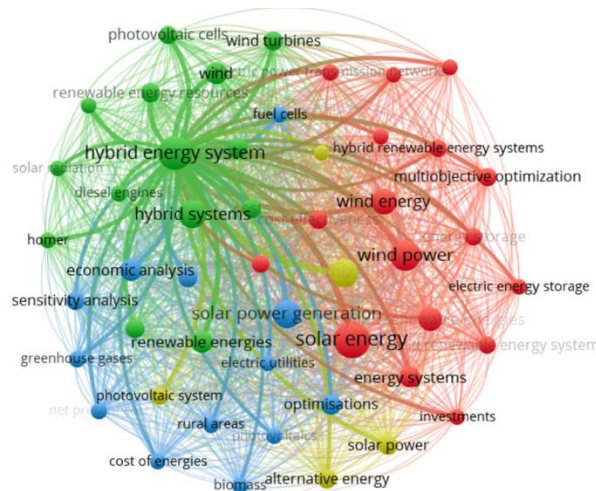


Figure 9. Mapping of co-occurrence keyword: Cluster 1 (red), Cluster 2 (green), Cluster 3 (blue), and Cluster 4 (yellow)

Cluster 4: This comprises five precisely selected keywords, focusing on the “integration and optimisation of power electronics and control systems” in HRES [36, 105]. Keywords such as “photovoltaic system,” “solar power,” and “alternative energy” highlight the emphasis on solar-based technologies and their integration within broader hybrid configurations. The inclusion of “energy storage” and “cost analysis” underscores ongoing research into reliable storage

solutions and economic feasibility, both crucial for ensuring system stability and cost-effective operation [106-108]. This reflects a growing interest in addressing the intermittency of renewable sources through advanced energy management strategies. The cluster also signals a technical shift towards sophisticated control architectures that enhance system responsiveness and grid compatibility. The emphasis on power electronics illustrates the necessity of precise power conditioning and real-time control in achieving efficient, stable, and scalable HRES deployment. Overall, this cluster demonstrates the field's technological progression towards smarter, more resilient renewable energy infrastructures.

3.9 Synthesis and Research Implications

The cluster analysis highlights key characteristics of current HRES research. It reveals a mature, interdisciplinary field that integrates engineering design, economic feasibility, environmental impact, and social development. Increasingly, researchers apply advanced computational methods to address the complex optimisation challenges of hybrid system configuration and operation. This finding aligns with the studies of [109-111]. Notably, there is a strong recognition of HRES as transitional technologies bridging conventional and fully renewable systems. The focus on cost-effectiveness and economic analysis signals a shift from theoretical modelling towards real-world application. This reflects the field's evolution towards delivering practical, scalable, and sustainable energy solutions. Overall, the analysis offers critical insights into the trajectory of HRES research, where innovation aligns with implementation and long-term environmental goals.

4. CONCLUSIONS

This bibliometric study presents a systematic exploration of global research trends in hybrid renewable energy systems (HRES), with a particular focus on the integration of solar photovoltaic (PV) and wind technologies. Based on 162 publications between 2009 and 2024, the field shows an impressive annual growth rate of 21.69%, signalling a shift from exploratory to applied, solution-oriented research. A defining feature of HRES research is its collaborative nature. International co-authorship appears in 46.91% of publications, with an average of 3.99 authors per paper, reflecting the field's interdisciplinarity and its global research network [50]. The 471 unique author keywords highlight the dominant research themes used across studies suggest a rich thematic spread, encompassing technical optimisation, environmental impact, economic analysis, and social considerations.

The average citation count of 40.39 per publication across the full retrieved dataset indicates high impact across academic and policy domains. Particularly influential are works by Maleki (2017), which have significantly shaped methodological and design discourse in HRES. Author productivity analysis shows that while 93% of contributors published only once, a core group of prolific researchers, likely tied to established research hubs, have made sustained contributions, confirming Lotka's Law patterns.

Citation-based country analysis reveals Iran (1,505 citations) and India (903 citations) as leading contributors, followed by Malaysia, Turkey, China, and Germany. This highlights the truly international character of HRES research and its relevance beyond traditional centres of academic power. Keyword frequency analysis underscores the dominance of solar energy (90 mentions) and wind power (78), reaffirming the emphasis on hybridising these complementary sources to tackle intermittency issues. Optimisation (48), economic viability (39), energy storage (batteries: 30; hydrogen: 16), cost-benefit analyses, and greenhouse gas mitigation emerge as central themes, pointing to the field's increasing maturity and real-world applicability.

Cluster analysis identifies four major thematic areas. Cluster 1 addresses rural electrification and decentralised generation, particularly in energy-poor regions. Cluster 2 focuses on techno-economic assessments and design strategies. Cluster 3 examines multi-source integration with PV systems, while Cluster 4 explores power electronics and control systems for stable output from variable energy sources.

From these insights, several research priorities emerge:

- Future work should advance adaptive HRES configurations suited to diverse climatic and geographic conditions, supported by AI-based prediction and optimisation tools.
- Research must focus on scalable and cost-effective storage, including next-generation batteries and green hydrogen technologies.
- Studies should explore smart grids, real-time monitoring, and advanced control algorithms for seamless integration with existing infrastructure.
- Incorporating environmental lifecycle analysis is essential to ensure long-term sustainability and reduce embedded emissions.
- Stronger ties between researchers, industry stakeholders, and policymakers are needed to bridge the gap between research and practical implementation.

Future studies should assess the socio-economic impacts of HRES deployment, including energy equity, job creation, and resilience. In conclusion, the global expansion, interdisciplinary collaboration, and growing practical relevance of HRES research demonstrate its critical role in shaping sustainable energy futures. The field's trajectory suggests it is poised to offer innovative, scalable solutions that support global climate targets and energy security objectives.

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CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHORS' CONTRIBUTION

A. A. Razak (Conceptualisation; Methodology; Data collection; Analysis; Manuscript review)

L. Raji (Data analysis; Bibliometric visualisation; Manuscript writing)

R. Sukarno (Conceptualisation; Manuscript review)

AVAILABILITY OF DATA AND MATERIALS

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

ETHICS STATEMENT

This study did not involve human participants or animals. Ethical approval was therefore not required.

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