

Review

Simulation and Modelling as Catalysts for Renewable Energy: A Bibliometric Analysis of Global Research Trends

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Abstract: This study investigates the application of advanced simulation and modeling technologies to optimize the performance and reliability of renewable energy systems. Given the urgent need to combat climate change and reduce greenhouse gas emissions, integrating renewable energy sources into existing infrastructure is essential. Using bibliometric methods, our research spans from 1979 to 2023, identifying key publications, institutions, and trends. The analysis revealed a significant annual growth rate of 16.78% in interest in simulation and modeling, with a notable surge in published articles, reaching 921 in 2023. This indicates heightened research activity and interest. Our findings highlight that optimization, policy frameworks, and energy management are central themes. Leading journals like *Energies*, *Energy*, and *Applied Energy* play significant roles in disseminating research. Key findings also emphasize the importance of international collaboration, with countries like China, the USA, and European nations playing significant roles. The three-field plot analysis demonstrated interconnections between keywords, revealing that terms like “renewable energy sources”, “optimization”, and “simulation” are central to the research discourse. Core funding agencies, such as the National Natural Science Foundation of China (NSFC) and the European Union, heavily support this research. This study underscores the importance of policies and sustainability indicators in promoting renewable energy technologies. These insights emphasize the need for ongoing innovation and interdisciplinary collaboration to achieve a sustainable energy future.

Keywords: renewable energy; bibliometric analysis; sustainable energy; simulation; modelling; RStudio



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1. Introduction

Renewable energy has become an essential component of global energy policy, given the current situation with climate change and the urgent need to reduce carbon emissions. Advanced modeling and simulation are vital tools for optimizing and integrating these technologies into existing networks [1].

Simulation and modeling, as catalysts for renewable energy, are essential concepts in the development and optimization of renewable energy technologies. These techniques allow researchers and engineers to evaluate and improve the performance of renewable energy systems before they are actually implemented. For example, Wilberforce et al. [2] consider the field of modeling to play an important role in planning and evaluating models regarding urban energy generation. Thus, the authors comprehensively investigate how the integration of specific renewable energy solutions can be achieved. Simulation and modeling enable the creation of virtual models of renewable energy systems [3–5]. These virtual models are essential to understanding the behavior of systems under various conditions and to optimize their design. Simulation techniques are also used to predict the performance of renewable energy systems under varying environmental and operating conditions [1,6]. These predictions are crucial to assess the long-term reliability and efficiency of systems.

Modeling and simulation are used to analyze the impacts of various scenarios on the performance of renewable energy systems. These analyses can include evaluating the impact of climate change, variations in energy demand, or integration with other energy sources. This allows for the development of adaptation and optimization strategies for systems to cope with these variations. For instance, Androniceanu et al. [7] conducted a study in which they analyzed the energy sector in Romania as a cybernetics system. In addition, they applied a modeling tool called autoregressive distributed lag to explore both the short-term and long-term impacts of greenhouse gas emissions and renewable energy on GDP. Economic modeling and financial simulations are used to assess the costs and benefits of implementing renewable energy technologies [8,9]. These assessments help in making informed decisions about renewable energy investments, highlighting long-term profitability and benefits. Another study relevant to renewable energy is the research conducted by El-Sebaeya et al. [10], as flat plate solar collectors (FPSCs) are essential components in capturing and utilizing solar energy, an important source of renewable energy. The performance improvement methods presented in the study, such as the use of PCMs, nanofluids, turbulence generators, and reflectors, are crucial for increasing the efficiency of solar collectors. These technological advancements contribute to optimizing the conversion of solar energy into thermal energy, making solar technologies more efficient and viable for widespread use. Additionally, in another study [11], the authors discuss performance improvements such as the use of CFD models to simulate and optimize heat transfer and the inclusion of various technologies, which are also important for increasing the efficiency of FPSC systems. These technological advancements contribute to optimizing the conversion of solar energy into thermal energy, making solar technologies more efficient and viable for widespread use. The study's results have direct implications for the development and application of renewable energy solutions, contributing to the reduction in dependence on traditional energy sources and promoting the use of sustainable and eco-friendly energy sources.

The main objective of this investigation is to examine the evolution of research in the field of renewable energy, highlighting the most significant contributions and future development directions. This paper identifies key trends, differences, and controversial hypotheses in recent studies on the modeling and simulation of renewable energy systems through a bibliometric analysis of the specialized literature. Special attention is given to significant works in this field and the impact of new modelling techniques on sustainable energy policy. Despite substantial progress in modeling complex renewable energy systems, there is still no consensus on the most effective methods for simulation and integration. This indicates a need for innovative approaches to address technological, economic, and regulatory uncertainties. This study aims to provide a comprehensive understanding of the current research landscape and establish a foundation for future advancements by presenting this framework. Additionally, it offers a detailed analysis of how modeling and simulation influence the progress of renewable energy technologies and their impact on sustainability policies. In addition to the aforementioned objectives, this study addresses the following research question (RQ):

RQ1: What are the main trends and future directions in research on the modeling and simulation of renewable energy systems?

RQ1 proposes exploring the use of simulation technologies to model and anticipate the behavior of renewable energy systems under the influence of various factors, such as climate change, variations in energy demand, and integration with other energy sources. This research question is detailed through the following sub-questions:

- What are the significant contributions and key trends in research on modeling and the simulation of renewable energy systems over the past decade?
- How have the methods and tools for simulating renewable energy systems evolved over time, and what are the future directions for their development?
- What are the controversial hypotheses and major differences in recent studies on the modeling and simulation of renewable energy systems?

- What is the impact of new modeling techniques on sustainable energy policies and the progress of renewable energy technologies?

This study is structured into several sections. Section 2 will present the methodological flows for conducting the proposed bibliometric analysis. Section 3 is dedicated to performing the analyses and presenting the results. The next part, Section 4, will discuss the general perspective of the obtained results and address each raised research question. Section 5 presents the general conclusions of this study, its limitations, and future research directions.

2. Methodology and Data Collection

Bibliometric analysis employs statistical methods and specialized software tools to extract, process, and interpret data related to scientific publications [12,13]. The main goal of this approach is to provide an objective overview of the developments within a research domain, highlight the contributions of authors or institutions, and identify potential avenues for future research. In this research, we conducted a bibliometric analysis using RStudio (version number 2023.09.1), specifically utilizing the bibliometrix package and its biblioshiny function for interactive visualization [14,15]. Biblioshiny utilizes the shiny package to encapsulate bibliometrix's core code and create a web-based online data analysis framework [16].

Several sources emphasize the benefits provided by this function in RStudio due to the diverse functionalities it offers in a bibliometric analysis process. The "biblioshiny ()" function enables data extraction from multiple sources, including Web of Science (WoS), Scopus, and Dimensions [14,17,18]. Additionally, it offers the possibility to conduct quantitative and qualitative analyses supported by the ability to create graphical and interactive visualizations such as networks, diagrams, cluster analyses, and geographic maps [19].

The methodology we applied follows the steps proposed and adapted by Zupic and Čarter [20], as well as Silva et al. [21], which have been followed by several studies in the field. Therefore, the bibliometric study went through the following stages:

- Step 1: The study design was conducted based on the narrative descriptions of some research questions. Based on these, specific keywords related to the analyzed subject were selected, and a bibliometric database was chosen;
- Step 2: In this stage, we synthesized the extracted bibliometric data;
- Step 3: We analyzed the bibliometric data using the RStudio software solution and the biblioshiny function. During this stage, we also assessed the quality of the data;
- Step 4: This stage was dedicated to the visualization of the results using various graphical methods;
- Step 5: In this stage, we used the extracted graphical representations and tables to interpret the results.

Step 1 was conducted in the introduction section by defining the five research questions. For the extraction of the database and for the data collection stage, as described in the second step, we used the WoS platform. Our choice was based on the recommendations of Liu [22] and Liu [23], who suggested that the results of bibliometric analyses heavily depend on the access users have to specific indexes offered by WoS. Additionally, this platform has extensive coverage of disciplines and fields and is recognized for its strong reputation in the scientific community [24–27]. Regarding Step 3, using the RStudio software solution, version number 2023.09.1, and the bibliometrix platform, the quality of the data was verified. Step 4 involved the graphical analyses, which we presented in the results section. Step 5 was dedicated to interpreting the results based on the visualization of the graphical analyses.

Table 1 provides a summary of the queries and steps undertaken to construct the database. We used the WoS [28] platform to gather papers related to simulation and modeling and renewable energy. The analysis was conducted through several stages, highlighting our detailed process for pinpointing relevant studies. Titles, abstracts, and keywords are utilized to cover various aspects of each paper.

Table 1. Summary of Data Selection Steps and Filters Applied.

Exploration Steps	Applied Filters	Description	Query	Query Number	Count
1	Title	Contains one of the simulations and modelling specific keywords	((TI = ("simulation")) OR TI = ("modeling")) OR TI = ("modelling") OR TI = ("modeling and analysis") OR TI = ("modelling and analysis")	#1	1,198,535
		Contains one of the renewable energy sectors keywords	(((((TI = ("renewable energy system")) OR TI = ("renewable energy sources")) OR TI = ("energy system performance")) OR TI = ("energy policy")) OR TI = ("renewable energy economics")) OR TI = ("renewable energy grid integration")) OR TI = ("sustainable energy systems") OR TI = ("renewable energy technologies") OR TI = ("renewable energy forecasting")) OR TI = ("renewable energy integration")	#2	8694
		Contains one of the simulations, modelling and renewable energy sectors keywords	#1 AND #2	#3	272
2	Abstract	Contains one of the simulations and modelling specific keywords	((AB = ("simulation")) OR AB = ("modeling")) OR AB = ("modelling") OR AB = ("modeling and analysis") OR AB = ("modelling and analysis")	#4	3,227,867
		Contains one of the renewable energy sectors keywords	(((((AB = ("renewable energy system")) OR AB = ("renewable energy sources")) OR AB = ("energy system performance")) OR AB = ("energy policy")) OR AB = ("renewable energy economics")) OR AB = ("renewable energy grid integration")) OR AB = ("sustainable energy systems") OR AB = ("renewable energy technologies") OR AB = ("renewable energy forecasting")) OR AB = ("renewable energy integration")	#5	46,345
		Contains one of the simulations, modelling and renewable energy sectors keywords	#4 AND #5	#6	8531
3	Keywords	Contains one of the simulations and modelling specific keywords	((AK = ("simulation")) OR AK = ("modeling")) OR AK = ("modelling") OR AK = ("modeling and analysis") OR AK = ("modelling and analysis")	#7	938,884
		Contains one of the renewable energy sectors keywords	(((((AK = ("renewable energy system")) OR AK = ("renewable energy sources")) OR AK = ("energy system performance")) OR AK = ("energy policy")) OR AK = ("renewable energy economics")) OR AK = ("renewable energy grid integration")) OR AK = ("sustainable energy systems") OR AK = ("renewable energy technologies") OR AK = ("renewable energy forecasting")) OR AK = ("renewable energy integration")	#8	14,298
		Contains one of the simulations, modelling and renewable energy sectors keywords	#7 AND #8	#9	1043
4	Title/Abstract/Keywords	Contains one of the specific keywords	#3 OR #6 OR #9	#10	9514
5	Language	Limit to English	(#10) AND LA = (English)	#11	9451
6	Document Type	Limit to Article	(#11) AND DT = (Article)	#12	5983
7	Year published	Exclude 2024	(#12) NOT PY = (2024)	#13	5503

➤ Step 1: Keyword search in titles

- We defined keywords related to simulation and modeling in titles, obtaining a total of 1,198,535 articles;

- We applied a filter to include titles related to renewable energy sectors, resulting in 8694 articles;
 - Combining the keywords (simulation, modeling, and renewable energy) in titles led to a selection of 272 articles.
- Step 2: Keyword search in abstract
- We expanded the search to abstracts using the same keywords for simulation and modeling, obtaining a total of 3,227,867 articles;
 - Adding the filter for renewable energy sectors in abstracts reduced the number to 46,345 articles;
 - Intersecting the keywords in abstracts led to the identification of 8531 articles.
- Step 3: Keyword search in article keywords
- We focused on searching within the keywords of the articles for simulation and modeling, which returned 938,884 articles;
 - Applying the filter for renewable energy in keywords identified 14,298 articles;
 - Combining these keywords reduced the number to 1043 articles.
- Step 4: Combining results
- We combined the results from the previous steps and obtained a total of 9514 articles that contain related keywords in the title, abstract, or keywords;
- Step 5: Language and document type filters
- We restricted the articles to those published only in English, considered the international language, reaching a total of 9451 articles;
 - An additional restriction was applied by retaining only scientific articles, resulting in 5983 scientific documents;
 - Considering that 2024 is still ongoing and new scientific articles in the analyzed field may appear, we excluded this year to avoid influencing the scientific trend, arriving at 5501 scientific articles to be included in the analysis.

These detailed steps from Table 1 demonstrate a systematic and rigorous data selection process, ensuring that the final set of articles is relevant and specific to the study of the use of simulation and modeling in the field of renewable energy. Each applied filter refined the search, reducing the vast initial number of articles to a manageable and specific set of works that for further analysis. This process guarantees that this research is based on the most relevant and current scientific contributions in the field.

The bibliometric study extracted articles from the Web of Science covering a wide range of scientific categories, highlighting the interdisciplinary nature of research in the field of simulation and modeling for renewable energy. The main categories include “Energy Fuels”, “Electrical Electronic Engineering”, and “Green Sustainable Science Technology”, emphasizing the importance of optimizing the use of fuels and developing sustainable technologies. The significant presence of the “Environmental Sciences” and “Environmental Studies” categories reflects concerns for the environmental impact and ecological sustainability of renewable energy sources. Additionally, the categories “Thermodynamics” and “Computer Science Information Systems” suggest intensive use of thermodynamic analysis and computer systems for energy performance modeling. The diversity of engineering categories, such as “Chemical Engineering” and “Multidisciplinary Engineering”, reflects the multidisciplinary approaches needed to optimize energy processes and develop new materials.

Figure 1 represents these categories, illustrating the comprehensive scope of the research covered in this study. Overall, the analysis of the WoS categories shows that simulation and modeling research for renewable energy is broad and diverse, involving collaboration between various scientific and technical fields to advance the knowledge and implementation of sustainable energy sources.

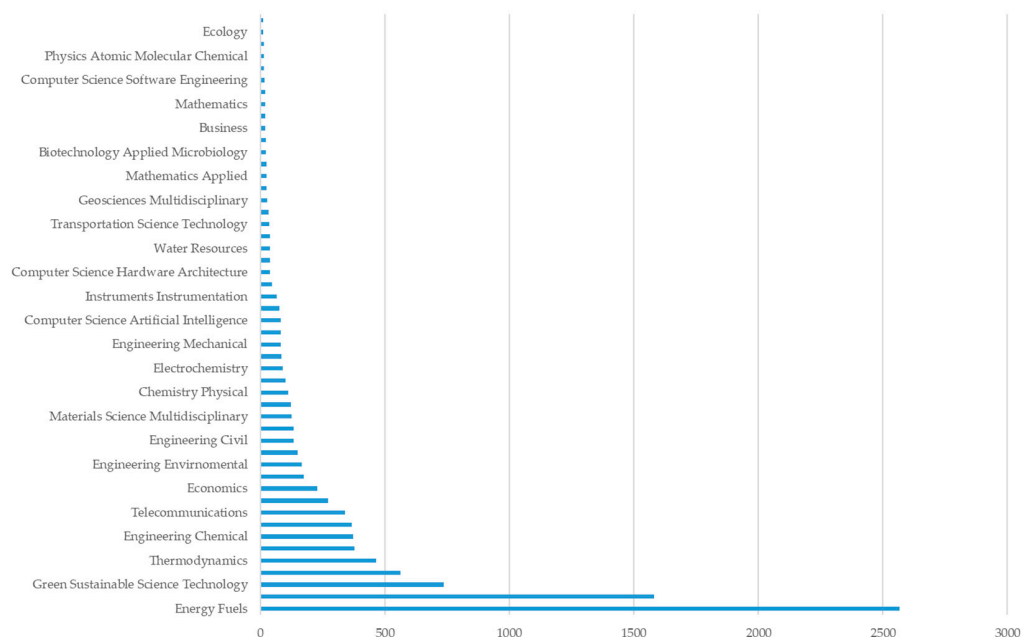


Figure 1. Web of Science Categories.

Figure 2 represents the distribution of extracted articles according to the Web of Science (WoS) indexes, highlighting the diversity of research sources and their impact on the field of simulation and modeling for renewable energy. The analysis of these indexes provides insight into the quality and relevance of the literature used. With 4691 articles, the SCI-Expanded index dominates the database, indicating that the majority of the extracted research comes from high-quality scientific journals recognized for their rigor and impact in the scientific community. This underscores the relevance and credibility of the results obtained in this bibliometric study. A total of 790 articles are indexed in the SSCI, reflecting a significant contribution from the social sciences to renewable energy research. This suggests that social, economic, and political aspects play an important role in the implementation and adoption of renewable energy technologies. With 640 articles, the ESCI indicates the presence of emerging research and journals that are becoming influential. This shows that the field of simulation and modeling for renewable energy is dynamic and continuously growing, including new and innovative research sources. A total of 200 articles come from conference proceedings, emphasizing the importance of scientific events for the rapid dissemination of new findings and the facilitation of idea exchange among researchers. With 27 and 12 articles, respectively, the BKCI-S and BKCI-SSH indexes reflect the contribution of monographs and book chapters to the body of knowledge in the field of renewable energy. They offer in-depth perspectives and synthesize existing research, being useful for a comprehensive understanding of the subject. With only five articles each, the CPCI-SS and A&HCI indexes represent a minor but relevant contribution, highlighting that the humanities and social sciences also contribute to the holistic understanding of the transition to renewable energy sources.

Figure 3 represents the distribution of articles according to funding agencies, highlighting their importance in supporting research in the field of simulation and modeling for renewable energy. With 420 funded articles, the National Natural Science Foundation of China (NSFC) tops the list, reflecting China's strategic priorities in promoting sustainable technologies. The European Union (EU) is second, with 200 articles, underscoring Europe's commitment to research and innovation in renewable energy. Funding agencies from the United Kingdom, such as UK Research Innovation (UKRI) and the Engineering Physical Sciences Research Council (EPSRC), have funded 118 and 104 articles, respectively, demonstrating the UK's active involvement. In the United States, the National Science Foundation (NSF) and the United States Department of Energy (DOE) have supported 93

and 68 articles, respectively, highlighting their important role in advancing research and developing innovative solutions for global energy challenges.

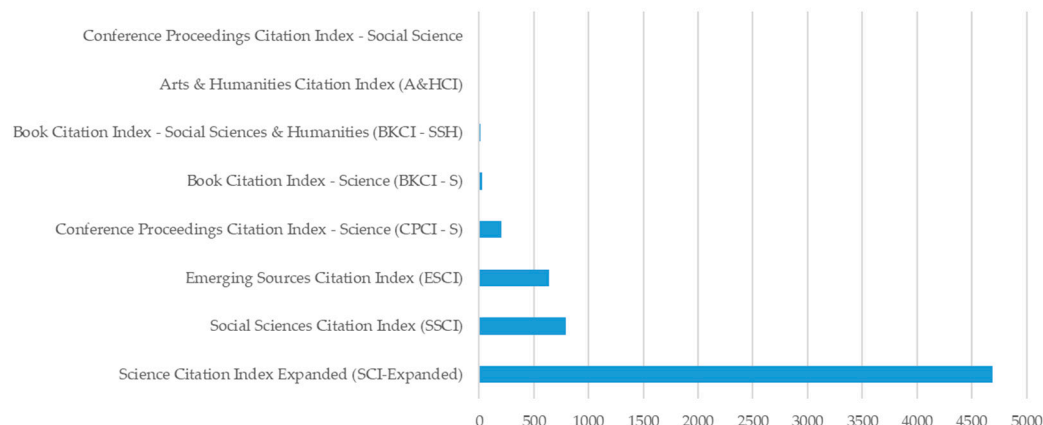


Figure 2. Web of Science Index.

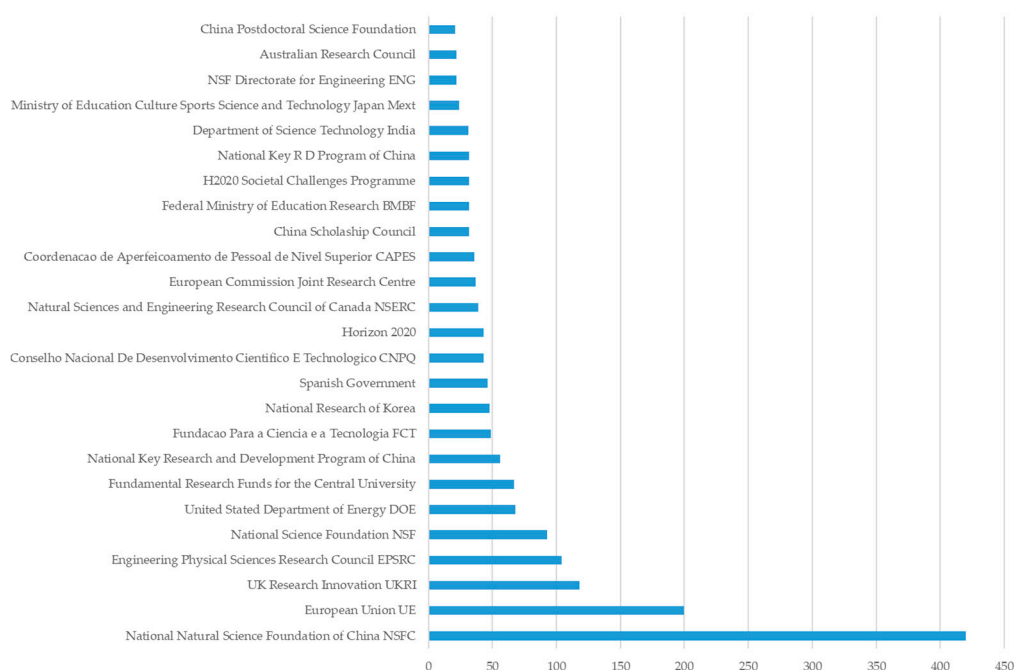


Figure 3. Funding Agencies.

In Table 2, the quality of the database extracted as per the queries from Table 1 was verified. Table 2 presents the completeness of the bibliographic metadata, highlighting the percentage of missing data for each metadata category and the general assessment of the quality of the information collected. We observe the following aspects regarding the final status of the metadata [29]:

- Excellent: The metadata for author (AU), document type (DT), journal (SO), language (LA), publication year (PY), scientific categories (SC), title (TI), and total citations (TC) are complete, with 0% missing, indicating an excellent quality of records for these categories;
- Good: The metadata for the article abstract (AB), corresponding author (RP), cited references (CR), affiliation (C1), DOI (DI), and keywords (DE) show a small number of missing entries, ranging from 0.18% to 5.78%. These categories are rated as having 'good' quality, indicating that most articles contain this information, but there are a few exceptions;

- Acceptable: The metadata for Keywords Plus (ID) have the highest percentage of missing data, 13.36%, which is rated as 'acceptable'. This suggests that, although the majority of the articles contain these data, there is a significant proportion, over 10%, that does not include them.

The conclusion we can draw from this analysis is that the dataset is generally very well maintained, with complete metadata for the most critical categories such as the author, document type, and title.

Table 2. Completeness of Bibliographic Metadata.

Metadata	Description	Missing Count	Missing (%)	Status
AU	Author	0	0.00%	Excellent
DT	Document type	0	0.00%	Excellent
SO	Journal	0	0.00%	Excellent
LA	Language	0	0.00%	Excellent
PY	Publication Year	0	0.00%	Excellent
SC	Science Categories	0	0.00%	Excellent
TI	Title	0	0.00%	Excellent
TC	Total Citation	0	0.00%	Excellent
AB	Abstract	10	0.18%	Good
RP	Corresponding Author	11	0.20%	Good
CR	Cited References	12	0.22%	Good
C1	Affiliation	22	0.40%	Good
DI	DOI	183	3.33%	Good
DE	Keywords	318	5.78%	Good
ID	Keywords Plus	735	13.36%	Acceptable

The bibliometric analysis in this study will investigate the main sources, authors, and scientific documents, and will also define several mixed analyses such as clustering analysis, collaboration networks, and factorial analysis. Regarding the mixed analysis called clustering by coupling that we will perform, it is calculated based on two metrics: the centrality of the bibliometric network and the impact of the articles. The network centrality is calculated based on keywords, while the impact is based on the global citation score. Additionally, the Walktrap algorithm is used for this analysis. The algorithm is based on the idea that short random walks tend to stay within the same community. By simulating random walks on the network, the algorithm can detect community structures [30,31]. Additionally, this Walktrap method will also be used in constructing the co-occurrence network. Regarding the factor analysis we will perform, we will use multiple correspondence analysis (MCA) as the method. This method is used in bibliometric analysis to analyze and represent associations between different attributes [19]. In this study, it will be used to analyze the associations between the authors' keywords. The graphical representation of the factor analysis will be done in two dimensions. Dimension 1 captures the largest part of the data variation, while Dimension 2 captures the second-largest part of the variation. These dimensions help illustrate how different keywords or attributes group together, indicating their associations and differences.

3. Results

In this section, we present the findings of the bibliometric analysis on the use of simulation and modeling in the field of renewable energy. The analysis aims to uncover global research trends, key contributions, and emerging areas of interest within this interdisciplinary domain. By employing a systematic and rigorous data-selection process, we have curated a comprehensive dataset, serving as the foundation for the exploration.

Table 3 presents some general information about the data extracted. The period analyzed is 1979–2023, which offers a long-term perspective on the evolution of research in

the field studied. Additionally, the number of sources, being 859, indicates a wide diversity of publishing platforms that contribute to the specialized literature. In total, based on all extraction criteria, we will analyze 5503 documents, representing the total volume of works analyzed from the specialized literature. The annual growth rate of 16.78% shows a sustained increase in interest and researchers in this field, once again underlining the importance of the study we are conducting. The average age of the documents, 4.98 years, indicates that the specialized literature is relatively recent and relevant. Moreover, an average of 22.4 citations per document suggests that the documents we have extracted are influential and frequently cited in other works. We also observe an extensive number of citations and interconnections in the specialized literature, with a total of 163,591 references.

Table 3. Key Bibliometric Indicators.

Research Metric	Results
Timespan	1979:2023
Sources (Journals, Books, etc.)	859
Documents	5503
Annual Growth Rate (%)	16.78
Document Average Age	4.98
Average citations per doc	22.4
References	163,591
Keywords Plus	4967
Author's Keywords	15,302
Authors	16,031
Authors of single-authored docs	228
Single-authored docs	249
Co-authors per doc	3.98
International co-authorships (%)	33.29

Also, Table 3 shows the number of Keywords Plus (4967), indicating that these additional keywords help improve searches and enhance the visibility of documents. Additionally, 15,302 author-defined keywords have been identified, reflecting the main focus and specificity of the research. From the authors perspective, there are a large number of contributors in the field we are analyzing, with 16,031 authors. The small number of only 228 authors of single-authored documents indicates that most of the work involves collaborations, highlighting the complexity and importance of the research in the studied field.

Regarding author collaboration, we observe that 249 single-authored documents were extracted, representing a relatively small fraction of the total number of documents, which again emphasizes the trend towards teamwork. Additionally, the collaborative nature of research in this field is supported by the average of 3.98 co-authors per document. The significant rate of international co-authorships, 33.29%, demonstrates a substantial degree of international collaboration, contributing to the global exchange of ideas and the expansion of knowledge in the field.

Figure 4 presents the annual scientific production in the field of simulation and modeling for renewable energy, reflecting a significant increase in the number of published articles over the decades. Starting with a very low number of articles in the 1970s and 1980s, scientific production has experienced rapid expansion in recent decades. Initially, scientific production was very low, with only a few articles published (one article in 1979, two in 1986, and one in each 1987 and 1988). This period marks the beginnings of research in this field.

During the 1990–1999 period, the number of articles published annually remained relatively low but began to gradually increase, reaching a maximum of eight articles in 1998. This reflects a growing interest in simulation and modeling in the context of renewable energy.

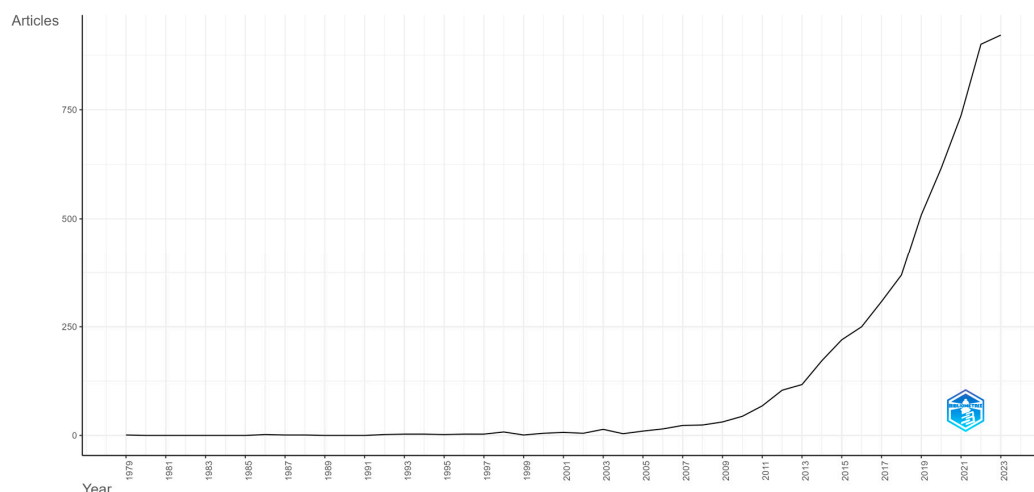


Figure 4. Annual Scientific Production.

The decade of 2000–2009 shows a steady and significant increase in the number of articles. From 5 articles in 2000, the number grew to 31 in 2009, with a significant peak in 2003 (14 articles). This indicates the consolidation of the field and a growing academic and practical interest.

We also observe that scientific production exploded in the 2010–2019 period, increasing from 44 articles in 2010 to 509 in 2019. Each year of this period showed significant growth, with an accelerated pace starting in 2011. This period highlights the maturation of the field and the recognition of its importance in the transition to sustainable energy sources.

In the last three years, the number of articles has continued to grow, reaching 921 in 2023. The year 2022 was particularly prolific, with 900 articles. This suggests a continued and intensified interest, possibly due to technological advancements and increased concerns about climate change and sustainability.

Figure 5 shows the average citations per year. This provides a perspective on the impact and influence of research published in the field of simulation and modeling for renewable energy over time. This analysis is based on the average number of citations received by articles each year, considering the time since they were published. We observe that the early stages of this research field are marked by a small number of published articles with variable impacts. In 1979, a single article recorded a high average of citations per year (1.13), and in 1988, an article had an average of 0.92 citations per year. During this period, fluctuations are significant, reflecting sporadic interest and slow development in the field. Starting from 2000, we see an increase in the number of articles and a relatively steady rise in average citations per year. The years 2001 and 2004 stand out with high average citations per year (2.28 and 4.74, respectively), indicating highly impactful works. The decade of 2010–2019 can be considered a period of maturation for this field, showing a consistent increase in both the number of published articles and the average citations per year. The year 2010 is notable, with an average of 4.53 citations per year, while 2019 reaches a peak of 5.02 citations per year, suggesting strong academic interest and recognition of the field's importance. In the recent period of 2020–2023, we observe a slight decline in the average citations per year, even though the number of published articles continues to grow. The year 2023 shows an average of only 1.48 citations per year, which can be explained by the fact that these articles are very recent and have not yet had sufficient time to accumulate citations.

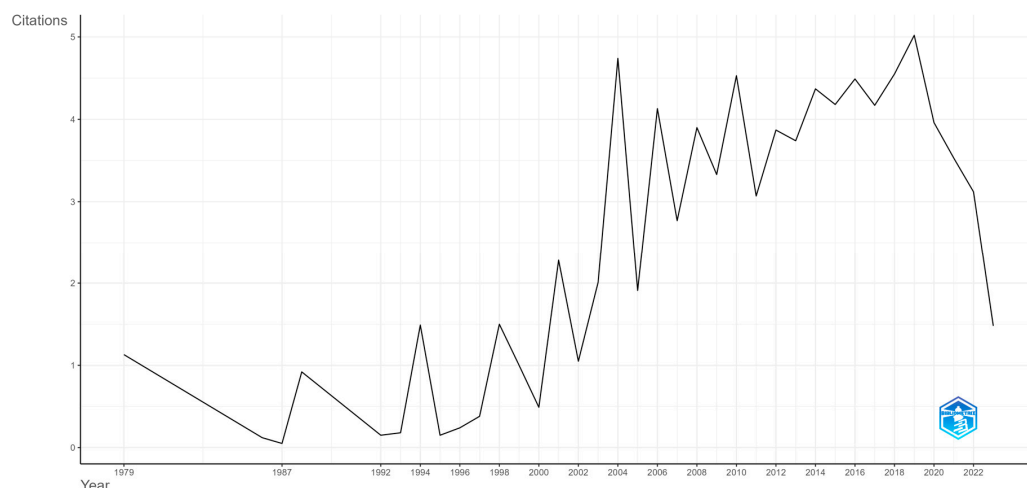


Figure 5. Average Citations per Year.

The three-field plot in Figure 6 provides a complex perspective on the interconnections between keywords, Keywords Plus, and the countries involved in this field of research. It helps to highlight international trends and collaborations as well as identify key areas of interest. Each column of colors is associated with the three fields: on the left, author keywords; in the center, countries; and on the right, Keywords Plus. The intensity of the color associated with each field varies according to the degree of connectivity. The stronger the color, the stronger or more frequent the association it indicates. We observe that “renewable energy sources” is a central keyword, having connections with all the countries presented in the graph, such as China, India, Iran, the USA, Spain, and Italy. This indicates that this term is frequently associated with other themes and international contributions. Additionally, the dominant Keyword Plus is “optimization”. This suggests that optimization plays a crucial role in research related to renewable energy, being a common theme in published articles. Other extended keywords include “renewable energy”, “uncertainty”, “load modeling”, “microgrid”, “energy management”, “costs”, “voltage control”, “power system stability”, “simulation”, and “energy policy”. These reflect the diverse aspects of renewable energy research, ranging from energy management and voltage control to uncertainty and load modeling.

In the bibliometric analysis of simulation and modeling as catalysts for renewable energy, identifying the most relevant sources is essential to understanding where the most influential and prolific research works are published. Thus, in Figure 7, we observe the top 15 most relevant sources. This graph highlights the journals that have had the highest scientific production and thus contribute significantly to the available knowledge in the field. We observe that the journal *Energies*, with an impressive number of 476 articles, stands out as a primary source for research in renewable energy. It covers a wide range of topics, including energy technologies, energy policies, and environmental impacts. The journal *Energy* publishes essential works on all aspects of energy, from generation and utilization to environmental impact. The number of 249 articles indicates that it is an important source for research on modeling and simulation in the context of renewable energy. With 243 articles, the journal *Applied Energy* ranks third. It focuses on energy applications and technological innovations, being crucial for studies exploring the use of renewable energy and the optimization of energy systems. The presence of the *IEEE Access* journal, with 235 articles, positions it in fourth place, with the journal offering access to a wide variety of research in engineering and technology, including studies on the simulation and modeling of energy systems.

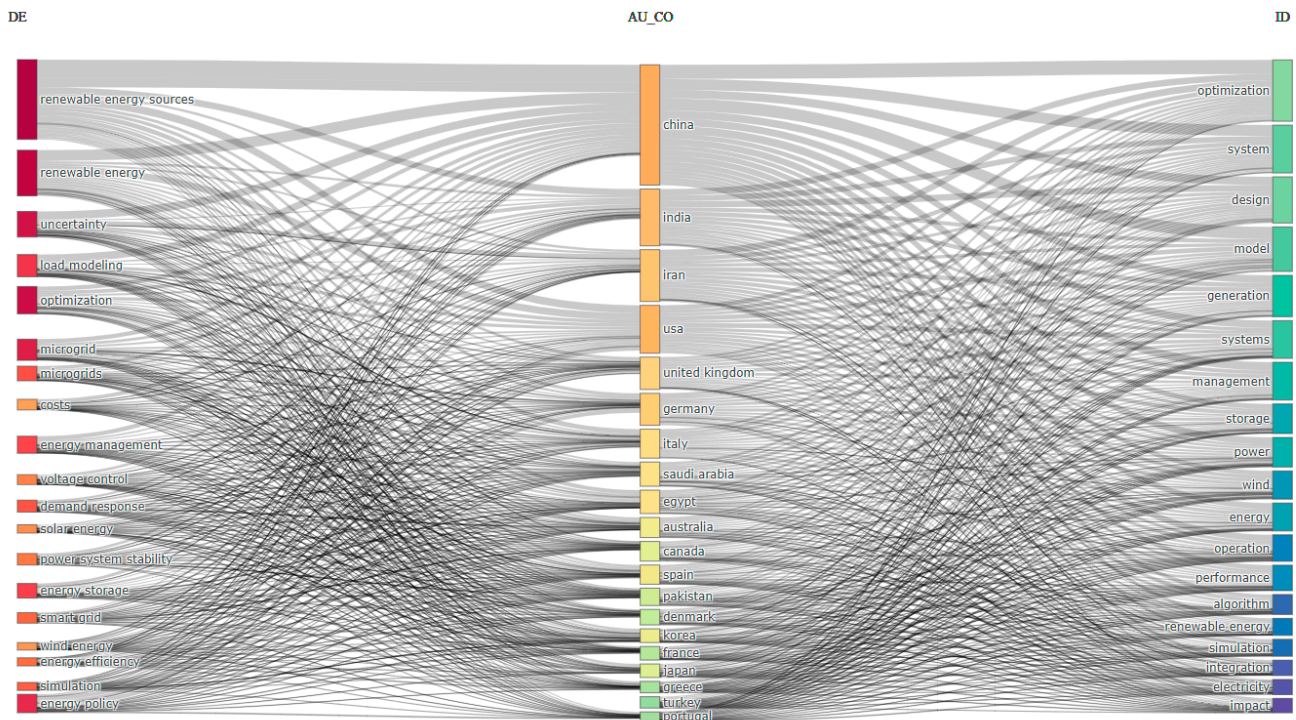


Figure 6. Three-Field Plot (left field—keywords, middle field—countries, right fields—Keywords Plus).

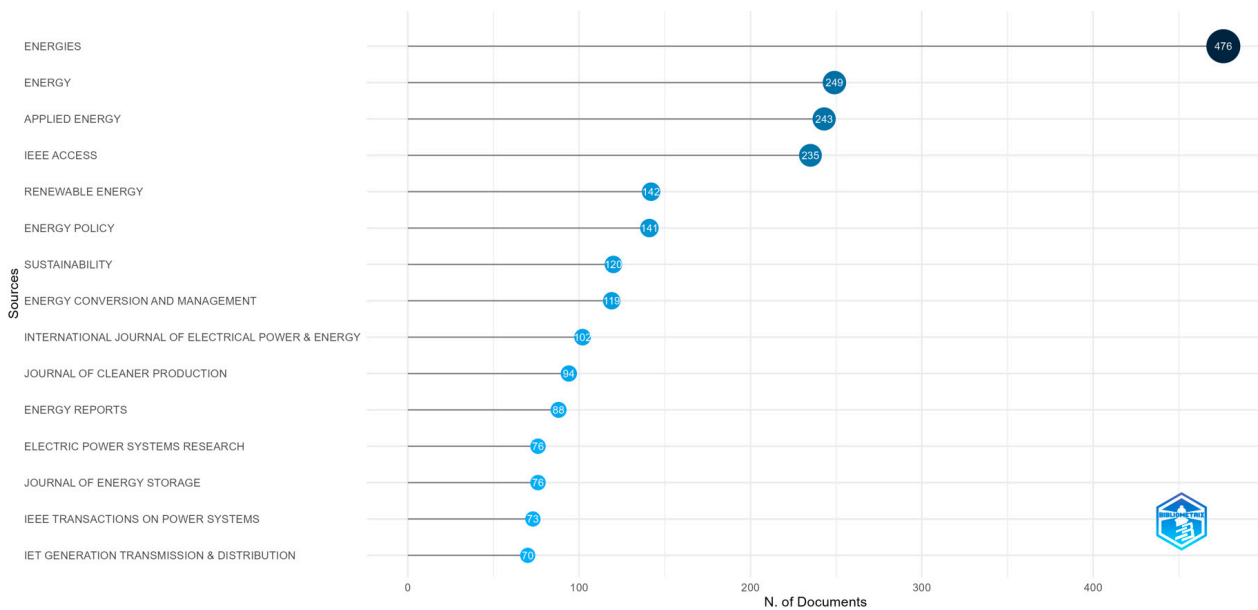


Figure 7. Top 15 Most Relevant Sources.

These sources represent the core of research in simulation and modeling for renewable energy, covering a wide range of topics from technology and engineering to policies and sustainability. They provide a solid foundation for understanding current trends and future developments in this dynamic field.

Figure 8 presents the zones classified according to Bradford’s Law. Bradford’s Law is used in bibliometrics to identify a set of core sources in a research field [32–34]. According to this law, sources are divided into three zones, each containing approximately the same number of relevant articles but with an unequal distribution of the numbers of sources. In the context of our bibliometric analysis of simulation and modeling as catalysts for renewable energy, interpreting the core sources according to Bradford’s Law helps us

identify the most influential journals in this field. This approach helps identify journals that, although they may have fewer articles, have a disproportionate influence due to their relevance and impact in the field. In Zone 1, considered core sources, the following journals stand out: *Energies*, *Energy*, *Applied Energy*, *IEEE Access*, *Renewable Energy*, *Energy Policy*, *Sustainability*, *Energy Conversion and Management*, and *International Journal of Electrical Power & Energy Systems*. These journals are the most prolific and influential in publishing research on renewable energy simulation and modeling. They cover a wide range of topics, from energy technologies, policies, and environmental impact to specific applications and technological innovations in energy systems.

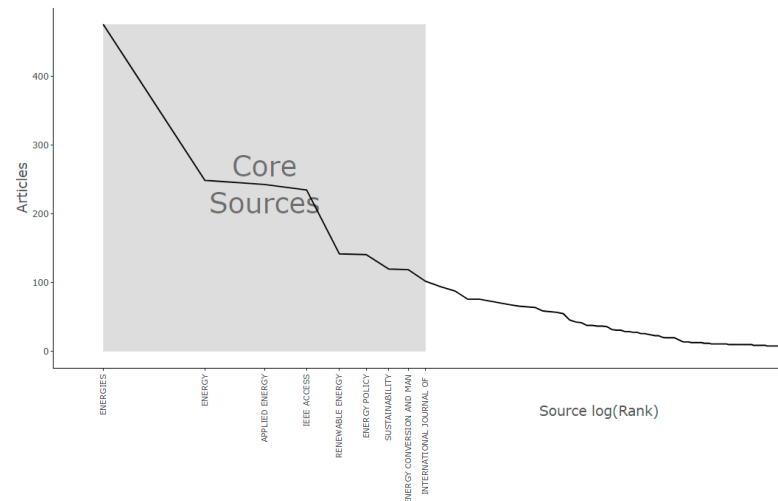


Figure 8. Core Sources by Bradford's Law.

Figures 7 and 8 offer complementary perspectives: one focuses on the quantity of published articles, and the other on the relevance and influence of journals, according to a theoretical distribution established by Bradford's Law. Both figures are necessary to gain a comprehensive understanding of the academic landscape in renewable energy research.

The analysis of source production over time in Figure 9 reflects the significant evolution and growth in the number of articles published in leading journals in the fields of renewable energy and modeling and simulation. The graph highlights five major sources: *Energies*, *Energy*, *Applied Energy*, *IEEE Access*, and *Renewable Energy*, and how their contributions have increased over the decades. The journal *Energies* did not publish relevant articles in this field until 2010. Since then, the number of articles has grown exponentially, reaching 476 articles in 2023. This indicates a massive increase in interest and research in this field, establishing *Energies* as one of the primary sources. The journal *Energy* began publishing relevant articles earlier, in 2002, but initially experienced slower growth. However, from the early 2010s, the number of articles increased significantly, reaching 249 articles in 2023. This reflects a constant growth in interest in energy topics. Similar to *Energy*, *Applied Energy* began publishing relevant articles in 1997. Since then, the journal has had steady and substantial growth in production, reaching 243 articles in 2023. This demonstrates the increased importance of research on energy applications and technological innovations. The journal *IEEE Access* started publishing relevant articles in 2017 and has seen rapid growth, reaching 235 articles in 2023. This suggests a significant increase in interest in engineering and technology in the context of renewable energy. The journal *Renewable Energy* began publishing relevant articles in 1998 and has shown constant growth over the years. In 2023, the number of articles reached 142, indicating a consolidation of research in the field of renewable energy sources. The graph highlights an impressive increase in academic production in the top journals in the fields of renewable energy and modeling and simulation. All five major sources have experienced significant growth in the last decade, reflecting increased attention and strategic importance of these fields in contemporary

research. This growth can be attributed to global concerns about sustainability, climate change, and the transition to cleaner and more efficient energy sources.

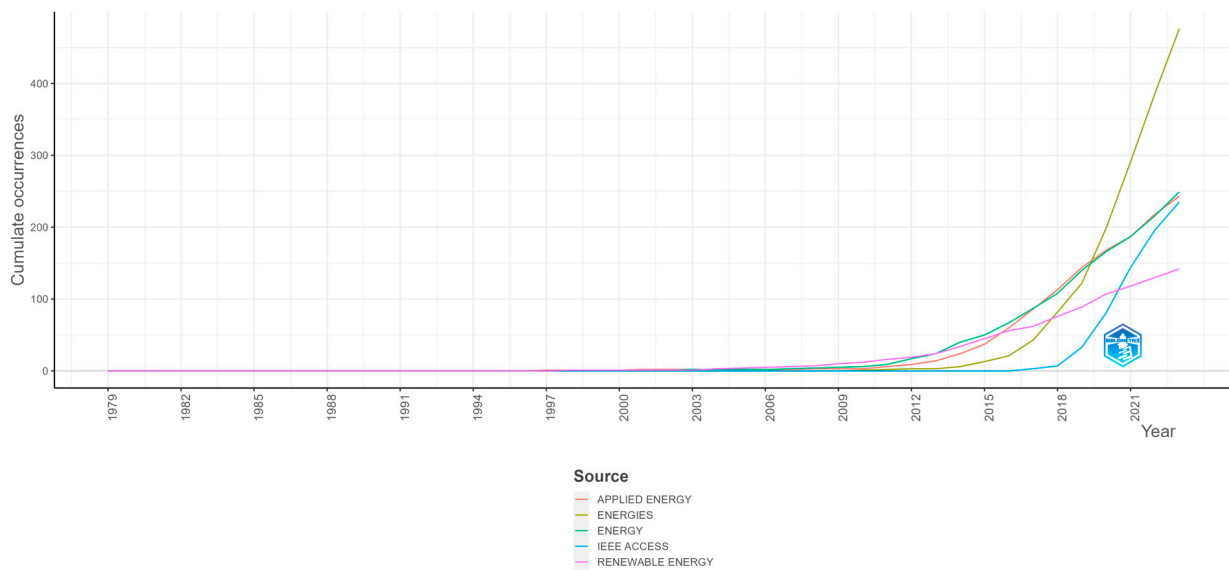


Figure 9. Sources' Production over Time.

The analysis of the top 15 most globally cited documents in Table 4 provides a comprehensive overview of the most influential research within the field of renewable energy simulation and modeling. These documents have been selected based on their total citations, total citations per year (TCY), and normalized total citations (NTC), offering a clear picture of their impact and significance.

The most cited paper, authored by Mao et al. in 2016 and published in the *IEEE Journal on Selected Areas in Communications*, boasts 1141 total citations, with an impressive TCY of 126.78 and an NTC of 28.26. This indicates its substantial influence and ongoing relevance in the academic community. Following closely, Liu et al.'s 2015 paper in *IEEE Transactions on Power Electronics* has 705 total citations, a TCY of 78.33, and an NTC of 17.46, reflecting its significant impact on power electronics research. Sensfuß et al.'s 2008 publication in *Energy Policy* has accumulated 544 total citations, maintaining a steady TCY of 32.00 and an NTC of 8.21, which shows its enduring relevance in energy policy discussions. Reznik et al.'s 2014 paper in *IEEE Transactions on Industry Applications*, has 457 total citations, a TCY of 41.55, and an NTC of 9.51, which highlights its importance in industrial applications. Mengelkamp et al.'s 2017 paper in *Computer Science—Research and Development* stands out for its rapid citation growth, achieving 438 total citations, a TCY of 62.57, and an NTC of 13.75, indicating an emerging significance of integrating computer science with energy research. Other notable papers include Karki et al.'s 2006 publication in *IEEE Transactions on Energy Conversion* and Sortomme et al.'s 2010 paper in *IEEE Transactions on Power Delivery*, which maintain strong citation rates and influence in their respective fields. Hafez et al.'s 2012 paper in *Renewable Energy* and Liu et al.'s 2012 paper in *IEEE Transactions on Energy Conversion* also demonstrate robust citation performance, underscoring their contributions to renewable energy and energy conversion research.

Overall, these documents collectively highlight the critical areas of focus and the evolving trends in renewable energy research, emphasizing the importance of interdisciplinary approaches and the integration of advanced technologies in addressing contemporary energy challenges.

Table 4. Top 15 Most Globally Cited Documents.

No.	Paper (First Author, Year, Journal, Reference)	Total Citations (TC)	Total Citations per Year (TCY)	Author Keywords
1	Mao, Y., 2016, <i>IEEE Journal on Selected Areas in Communications</i> , [35]	1141	126.78	Mobile-edge computing (MEC); energy harvesting (EH); dynamic voltage and frequency scaling (DVFS); power control; QoS; Lyapunov optimization DC-AC power converters; distributed power generation; droop control; microgrids; power control; power system dynamics; power system modeling; renewable energy sources (RES); state-space methods; virtual synchronous generator (VSG)
2	Liu, J., 2015, <i>IEEE Transactions on Power Electronics</i> , [36]	705	78.33	Renewable energy; electricity market; agent-based simulation
3	Sensfuß, F., 2008, <i>Energy Policy</i> , [37]	544	32.00	Filter; harmonics; inverter; power quality; pulsewidth-modulated (PWM) inverters
4	Reznik, A., 2014, <i>IEEE Transactions on Industry Applications</i> , [38]	457	41.55	Local energy markets; market design, decentralization; blockchain
5	Mengelkamp, E., 2017, <i>Computer Science—Research and Development</i> , [39]	438	62.57	Generation system; reliability evaluation, time-series model; wind power
6	Karki, R., 2006, <i>IEEE Transactions on energy Conversion</i> , [40]	409	21.53	Digital relay; distribution communication; distribution systems; high impedance fault; microgrid; protection
7	Sortomme, E., 2010, <i>IEEE Transactions on Power Delivery</i> , [41]	376	25.07	Microgrid; renewable energy; system planning; HOMER; environmental emissions
8	Hafez, O., 2012, <i>Renewable Energy</i> , [42]	362	27.85	Maximum power point tracking (MPPT); partially shaded condition (PSC); particle swarm optimization (PSO); photovoltaic (PV) generation system (PGS);
9	Liu, Y.H., 2012, <i>IEEE Transactions on energy Conversion</i> , [43]	354	27.23	Electric vehicle, load frequency control; smart charging; smart grid; state-of-charge; vehicle-to-grid
10	Ota, Y., 2012, <i>IEEE Transactions on Smart Grid</i> , [44]	340	26.15	Energy system modelling; energy storage; large-scale integration; Analysis and simulation; dc-to-dc converters; modeling; renewable energy systems; resonant converters;
11	Weitemeyer, S., 2015, <i>Renewable Energy</i> , [45]	336	33.60	Genetic algorithm; Aqua electrolyzer; Fuel cell; Diesel engine generator; Battery energy storage system; Wind turbine generator;
12	Li, X., 2010, <i>IEEE Transactions on Power Electronics</i> , [46]	322	21.47	EPBD 2010; Cost optimality; Genetic algorithm; Life-cycle cost; primary energy
13	Das, D.C., 2012, <i>International Journal of Electrical Power & Energy Systems</i> , [47]	317	24.38	Distributed power generation; grid interface; multilevel conversion; multivariable control; wind power system;
14	Hamdy, M., 2013, <i>Energy and Buildings</i> , [48]	309	25.75	
15	Alepuz, S., 2006, <i>IEEE Transactions on Industrial Electronics</i> , [49]	303	15.95	

Next, we will carry out a qualitative analysis of the 15 studies extracted in Table 4. Mao et al. [35], in their study, mentioned the importance of mobile-edge computing (MEC), given the new technical requirements that are being applied to new technology from the perspective of mobile applications. The researchers stated that the performance of mobile applications is directly impacted by the mobile's battery, and have spoken about the importance of achieving green computing, emphasizing how significant the renewable energy sources to power up mobile devices such as energy harvesting (EH), are. The authors analyzed how the offloading strategy works in the case of green MEC systems that

are operating on EH devices. For this, they proposed an algorithm called Lyapunov, its task being to decide how the main processes of mobile devices should run. More than this, the algorithm itself is based on the current performance state of the device.

In the second study [36] from Table 4, the authors underlined the disadvantages that the nowadays-traditional grid-control has. It was stated by the authors that the newer control methods, such as virtual synchronous generator (VSG) and droop control, are more efficient, the only difference between them being the inertia topic, with VSG emulating the swing equation and droop control having no inertia at all. Thus, the researchers studied the delay effects of both control mechanisms with the help of simulations, stating that both of them are more efficient than the traditional approach.

In next paper [37], the researchers studied the impact that renewable energy sources as a method of generating electricity had on Germany's price market. The authors examined this by employing simulations over an agent-based model tool, finding that the financial volume decreased along with the price reduction. Based on the results, the scientists emphasized that, from a short-term perspective, effects were distributed in such a way that the demanders had their savings increased; this only with the help of having the generator profits reduced. More than this, with regards to Germany's renewable energy generation for the year 2006, the renewable electricity generation was further funded with the help of the consumers.

Reznik et al. [38], in their study, put an emphasis on how important the power converters are when it comes to maximizing the power that can be transferred to the utility grid from renewable energy sources, like fuel cells that are hydrogen-based, wind energy, or solar energy. The authors stated that the LCL filter topic has not been fully covered by the existing papers, with systemic designs' methodology not being comprehensively described. By conducting this research, the authors proposed a new design methodology that can be considered for LCL filters when approaching the grid-interconnected inverters topic, but also how to reduce the harmonics. Furthermore, the authors stated that the techniques used in their article could also be used for small-scaled renewable energy, but could also be further extended to a medium- or large-scale grid-connected system.

Mengelkamp et al. [39] stated that there should be new approaches with regards to the market price, decentralized generation, and volatile distribution topics given the constant increase in the renewable energy sources that exist. The scientists shared a market design in which the local energy market of approximately 100 households was studied, based on their communication technology and distributed information, emphasizing the decentralized nature that the local energy markets have. This design took into consideration the energy consumers and providers with the help of a decentralized market platform that had the trade of local energy generation as its main target.

In the next article [40], the authors emphasized how important wind power as a renewable energy source is, especially considering how low its impact on the environment is. The scientists underscored how complex and difficult the process of making a reliability evaluation of wind power is, stating that very accurate measurements of wind speeds are mandatory, for which a significant amount of historical data with regards to wind speed are required. Compared to the Monte Carlo simulation that is widely used for these kinds of analyses, the authors proposed a simpler methodology for estimating the wind power. Based on the geographic locations (these wind power plants are located in Canada), the authors provided a six-step model that can be applied to a variety of geographic locations.

Sortomme et al. [41], in their study, discuss the microgrids approach, with it being responsible for integrating lots of renewable energy sources in distribution systems, underscoring the fact that it is lacking an adequate protection scheme. By their analysis, the scientists propose a better scheme for protecting the microgrid, considering also a communication network along with digital relays in their study. Simulated with the help of Matlab Simulink against a real-life distribution system, the authors proved that the primary and secondary relays were not impacted, continuing to perform their functions.

The authors from the next study [42] aimed to minimize the lifecycle cost of the renewable energy that is based on microgrids, also taking into account the environmental emissions that they produce. For this, the scientists considered the optimal planning, sizing, design, and operations of a renewable energy microgrid. More than this, there were a varying numbers of configuration use-cases considered, such as diesel-renewable, fully renewable, diesel-only, or external grid-connected, with the aim to compare all of them to the others from an economics, environmental emissions, and operational performance perspective. In order to achieve the results, the authors used the HOMER model to compare use-cases.

In the following study [43], the authors studied the MPPT device, which is responsible, under various environmental conditions, for extracting the highest available power from a photovoltaic module. It was mentioned by the scientists that the MPPT misses out on tracking the maximum power in a scenario of partial shading condition (PSC), which is the module's most common circumstance. Widely, the particle swarm optimization is used for these kinds of evaluations, but in their paper, the authors propose a new solution, combining PSO and ANN methods, leading to a better performance of the evaluation.

In the following paper [44], the authors emphasized how important is to have battery energy storage when integrating renewable energy sources amongst power grids. It is stated that vehicle-to-grid (V2G) should be the key player in further smart grid strategies with regards to electric vehicles (EV); thus, the scientists proposed a V2G control scheme that is autonomously distributed. For the proposed analysis, the authors came up with a smart charging control for an EV, for which the authors examined the overall satisfaction of EV users from a convenience point of view.

Weitemeyer et al. [45], in their research, focused on the integration of renewable energy sources (RES) that are non-dispatchable in power supply systems. Considering that the widespread integration approach is unclear, the authors used a high number of wind and solar energy data in order to employ a model that examines what the influence of efficiency and storage size on a 100% RES scenario is. The researchers applied their model against Germany's data, and its results proved that up to 50% of the overall electricity demand can be achieved by correctly mixing the solar and wind power.

Li et al. [46] describe, in their study, a bidirectional DC/DC converter with high-frequency isolation, which are gaining increasing attention in renewable energy systems due to their small size and high-power density. They analyze a resonant converter using two simple circuit analysis methods, considering only the fundamental components of voltages and currents.

In the following study [47], the authors use time-domain simulations to analyze the performance of installed controllers with the aim of reducing the frequency deviations of an energy system caused by sudden changes in load or generation. Additionally, the authors employ genetic algorithms for their study, and the results demonstrate the effectiveness of the introduced controllers.

Hamdy et al. [48], in their research, focus on finding cost-optimal solutions for near-zero-energy buildings (nZEB) in accordance with the European Energy Performance of Buildings Directive (EPBD-recast 2010). The authors introduce a simulation-based optimization method that is efficient, transparent, and time-saving for such explorations. The method is applied to find the cost-optimal and nZEB energy performance levels for a case study of a single-family house in Finland.

In the last study among the top 15, the authors [49] present an innovative approach for connecting renewable energy sources to the utility grid. Due to the increasing power capacity of the available generation systems, a three-level three-phase neutral-point-clamped voltage-source inverter is selected as the central element of the interfacing system. For the regulator, the authors utilize a multivariable control law due to the intrinsically multivariable structure of the system.

In Figure 10, the top 15 most relevant affiliations highlight the research institutions and universities that significantly contribute to the fields of renewable energy and modeling

and simulation. These affiliations are evaluated based on the number of articles published, indicating their influence and impact in this research area. Egyptian Knowledge Bank (EKB) leads the ranking with 347 articles, demonstrating Egypt's strong commitment to promoting research in renewable energy and associated technologies. The National Institute of Technology (NIT System) from India ranks second with 160 articles, highlighting the important role of technology and technical education in advancing renewable energy research. Islamic Azad University, with 137 articles, and Indian Institute of Technology System (IIT System), with 133 articles, underlines the significant contributions of universities from Iran and India, respectively, in this field. On the other hand, the United States Department of Energy (DOE) has 112 articles, indicates the American government's involvement in supporting research and development in renewable energy. Swiss Federal Institutes of Technology Domain has 72 articles, showing Swiss involvement in scientific and technological innovations. These affiliations illustrate the geographical and institutional diversity of renewable energy research, reflecting international collaborations and collective efforts to advance knowledge and technologies in this critical field.

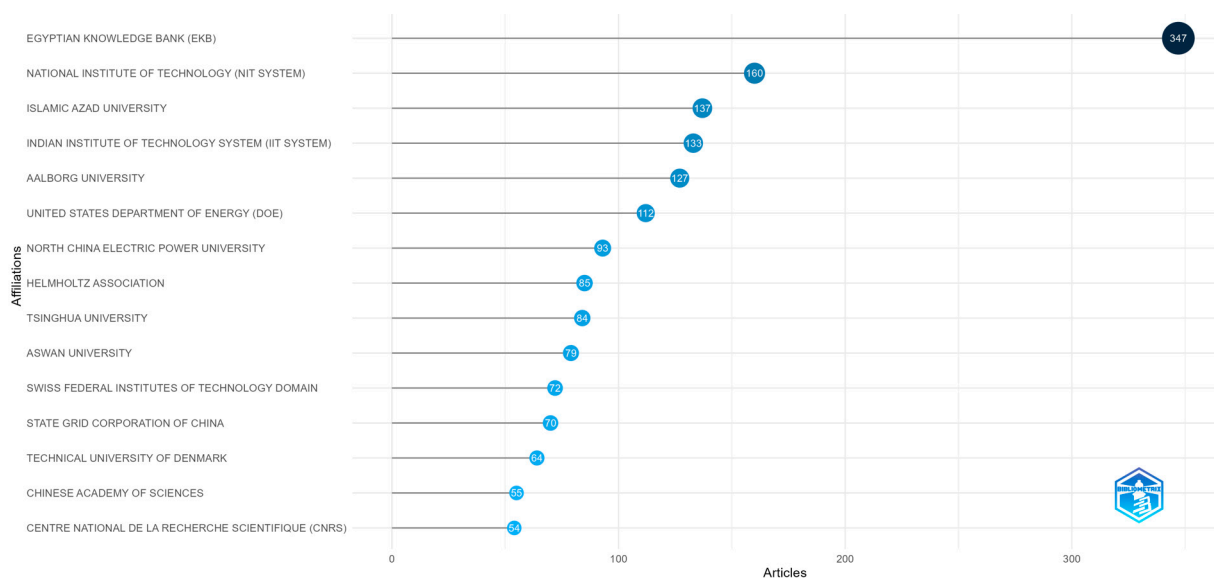


Figure 10. Top 15 Most Relevant Affiliations.

In Figure 11, the distribution of articles by the corresponding authors' countries provides insights into the global landscape of research in renewable energy and modeling and simulation. The data reveal a significant concentration of research output from specific countries, highlighting their contribution to the field. China leads with 851 articles, accounting for 15.5% of the total. Of these, 557 are single-country publications (SCPs), and 294 are multi-country publications (MCPs), representing 34.5% of China's total publications. This indicates a substantial level of international collaboration in China's research efforts. India follows with 524 articles (9.5%), with a higher proportion of SCPs (449) compared to MCPs (75), showing that most research is conducted domestically with limited international cooperation (14.3% MCPs). The USA is the third largest contributor with 368 articles (6.7%). The country has a significant number of MCPs (112), which is 30.4% of its total publications, reflecting strong international research partnerships. Iran and Germany also show substantial research activity with 289 (5.3%) and 251 (4.6%) articles, respectively. Iran has 28.4% MCPs, while Germany has 25.9% MCPs, indicating moderate levels of international collaboration. Italy and the United Kingdom both contribute notably with 237 (4.3%) and 223 (4.1%) articles. The UK, in particular, has a high percentage of MCPs (40.8%), suggesting robust international research networks. Korea and Egypt are also significant contributors, with Egypt showing a remarkably high MCP percentage (63.3%), indicating a strong tendency towards international collaboration. Other notable countries

include Canada (123 articles, 36.6% MCPs), Australia (113 articles, 34.5% MCPs), and Japan (102 articles, 37.3% MCPs), all demonstrating significant research output and international cooperation. Smaller contributors such as Malaysia, Pakistan, and Colombia show high MCP percentages (56.9%, 58.5%, and 56.7%, respectively), highlighting their reliance on international partnerships to advance research in renewable energy.

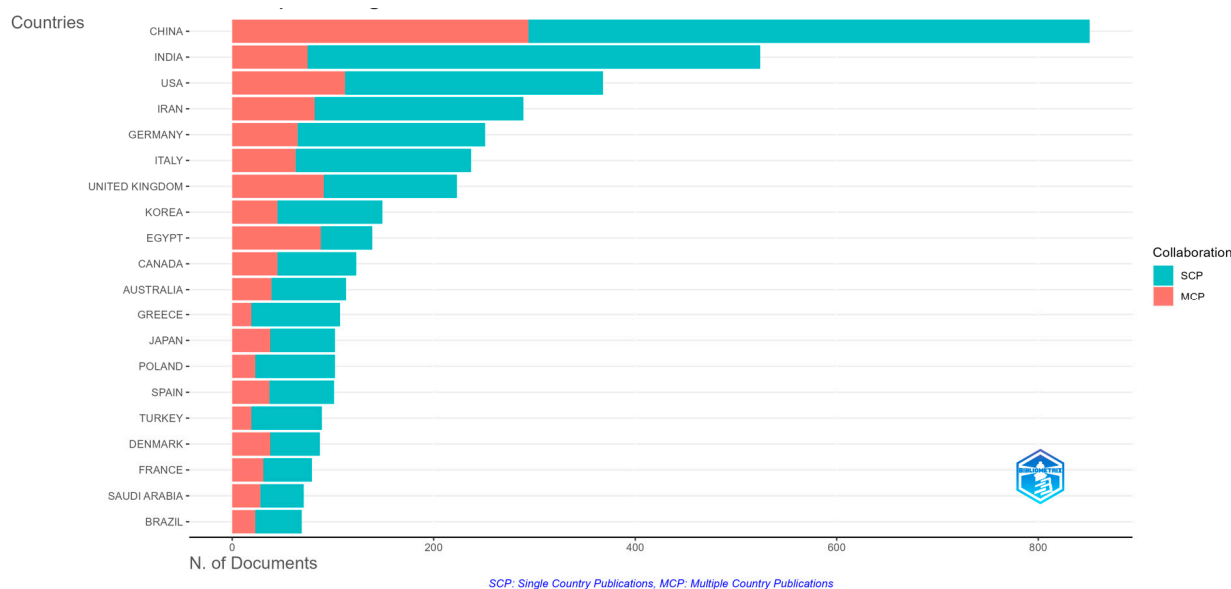


Figure 11. Corresponding Author's Countries.

In summary, the data illustrate that, while countries such as China and India have a high domestic research output, countries like the UK, Egypt, and several smaller nations significantly engage in international collaborations, enhancing the global exchange of knowledge and technological advancements in renewable energy and related fields.

The analysis of the reference spectroscopy from Figure 12 indicates a significant evolution in the number of citations over the years, reflecting the growing importance and utilization of spectroscopy in research. Starting from a modest 208 citations in 1979, there is a steady and notable increase in citations over the following decades, with some fluctuations. Throughout the 1980s and early 1990s, the citations increased gradually, demonstrating a rising interest in and application of spectroscopy. For instance, the citations rose from 208 in 1979 to 626 in 1992, with some years showing more substantial increases, such as 1989 with 486 citations (an increase of 190 compared to the median) and 1994 with 892 citations (an increase of 266 compared to the median). The late 1990s and early 2000s mark a significant surge in citations, indicating a rapid expansion of the field. Notably, the year 2000 saw a leap to 1706 citations, a substantial increase of 535 compared to the previous median. This trend continued with remarkable growth, reaching 2767 citations in 2004 and peaking at 4841 citations in 2007. This period reflects an era of heightened research activity and breakthroughs in spectroscopy. The subsequent years saw continued growth, with 6701 citations in 2009 and an impressive peak of 9617 citations in 2011. This period marks the zenith of citation activity, highlighting the peak influence and application of spectroscopy in various research domains. However, post-2011, there is a gradual decline in citations. By 2019, the citations had decreased to 16,544, followed by a more pronounced drop in the following years. The citations fell sharply to 12,258 in 2021 and plummeted to 7259 in 2022. The trend continued downward, reaching a low of 1775 citations in 2023. This decline could be attributed to various factors, such as the emergence of newer technologies, shifts in research focus, or changes in publication and citation practices. Overall, the graph depicts the rise and fall of reference spectroscopy's prominence in research, showcasing its peak periods of influence and subsequent decline in recent years.

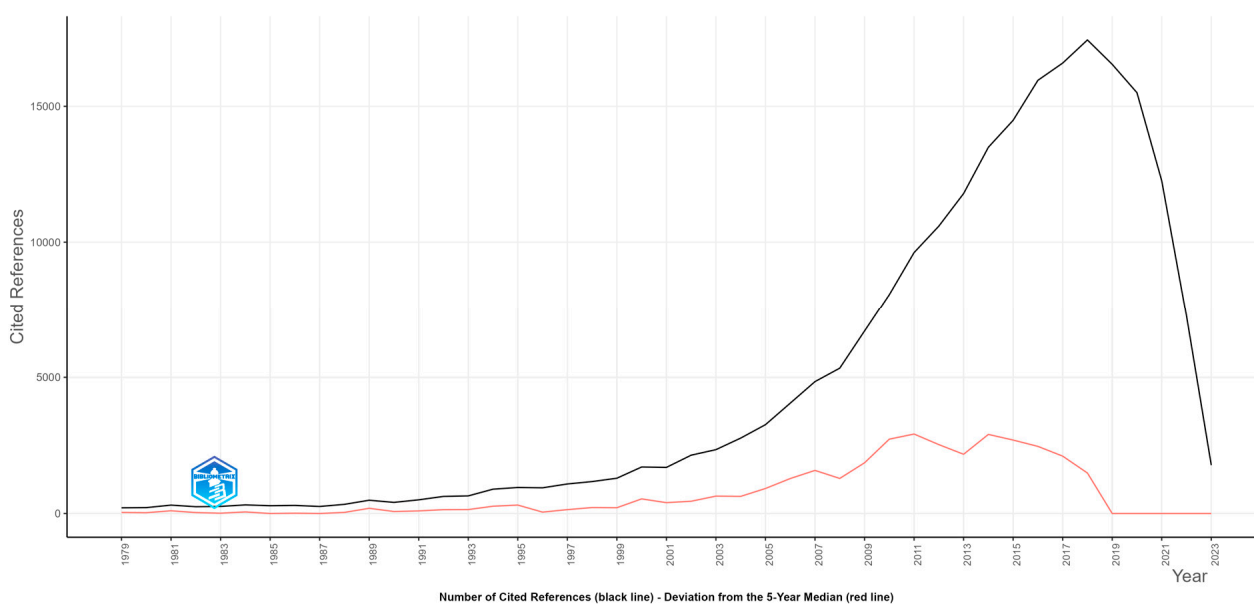


Figure 12. Reference Spectroscopy.

The word cloud depicted in Figure 13 provides a visual representation of the most frequently occurring keywords in the context of renewable energy simulation and modeling research. The prominence of certain terms reflects the major themes and focus areas within this field. “Optimization” emerges as the most frequently used keyword, indicating a significant focus on improving and fine-tuning various aspects of renewable energy systems. This includes optimizing the performance, efficiency, and cost-effectiveness of energy systems, which is crucial for enhancing the viability and sustainability of renewable energy solutions. “Design” and “system” are also highly prevalent, highlighting the importance of system design and integration in renewable energy research. The design phase is critical for developing robust and efficient renewable energy systems that can meet the growing energy demands while maintaining sustainability. The keywords “model” and “systems” underscore the role of modeling and simulation in understanding and predicting the behavior of complex renewable energy systems. These models are essential for planning, testing, and validating new technologies and strategies before their practical implementation. “Generation”, “management”, and “power” indicate a strong focus on the generation and management of renewable energy. The effective management of power generation, including the integration of various renewable sources like wind and solar, is vital for ensuring a stable and reliable energy supply. “Storage” and “energy” are key components, reflecting the ongoing research into energy storage solutions, such as batteries and other technologies, which are essential for balancing supply and demand in renewable energy systems.

The keywords “wind”, “performance”, “operation”, and “renewable energy” further highlight the specific areas of interest within the field. Wind energy, in particular, is a major focus, as indicated by the significant frequency of related terms. Performance and operation optimization are critical for maximizing the efficiency and effectiveness of renewable energy systems. “Simulation”, another frequently mentioned keyword, is fundamental to this research area, enabling researchers to create virtual models of energy systems to test and refine various approaches without the need for costly real-world trials.

Other notable terms include “algorithm”, “integration”, “electricity”, and “impact”, which suggest a focus on developing and implementing advanced algorithms for system control and optimization, integrating renewable energy into existing grids, and assessing the impacts of renewable energy adoption on the environment and economy.

research interests, from economic considerations and the integration of electric vehicles to the technical aspects of frequency control and distributed generation.



Figure 14. WordCloud of Author’s keywords.

Table 5 was created to present the frequency of occurrence of each keyword, offering a clearer and quantitative view of the data. This table, combined with the word clouds in Figures 13 and 14, provides a comprehensive overview of the most commonly used terms and their relevance to the scope of this study.

Table 5. Top 10 Most Used Keywords.

Keywords Plus	Occurrence	Author’s Keywords	Occurrence
Optimization	678	Renewable energy sources	876
Design	523	Renewable energy	541
System	518	Optimization	288
Model	461	Uncertainty	224
Systems	458	Microgrid	214
Generation	454	Energy policy	203
Management	378	Load modeling	197
Power	344	Energy storage	171
Storage	333	Energy management	144
Energy	329		

The clustering by coupling analysis from Figure 15 reveals significant thematic groups within the research, highlighting how certain topics are interconnected through co-citation patterns. This method uncovers the structural relationships between different research areas, providing insights into central themes and their impacts in the field of renewable energy simulation and modeling.

Cluster 1 (red), with the keywords “*optimization*” (confidence 33.3%), “*generation*” (confidence 30.5%), and “*renewable energy*” (confidence 56.2%), represents a crucial research area focused on optimizing renewable energy generation. The high frequency and centrality suggest that optimization techniques are vital for improving the efficiency and effectiveness of renewable energy systems. The significant impact score reflects the critical importance

of this cluster in advancing the field, with optimization strategies playing a central role in integrating and enhancing the performance of renewable energy technologies.

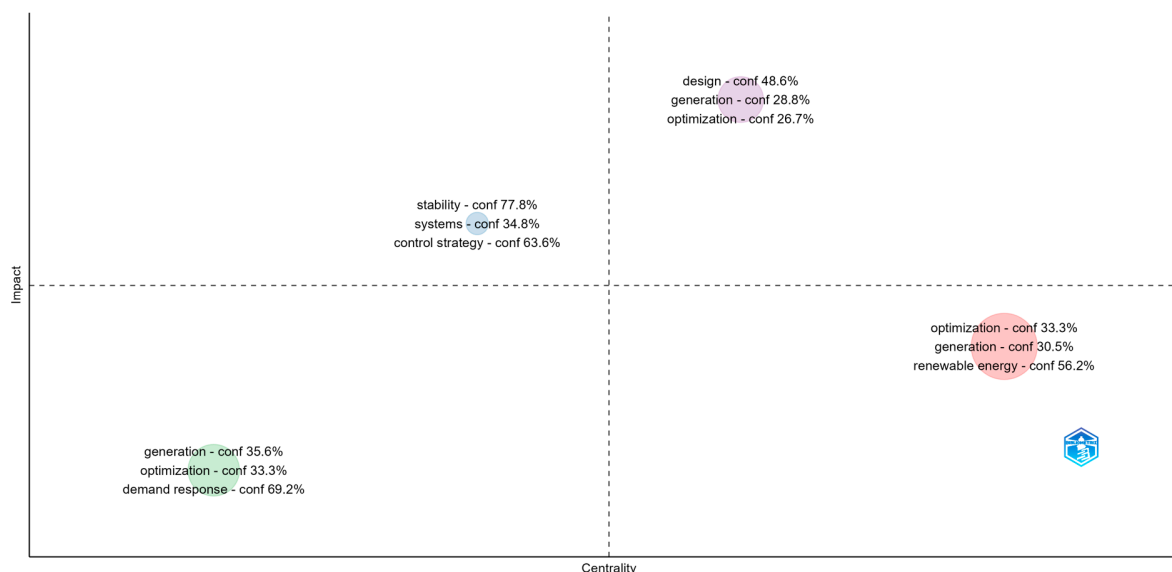


Figure 15. Clustering by Coupling.

Cluster 2 (blue), with the keywords “*stability*” (confidence 77.8%), “*systems*” (confidence 34.8%), and “*control strategy*” (confidence 63.6%), focuses on stability and control strategies within renewable energy systems. The high confidence in stability and control strategies indicates concentrated research efforts on ensuring the reliability and robustness of energy systems. The significant impact of this cluster underscores the importance of developing advanced control strategies to maintain system stability, which is essential for the safe and efficient operation of renewable energy grids.

Cluster 3 (green), with the keywords “*generation*” (confidence 35.6%), “*optimization*” (confidence 33.3%), and “*demand response*” (confidence 69.2%), links renewable energy generation with optimization and demand response strategies. The high confidence in demand response indicates a significant research focus on how energy demand can be managed to align with the supply of renewable energy. This approach is crucial for balancing the grid and ensuring the efficient use of renewable energy sources. The centrality and impact scores highlight the relevance of integrating demand response with generation and optimization techniques to improve the overall performance of renewable energy systems.

Cluster 4 (purple), with the keywords “*design*” (confidence 48.6%), “*generation*” (confidence 28.8%), and “*optimization*” (confidence 26.7%), emphasizes the design aspects of renewable energy systems, alongside generation and optimization. The high frequency and centrality suggest that efficient design is crucial for optimizing energy generation processes. The very high impact score indicates that innovative design methodologies are essential for advancing renewable energy technologies and ensuring their efficiency, scalability, and capability to meet future energy demands.

The co-occurrence network analysis from Figure 16 provides a detailed perspective of the relationships and interactions between key terms in the field of renewable energy simulation and modeling. This analysis helps to identify central themes and how they interlink, offering insights into the research’s structural organization.

Cluster 1 (red) focuses on policy and efficiency, with “*energy policy*” showing high betweenness and closeness centrality, indicating its significant role in the network. “*Energy efficiency*”, “*sustainability*”, and “*energy transition*” are also prominent, suggesting that policy and efficiency are crucial components driving research in renewable energy.

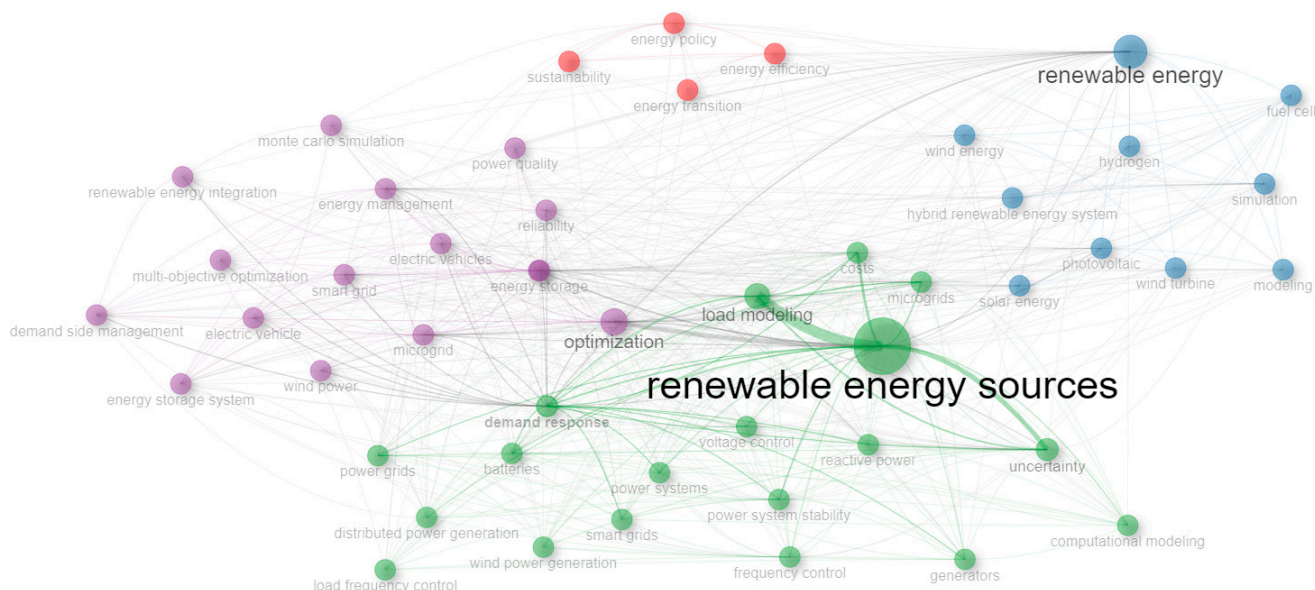


Figure 16. Co-occurrence Network.

Cluster 2 (blue) includes terms such as “renewable energy”, “simulation”, “solar energy”, “wind energy”, “photovoltaic”, and “fuel cell”. “Renewable energy” stands out with the highest betweenness centrality, highlighting its central importance in the network. This cluster emphasizes technological advancements and applications in renewable energy, focusing on simulation and specific energy types like solar and wind.

Cluster 3 (green) is characterized by keywords related to system stability and control, such as “renewable energy sources”, “uncertainty”, “load modeling”, “microgrids”, and “demand response”. “Renewable energy sources” has the highest betweenness centrality in this cluster, underscoring its foundational role in the network. This cluster highlights the importance of managing and optimizing energy systems for stability and efficiency.

Cluster 4 (purple) includes terms related to optimization and management, such as “optimization”, “microgrid”, “energy storage”, “energy management”, and “smart grid”. “Optimization” shows high betweenness and closeness centrality, indicating its critical role in improving renewable energy systems. This cluster emphasizes strategies and technologies for optimizing energy generation, storage, and management.

These clusters reflect the comprehensive and interconnected nature of research in this field, aligning with the overarching theme of using simulation and modeling to advance renewable energy technologies and systems. The analysis provides a clear picture of how different research areas are interlinked, highlighting key themes and their importance in driving the transition to sustainable energy solutions.

In Figure 17, a factorial analysis was carried out based on the authors’ keywords. The factorial analysis provides a detailed examination of how different keywords related to renewable energy research are grouped and positioned within a two-dimensional space (Dim1 and Dim2). This analysis helps to identify the underlying structure and relationships between these keywords, which can be clustered based on their similarity and relevance to each other.

Cluster 1 (red) comprises a majority of the keywords and represents the core technical and application-related terms in renewable energy research. Keywords like “optimization”, “generation”, “management”, “storage”, “renewable energy”, “wind”, and “solar” are central to this cluster. These terms are closely associated with the practical aspects of renewable energy systems, such as improving efficiency, managing energy resources, and integrating renewable technologies. The high positive values in Dim1 and varying values in Dim2 indicate their significant impact and relevance across different dimensions of renewable energy research.

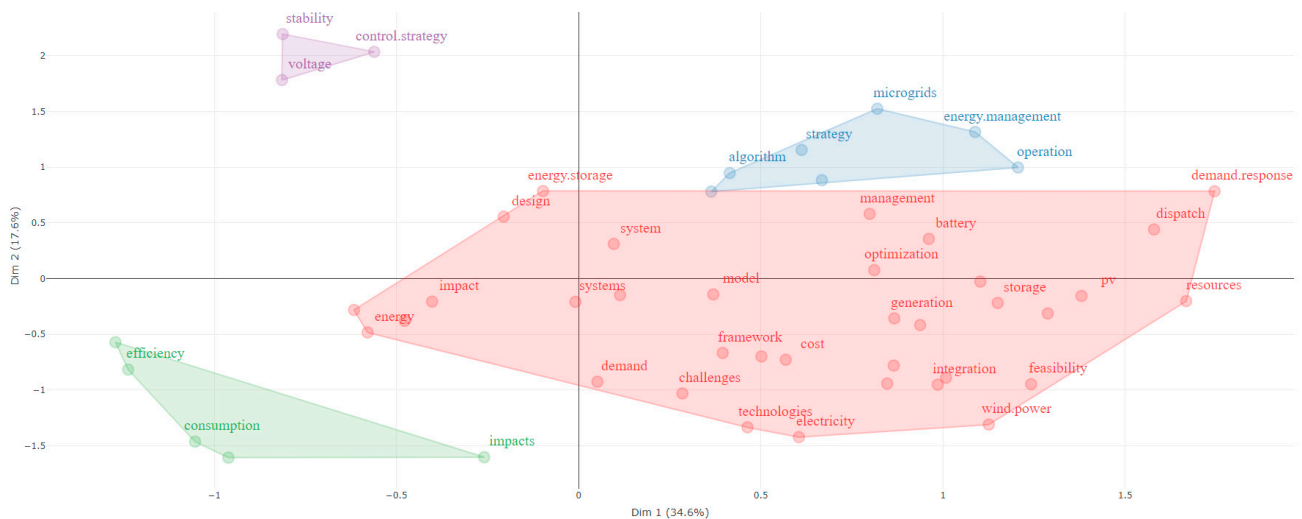


Figure 17. Factorial Analysis.

Cluster 2 (blue) includes keywords such as “operation”, “algorithm”, “strategy”, “power system”, “microgrids”, and “energy management”. These terms are more focused on the operational and strategic aspects of renewable energy systems. The presence of keywords such as “operation” and “microgrids” with high positive values in both dimensions suggests a strong focus on the practical implementation and management strategies in renewable energy.

Cluster 3 (green) contains keywords like “consumption”, “efficiency”, “impacts”, and “emissions”. These terms are related to environmental impacts, energy consumption, and efficiency. The negative values in both dimensions for most terms in this cluster indicate their distinct focus on environmental concerns and the efficiency of energy systems. This cluster highlights the importance of addressing environmental impacts and improving the efficiency of renewable energy systems.

Cluster 4 (purple) is represented by keywords such as “control strategy”, “stability”, and “voltage”. These terms are crucial for the control and stability of renewable energy systems. The high positive values in Dim2 for terms like “stability” and “control strategy” indicate their significant role in ensuring the reliable and stable operation of energy systems.

Overall, this factorial analysis provides a comprehensive view of the main themes and research directions in renewable energy simulation and modeling. It highlights the interconnected nature of technical, operational, environmental, and control aspects, all of which are essential for advancing renewable energy technologies and achieving sustainable energy solutions.

The country collaboration map from Figure 18 highlights the extensive international cooperation in renewable energy research, illustrating the interconnectedness and global nature of efforts to advance this field. Many countries are involved in extensive bilateral collaborations, indicating a strong global network. For example, the United States has collaborations with a wide range of countries including Australia, Canada, India, Japan, and the United Kingdom, among others. This demonstrates the USA’s central role in renewable energy research, facilitating knowledge exchange and innovation across continents.

Several regional partnerships are evident, reflecting geographical and possibly cultural proximities that facilitate easier collaboration. For instance, European countries such as Germany, France, and the United Kingdom show significant inter-collaboration with neighboring countries like Austria, Italy, and Spain. Similarly, Australia’s collaborations with countries in the Asia-Pacific region, including Malaysia, Japan, and New Zealand, highlight regional cooperation.

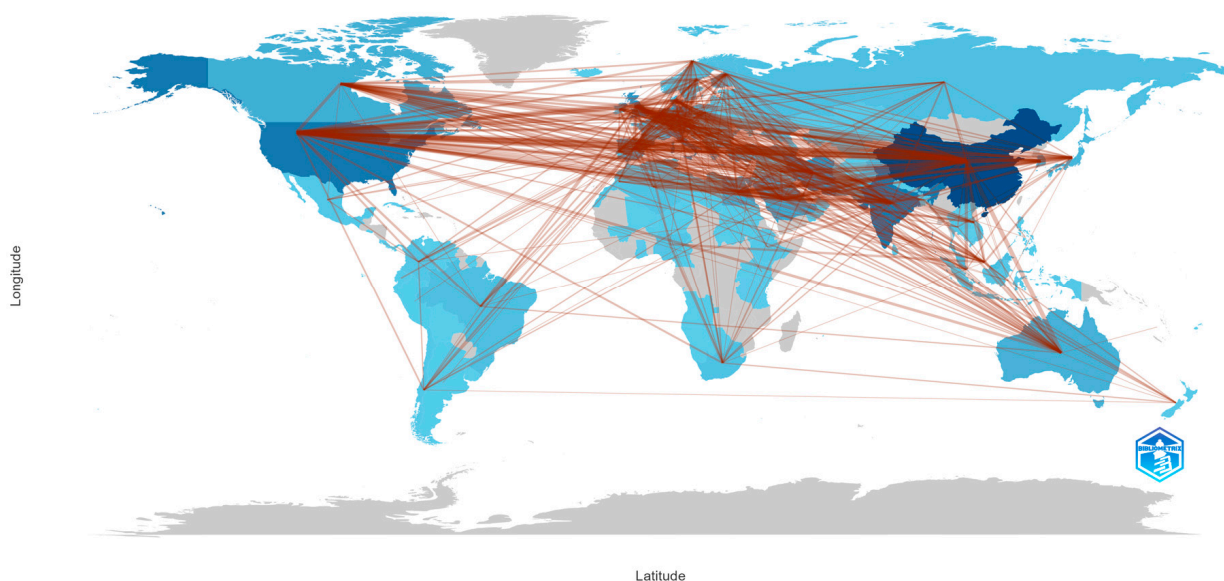


Figure 18. Country Collaboration Map.

There are notable instances of north–south collaborations, where developed countries partner with developing nations. This is crucial for technology transfer and capacity building in renewable energy sectors in the developing world. Examples include Canada’s partnerships with countries like Algeria, Jordan, and Malaysia, and China’s collaborations with Pakistan, Indonesia, and Ethiopia.

Certain countries emerge as significant hubs of collaboration, suggesting their leadership or significant roles in specific areas of renewable energy research. China, for instance, has a broad network extending to the United States, Germany, Denmark, and various countries across Asia and Africa. Similarly, Saudi Arabia shows extensive collaboration efforts with Egypt, Pakistan, and Malaysia, highlighting its role in renewable energy research within the Middle Eastern context.

These international collaborations are essential for advancing global renewable energy research. By pooling resources, expertise, and technology, these partnerships enhance research quality, foster innovation, and accelerate the development and deployment of renewable energy solutions. This global network is essential for addressing the common challenges of energy sustainability, climate change, and transitioning to cleaner energy sources.

4. Discussion

This study explored various aspects of modeling and simulation as catalysts for renewable energy. The bibliometric analysis provided valuable insights into the evolution of research in this field and identified the main sources and emerging trends. In this section, we will discuss the results obtained in the context of our research questions, highlighting their implications and relevance.

The results show that modeling and simulation are essential for understanding the behavior of renewable energy systems under the influence of climate change, variations in energy demand, and integration with other energy sources (RQ1). Relevant articles in leading journals such as *Renewable Energy* and *IEEE Transactions on Energy Conversion* have demonstrated the use of advanced simulation techniques to assess the performance and reliability of these systems. For example, the studies included in the analysis used simulations to predict the impacts of variable weather conditions on wind and solar energy production. The word clouds created herein also highlighted keywords that frequently appear in the research, such as “simulation”, “modeling”, “performance”, “operation”, and “uncertainty”. This indicates a significant focus on the use of advanced simulation techniques. The high frequency of the word “simulation” in both the keywords and authors’ keywords suggests a strong emphasis on the application of advanced simulation techniques

in renewable energy research. Also, the results of the co-occurrence network reveal essential information for RQ1. Nodes such as “simulation”, “modelling”, “renewable energy”, and “performance” being central to the network emphasizes the interconnectedness and importance of simulation in predicting system performance and reliability.

The analysis highlighted that policies and regulations play a crucial role in promoting renewable energy. Author affiliation and co-citation analysis indicated significant collaboration between academic and government institutions, highlighting the importance of well-designed policies. Countries such as China and the United States, which have a large number of international articles and collaborations, have implemented effective policies that stimulate renewable energy research and development. Also, both the word clouds and the co-occurrence network highlight essential information to answer RQ2. Terms such as “energy policy”, “renewable energy” and “sustainability” reflect an emphasis on policy and its impact on the adoption of renewable energy. Furthermore, the prominence of “energy policy” in the co-occurrence network indicates its central role in the research landscape. Also, the centrality and interconnectedness of “energy policy” with other key terms such as “renewable energy” and “sustainability” suggest that much of the research has focused on understanding and evaluating policy frameworks.

The integration of sustainability indicators in renewable energy projects is essential to ensure the long-term positive impact of these projects. The reviewed studies used various sustainability metrics to assess the efficiency and environmental impact of renewable energy projects. Terms such as “sustainability”, “energy efficiency”, “impact” and “renewable energy integration” indicate a significant interest in sustainability metrics in research. Also, the appearance of the term “sustainability” and associated terms in both the keywords and authors’ keywords suggests a strong interest in integrating these metrics into renewable energy planning. The factorial analysis carried out highlights clusters involving “sustainability”, “efficiency” and “integration of renewable energy”. They demonstrate the integration of sustainability metrics into renewable energy research.

Emerging technologies such as advanced solar cells, energy storage, and the use of hydrogen have significant potential to transform the current energy landscape. The results showed an exponential growth of interest in these technologies, evidenced by the number of published articles and their citations. For example, advanced simulations have been used to optimize the design and performance of energy storage systems, which can contribute to a greater stability and efficiency of energy networks. Nodes in the realized co-occurrence network such as “energy storage”, “solar energy”, “wind energy”, “fuel cells”, and “smart grids” being central to the network shows the interconnectedness and significance of these emerging technologies. Also, in the bibliometric analysis, several modeling and simulation tools commonly used in renewable energy research were identified. These include: ANSYS, MATLAB/Simulink, HOMER, R Studio, EViews, agent-based modeling, artificial neural networks (ANNs), and TRNSYS. These software and modeling solutions are used for dynamic systems simulation and control, economic modeling, and energy systems simulation. They enable the modeling and performance analysis of various renewable energy technologies in an integrated environment. For example, Sensfuß et al. [37] used agent-based models to simulate the impact of renewable energy sources on the electricity market in Germany, while Liu et al. [43] combined PSO and ANN methods to improve the performance of MPPT (maximum power point tracking) evaluations under partial shading conditions. Studies show a varied efficiency of these tools and models. For example, the article by Mao et al. [35] demonstrated the efficiency of mobile-edge computing systems under renewable energy conditions using a Lyapunov optimization algorithm. Other studies, such as Mengelkamp et al. [39], highlighted that local energy markets can be efficiently optimized through simulation methods and decentralized models. This suggests that, while some tools are highly efficient in certain contexts, the overall efficiency may vary depending on specific conditions and targeted applications.

The widespread deployment of renewable energy presents both significant economic benefits and challenges. The studies reviewed highlighted that the transition to renewable

energy can lead to job creation and lower long-term energy costs, and boost local economies. However, challenges include large upfront investments and managing the intermittency of renewables. The analysis of international collaborative networks suggests that partnerships and collaborations can play a crucial role in overcoming these challenges by sharing knowledge and resources. The word clouds highlighting terms such as “cost”, “economic”, “impact”, “feasibility”, “efficiency”, and “challenges” reflects the economic aspects of implementing renewable energy. The frequency of the terms “cost” and “economic” indicates a research focus on economic implications.

Studies have identified several barriers. For example, Reznik et al. [38] highlighted the difficulty of using systemic methodologies for designing LCL filters in grid-connected inverters, noting a high complexity and significant costs. Karki et al. [40] discussed the necessity for very precise wind-speed measurements, which can be challenging and expensive. Additionally, many studies mention the difficulty of obtaining precise and sufficient data for accurate and reliable simulations.

In conclusion, the results highlight the importance of using simulation and modeling technologies in renewable energy research and development. Effective policies and the integration of sustainability indicators are essential for the long-term success of these projects. Emerging technologies offer promising opportunities for transforming the energy landscape, and the economic benefits of renewable energy can outweigh the initial challenges if managed correctly. International collaborations and partnerships are crucial to advancing this vital field.

5. Conclusions

This bibliometric study is highly relevant in the current context of the global energy transition. As global society faces the challenges of climate change and the urgent need to reduce greenhouse gas emissions, the adoption and optimization of renewable energy sources is becoming essential. Advanced simulation and modeling technologies play a crucial role in the development and implementation of these power sources, enabling a detailed analysis of their performance and reliability under various conditions.

The evolution of the annual scientific output has shown an exponential growth in interest and research activity in the field of simulation and modeling for renewable energy. This trend reflects the growing recognition of the importance of these technologies in developing sustainable solutions for the global energy future. The continued increase in the number of published articles indicates a vibrant and dynamic field with significant potential for future innovations and advances.

Additionally, the analysis of the average citations per year reflected the evolution and growing impact of simulation and modeling research for renewable energy. While the beginnings were marked by variable interest and impact, the last two decades have shown a significant increase in both the number of publications and their impact. Although the average citations per year has decreased slightly in recent years, this is to be expected given the recency of the publications. Taken together, these data indicate a vibrant and expanding field with recognized and influential scientific contributions.

The three-field plot made herein highlighted the interdependencies and international collaborations in the field of renewable energy, with a special focus on optimization and sources of renewable energy. Countries such as China, the USA, and other nations play a crucial role in advancing research, contributing to a wide range of topics of interest. These interconnections reflect the interdisciplinary and global nature of research in simulation and modeling for renewable energy, underscoring the importance of international collaboration and a multifaceted approach to sustainable energy transition issues.

Regarding the analysis of specialized journals, Bradford’s law highlighted the journals *Energies*, *Energy*, and *Applied Energy* as the main sources in the field of simulation and modeling for renewable energy. These sources are fundamental to understanding current trends and future developments, providing a solid foundation for our research.

Overall, the co-occurrence network analysis herein reveals four major thematic clusters in the research on renewable energy simulation and modeling: policy and efficiency, technological advancements, system stability and control, and optimization and management.

Future research in the field of renewable energy simulation and modeling should focus on several key areas to advance the field and address the challenges associated with the global energy transition. A significant area of focus should be the integration of emerging technologies, such as advanced solar cells, energy storage systems, and hydrogen technologies, into the existing energy infrastructure. Studies should concentrate on how these technologies can be combined to maximize the efficiency and reliability of renewable energy systems. Another important research direction is investigating how climate change affects the performance and reliability of renewable energy sources. Advanced simulations and models can help anticipate these impacts and develop effective adaptation strategies to ensure the resilience of renewable energy systems in a changing climate. Integrating sustainability metrics at all stages of renewable energy projects is also essential. Future research should develop methods for evaluating sustainability to ensure that renewable energy projects have minimal environmental impacts and maximum efficiency. This involves creating comprehensive sustainability indicators that can guide the planning, implementation, and evaluation of renewable energy initiatives. The development and refinement of advanced simulation techniques is important for improving the prediction of the performance and reliability of renewable energy systems under various conditions. New optimization algorithms should be proposed and validated for the efficient management of renewable energy resources, enhancing the overall performance of these systems. Also, effective policy frameworks that promote the adoption and development of renewable energy technologies are vital for the transition to sustainable energy sources. Future research should investigate and implement policies based on data and results from simulations to facilitate a smooth and efficient energy transition. This includes exploring how different policy measures can incentivize the adoption of renewable technologies and support their integration into the energy grid. Interdisciplinary approaches should be explored to identify new opportunities for innovation at the intersection of renewable energy and other fields, such as artificial intelligence and blockchain technologies. These intersections can lead to the development of novel solutions that enhance the efficiency and effectiveness of renewable energy systems. Finally, fostering international collaboration is essential for advancing global renewable energy research. The bibliometric analysis highlighted the importance of international partnerships in enhancing research quality and innovation. Future research should continue to build on these collaborations, pooling resources, expertise, and technology to address the common challenges of energy sustainability, climate change, and the transition to cleaner and more efficient energy sources.

Another important aspect of any scientific study is recognizing its limitations to address them in future research directions. This bibliometric study focused on scientific articles, excluding other forms of research such as books, technical reports, and policy documents, which could provide additional insights. Additionally, the results reflect trends up to the time of data collection, and recent changes in the renewable energy field may require continuous updates of the analysis. Furthermore, citation analysis can be influenced by variability in citation practices and the accessibility of articles. Recent articles may have fewer citations simply because they have not had enough time to be cited. Although this study identifies global trends, there is a risk that certain conclusions may not be applicable at the local or regional level due to differences in energy policies, available resources, and specific climatic conditions.

Additionally, the results from this bibliometric study have highlighted that, starting from 2017, the focus of research in the field of renewable energy has shifted. This change appears to be influenced by the emergence of new technologies and an increased emphasis on the economic and regulatory aspects of integrating renewable energy into existing grids. We have found that recent research tends to focus more on the practical applicability of renewable energy technologies and on optimizing systems to address technological and

economic challenges. There is also a growing interest in developing predictive models to address the variability in and intermittency of renewable energy sources. The word clouds generated indicate that research in the field of renewable energy has increasingly focused on optimization, system design, management, and integration into smart grids. Moreover, the clustering through coupling analysis, as well as the co-occurrence network, reflect four major thematic groups: (i) the optimization of renewable energy generation, where optimization techniques are essential for system efficiency; (ii) stability and control strategies, emphasizing the importance of maintaining the reliability and robustness of energy systems; (iii) demand response and generation integration, focusing on managing energy demand according to the supply of renewable sources; (iv) system design and optimization, showing that innovative design methodologies are critical for advancing renewable technologies. Thus, we consider that perspectives on future trends will focus on advanced simulation and modeling technologies, which will continue to play an essential role in planning and optimizing systems, on energy policies and management strategies, which will become increasingly important for creating a supportive regulatory environment and for the widespread adoption of renewable sources, and on energy storage solutions and microgrids, which will be essential for ensuring a balance between supply and demand, as well as for enhancing the resilience and reliability of energy systems.

In conclusion, this research highlights the critical importance of using modeling and simulation technologies in optimizing and implementing renewable energy sources. In the current context of climate change and the need to reduce greenhouse gas emissions, these technologies offer valuable solutions to ensure an efficient and sustainable transition to a greener and more sustainable energy future.

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