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An Analysis of Research Trends and Knowledge Structure in the Field of Affordable and Clean Energy

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Abstract

INTRODUCTION: Energy is the foundation of all human endeavors and is intertwined with human progress. The access to sustainable energy services is a fundamental requirement for sustainable development, encompassing poverty eradication, food security, health, well-being, and education quality. Affordable and clean energy is explicitly recognized as one of the 17 sustainable development goals.
OBJECTIVE: to analyse research trends and the knowledge structure in the field of affordable and clean energy.
METHODS: This study was based on a descriptive bibliometric analysis of SDGs 7 "Affordable and Clean Energy". The Scopus database was used as a source of information, between 2012 and 2021.
RESULTS: The trend of documents on Affordable and Clean Energy reveals a steady increase in the number of published papers related to this topic, indicating a growing interest and activity in researching and disseminating information about sustainable energy. It is observed that international collaboration accounts for 21.8% of the analyzed documents, indicating a significant involvement of researchers from different countries. Engineering emerges as the leading subject area with 591,146 scholarly outputs, indicating a strong focus on technological advancements and innovation.
CONCLUSIONS: Scientific production in the field of affordable and clean energy has experienced steady growth, reflecting an increasing interest in research and development of sustainable energy solutions. However, it is important to recognize that this increase in the number of published papers has not translated into greater impact and recognition in the scientific community. Although more knowledge is being generated, its influence seems to be diminishing. Countries that participate in joint research obtain a higher number of citations, indicating the importance of establishing international linkages to maximize the visibility and impact of research.

Keywords: affordable and clean energy; bibliometric; green energy; renewable energy; innovation; trends; bibliometric analysis.

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1. Introduction

The sustainable development goals (SDGs) comprise 17 goals, accompanied by 169 long-term targets and 231 distinct indicators that address crucial sustainability issues. They also provide a roadmap for achieving these goals. In comparison to the Millennium Development Goals (MDGs), highlights three key differences in the SDGs: (1) Universalism, as the goals are meant to be implemented by all states, regardless of their economic status, as agreed upon in the 2030 Agenda; (2) The SDGs form an interconnected set of global priorities and objectives,

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recognizing their inherent interdependence; and (3) This policy framework, based on goals and targets, necessitates thorough monitoring and evaluation, which should be integrated into the implementation process.[1–4]

Energy is the foundation of all human endeavors and is intertwined with human progress. It played a crucial role in driving and expediting the initial industrial revolution over two hundred years ago, and since then, it has significantly contributed to continuous global economic growth.[5–7] Energy services, such as transportation, comfort, lighting, and electricity for devices and industries, meet essential human needs and are pervasive in industrialized societies.[8–10]

While energy production and consumption are essential for economic advancement, they also have adverse effects on the environment and human well-being, such as climate change and the rise in global temperatures caused by increased carbon dioxide emissions.[11,12] On the other hand, access to sustainable energy services is a fundamental requirement for sustainable development, encompassing poverty eradication, food security, health, well-being, and education quality.[13,14] Therefore, affordable and clean energy is explicitly recognized as one of the 17 SDGs outlined by the United Nations in 2015. [15,16]

Theoretically, the bibliometric method can be applied to any worthwhile field of research, and the method has become an important branch of information science and philology.[17,18] The application of bibliometric analysis methods includes identification of basic literature, evaluation of publications, survey of literature use, analysis of disciplinary points, determination of disciplinary boundaries, development of disciplinary development and cooperation networks of authors/institutions.[19,20]

The objective of this research is to analyze research trends and the knowledge structure in the field of affordable and clean energy, in order to identify the main research topics, emerging areas of focus, and interdisciplinary connections within the field.

2. Methods

This study was based on a descriptive bibliometric analysis of SDGs 7 "Affordable and Clean Energy". The Scopus database was used as a source of information.

The bibliometric review is based on the use of various approaches for the characterization of quantitative, qualitative and structural changes in scientific research and the profile of publications in a selected thematic area. The main classification factors of publications used by bibliometrics are journals, authors, institutions, countries, keywords and references.[21–23]

For document retrieval, an advanced search was performed using the following search strategy: TITLE-ABS-KEY (({energy efficiency} OR {energy consumption} OR {energy transition} OR {clean energy technology} OR {energy equity} OR {energy justice} OR {energy poverty} OR {energy policy} OR renewable* OR {2000 Watt society} OR {smart micro-grid} OR {smart grid} OR {smart micro-grids} OR {smart micro-grids} OR {smart grids} OR {smart microgrids} OR {smart meter} OR {smart meters} OR {affordable electricity} OR {electricity consumption} OR {reliable electricity} OR {clean fuel} OR {clean fuel} OR {clean cooking fuel} OR {fuel poverty} OR energiewende OR {life-cycle assessment} OR {life-cycle assessment} OR {life-cycle assessments} OR {life cycle assessments} OR ({photochemistry} AND {renewable energy}) OR photovoltaic OR {photocatalytic water splitting} OR {hydrogen production} OR {water splitting} OR {lithium-ion batteries} OR {lithium-ion battery} OR {heat network} OR {district heat} OR {district heating} OR {residential energy consumption} OR {domestic energy consumption} OR {energy security} OR {rural electrification} OR {rural electrification} OR {energy ladder} OR {energy access} OR {energy conservation} OR {low-carbon society} OR {energy security} OR {rural electrification} OR {energy conservation} OR {low-carbon society} OR {hybrid renewable energy system} OR {hybrid renewable energy systems} OR {fuel switching} OR ({foreign development aid} AND {renewable energy}) OR {energy governance} OR ({official development assistance} AND {electricity}) OR ({energy development} AND {developing countries})) AND NOT ({wireless sensor network} OR {wireless sensor networks}))).

A time constraint was made between 2012 and 2021, with no other geographic, language or subject category limitation.

In the research design phase, we defined the research questions and selected the optimal bibliometric methods. The following research questions are posed in this paper:

- What is the structure of the research on Affordable and Clean Energy?
- What is the scientific impact of the research on Affordable and Clean Energy?
- What are the most impactful journals, category, and countries on Affordable and Clean Energy?
- What is the impact of scientific collaboration in the field of Affordable and Clean Energy?
- What is the intellectual structure in the field?
- Which are the research topics most addressed in the domain?
- What are the implications of the results in terms of technological advancement and sustainable practices in the field of Affordable and Clean Energy?

For the analysis of the results, the primary data was downloaded as the authors planned to use it for visualization in the VOSviewer software, which requires CSV or TXT files. SciVal was used as the analysis tool since it has built-in parser functions, an initial descriptive analysis was performed using these functions and then Excel was used. Tables and graphs were created to provide quantitative data. On the other hand, VOSviewer software, version 1.6.18, was used to quantitatively and visually analyze the selected publications, using co-occurrence techniques and bibliometric coupling maps.

3. Results

The trend of documents on Affordable and Clean Energy reveals a steady increase in the number of published papers related to this topic, indicating a growing interest and activity in researching and disseminating information about sustainable energy.

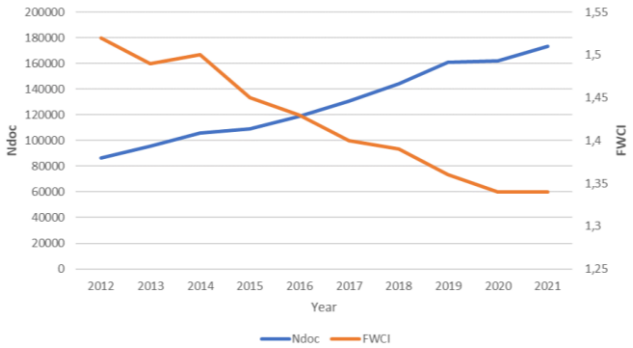

Figure 1. Bibliometric indicators by year.

However, it is important to highlight that despite the increase in document production, there is a significant decrease in the number of citations received per published paper. This suggests that although a greater amount of knowledge is being generated in the field of affordable and clean energy, its impact and recognition in the scientific community appear to be declining.

The Field-Weighted Citation Impact (FWCI) remains relatively stable over the years without showing a clear trend. This may indicate that the quality and relevance of the published papers have remained consistent. This translates to the fact that despite the growing number of documents on affordable and clean energy, it is necessary to evaluate and improve the strategies for disseminating and increasing the visibility of research to enhance its impact within the scientific community and in the pursuit of sustainable solutions for the energy sector.

There is a clear disparity in the distribution of publications among the quartiles, with a progressive decrease in the number of publications as we move towards the lower quartiles. The Q1 quartile represents 57.9% of the publications. This indicates a concentration of publications in Q1, suggesting higher research activity and scientific production in that group compared to the other quartiles. On the other hand, the Q2, Q3, and Q4 quartiles represent progressively lower percentages of the total publications, with 17.6%, 13.5%, and 11.0% of publications respectively.

Table 1. International, national and institutional collaboration.

Metric	%	Ndoc	Ncit	Cpd	FWCI
International collaboration	21.8%	280607	9536813	34	1,99
Only national collaboration	32.4%	416551	9050380	21,7	1,35
Only institutional collaboration	39.3%	506167	9308158	18,4	1,24
No collaboration	6.5%	83778	776690	9,3	0,77

When critically analyzing Table 1, it is observed that international collaboration accounts for 21.8% of the analyzed documents, indicating a significant involvement of researchers from different countries. These documents received a high total number of citations.

Exclusive national collaboration represents 32.4% of the documents, indicating that the majority of research is conducted in collaboration within the same country. However, the total number of citations per document in this category is relatively low compared to international collaboration.

Exclusive institutional collaboration represents 39.3% of the analyzed documents. Although this form of collaboration is common, the total number of citations per document is lower compared to both international and exclusive national collaboration.

The results highlight the importance of international collaboration in research in the studied field, as it is associated with a higher number of citations. However, it is also observed that both exclusive national collaboration and exclusive institutional collaboration have an impact on scientific production. It could be inferred that it is essential to seek a balance between national and international collaboration to maximize the visibility and impact of research in this field.

The 4.5% of the analyzed academic production involves collaboration between academic and corporate institutions, and these documents received approximately 19.7 times more citations. Although academic-corporate collaboration represents a relatively small percentage in the overall academic production, the resulting documents tend to receive a higher number of citations compared to those without such collaboration. These findings suggest that collaboration between academic and corporate institutions can have a positive impact on the visibility and recognition of research, which can be beneficial for scientific advancement in certain fields.

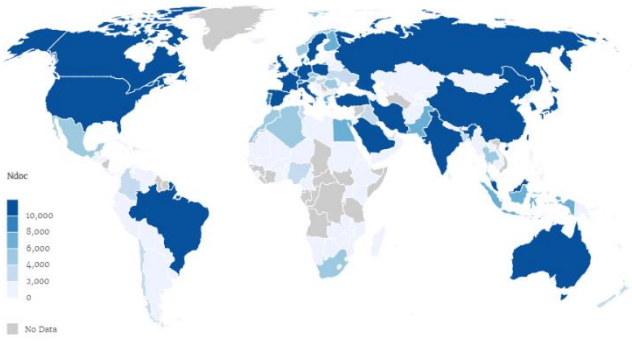

Figure 2. Distribution of documents by country.

An analysis of the number of documents on Affordable and Clean Energy by country reveals varying levels of research

activity in different regions (Figure 2 and 3). Some key findings include:

1. Leading countries: China has the highest number of documents, followed by the United States and India. These countries demonstrate a strong commitment to research in the field of affordable and clean energy.
2. Regional representation: Europe is well-represented in the list, with countries like Germany, the United Kingdom, Italy, Spain, and France appearing among the top contributors. Other regions, such as Asia (South Korea, Japan, Taiwan), North America (Canada), and the Middle East (Iran, Saudi Arabia), also make notable contributions.
3. Emerging countries: Several emerging economies, such as Brazil, Malaysia, Turkey, and South Africa, are actively engaged in research on affordable and clean energy. This highlights the global interest in sustainable energy solutions.
4. Diverse representation: Countries from various regions, including Australia, Russia, Singapore, Egypt, and Mexico, are actively involved in contributing to the research on affordable and clean energy.
5. Global participation: The list includes countries from different continents, demonstrating the worldwide importance of addressing the challenges of affordable and clean energy.

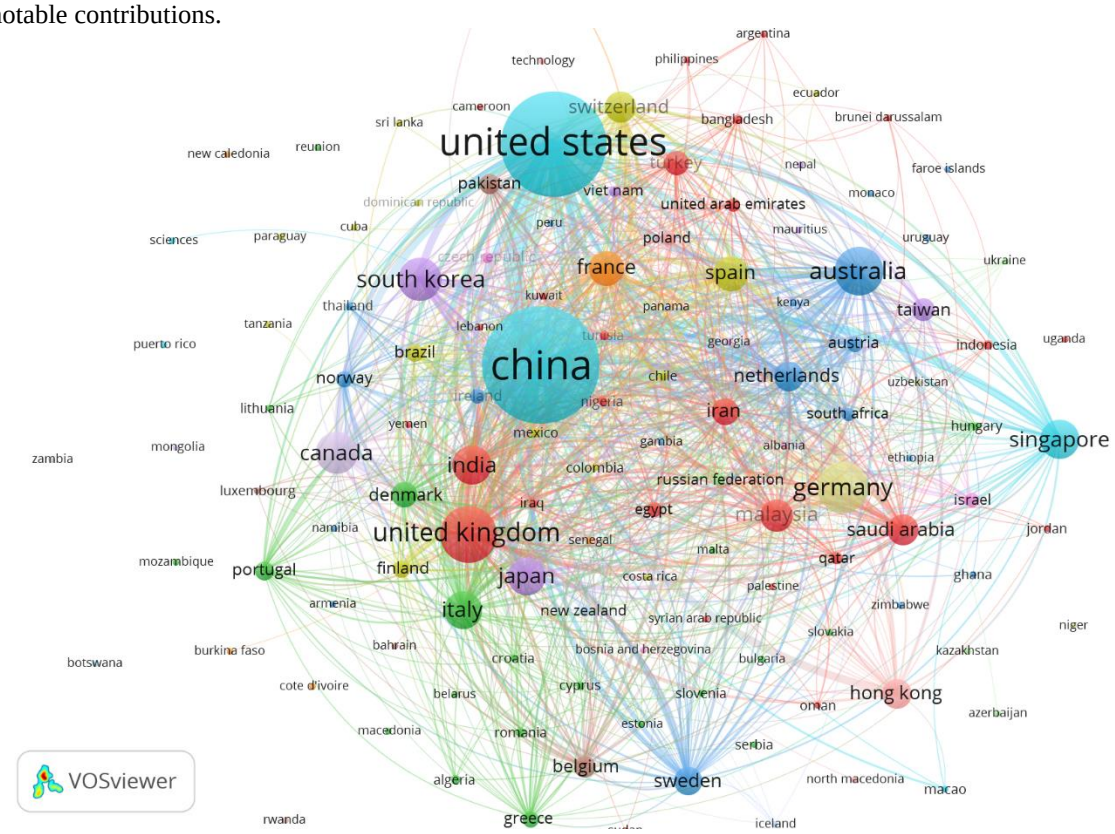

Figure 3. Collaboration networks between countries.

Four numbers were identified in the term co-occurrence analysis (Figure 4 and 5). These clusters represent key areas of research and development within the affordable and clean energy field. By analyzing the co-occurrence of terms, we gain valuable insights into the trends, priorities, and interconnectedness of different topics. This information can guide further exploration and innovation in the pursuit of sustainable and accessible energy solutions:

1. Cluster 1: Solar Energy and Hydrogen Production This cluster includes terms such as "solar cells," "solar energy," and "hydrogen production." These terms highlight the research focus on harnessing solar power and developing efficient methods for hydrogen production. The cluster indicates a significant emphasis on renewable energy sources and the exploration of solar energy as a viable and sustainable solution.
2. Cluster 2: Environmental and Economic Aspects Terms like "environmental impact," "costs," and "economic analysis" form this cluster, emphasizing the consideration of sustainability and cost-effectiveness in the development of affordable and clean energy solutions. This cluster suggests a growing awareness of the need to evaluate the environmental consequences and economic viability of different energy technologies.
3. Cluster 3: Energy Efficiency and Renewable Resources This cluster comprises terms such as "energy efficiency," "renewable energy resources," and "energy conservation." It highlights the importance of optimizing energy

usage, promoting energy efficiency, and utilizing renewable resources. The cluster underscores the focus on sustainable practices and the transition to cleaner and more efficient energy systems.

4. Cluster 4: Lithium-ion Batteries and Electrode Materials Terms like "lithium-ion batteries," "electrodes," and "lithium compounds" form this cluster, indicating the significance of advancements in battery technology. The cluster suggests a strong focus on improving the performance and efficiency of lithium-ion batteries, as they play a crucial role in energy storage and the widespread adoption of renewable energy sources.

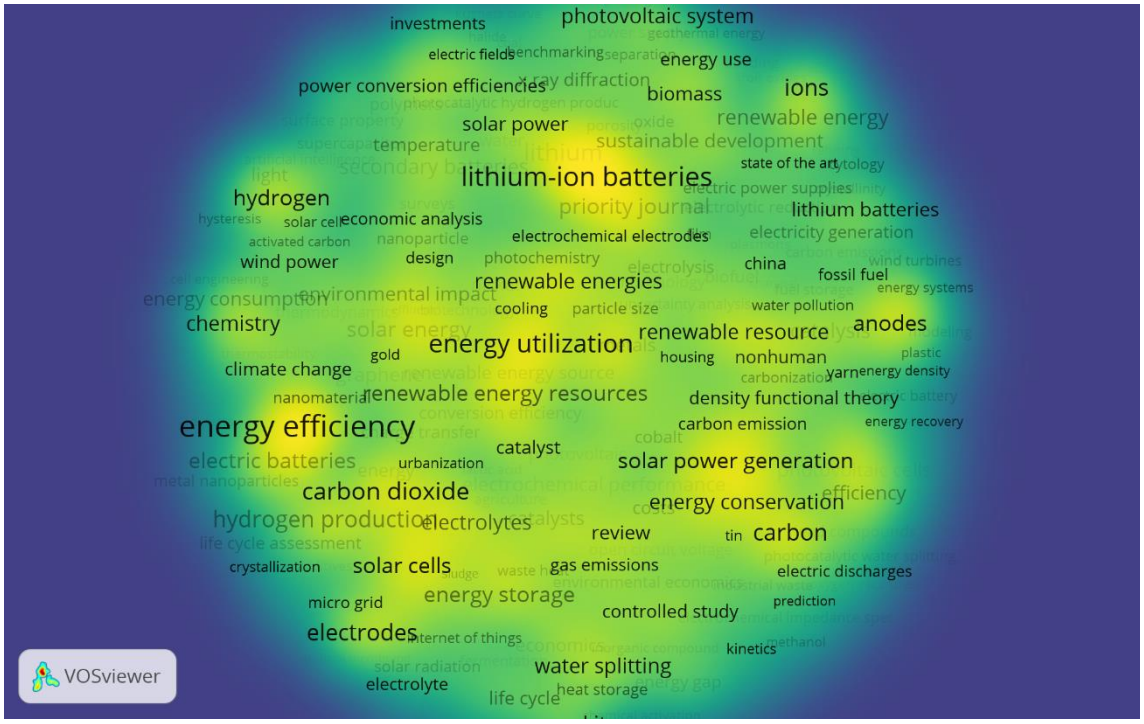

Figure 4. Density Visualization

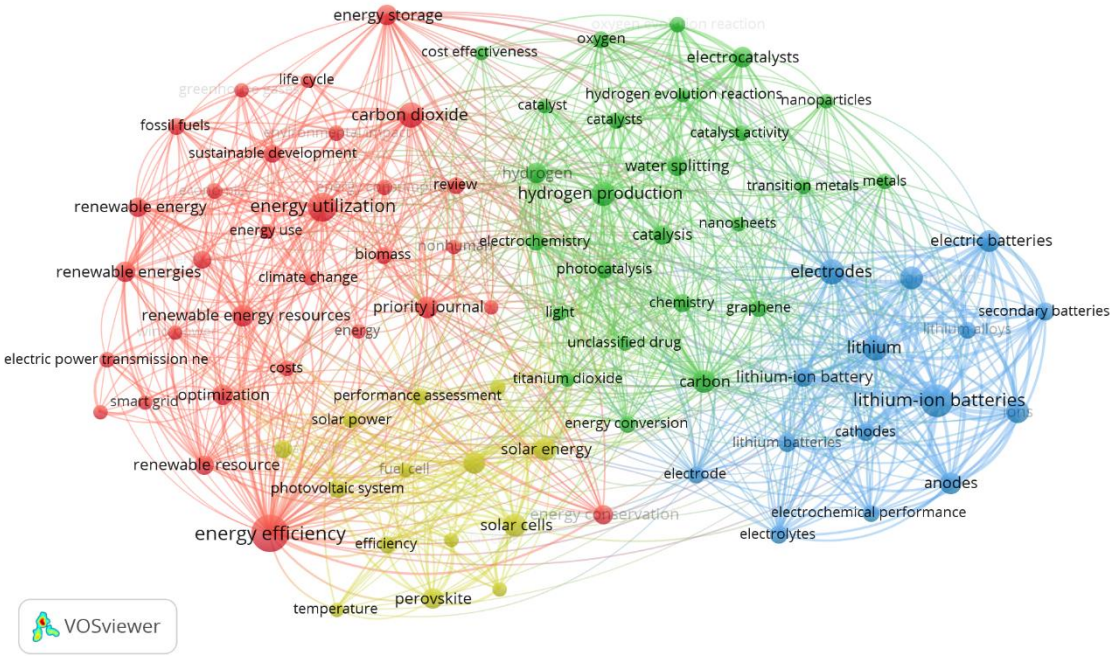

Figure 5. Network Visualization (Cooccurrence = 500).

The analysis of scholarly output across different subject areas reveals interesting patterns and insights into the distribution of research efforts (Figure 6). Engineering emerges as the leading subject area with 591,146 scholarly

outputs, indicating a strong focus on technological advancements and innovation. This is followed closely by Energy, with 432,569 outputs, which highlights the significance of research in the field of energy generation, conservation, and sustainable practices.

Materials Science and Physics and Astronomy also demonstrate substantial scholarly output, with 292,298 and 232,571 publications respectively. These subject areas are essential for the development of new materials, understanding physical phenomena, and advancing technological applications. Computer Science and Chemistry exhibit considerable scholarly output as well, with 215,679 and 209,998 publications respectively. These disciplines contribute to the advancement of computing technologies, software development, and the exploration of chemical properties and reactions.

Environmental Science, Chemical Engineering, and Mathematics also show notable scholarly output, indicating the growing importance of environmental sustainability, process optimization, and mathematical modeling in various fields. While Engineering and the natural sciences dominate the top positions, it is noteworthy that Social Sciences, Earth and Planetary Sciences, and Biochemistry, Genetics, and Molecular Biology also make significant contributions, with 45,757, 45,177, and 42,296 scholarly outputs respectively. These subject areas address social dynamics, planetary processes, and fundamental biological research.

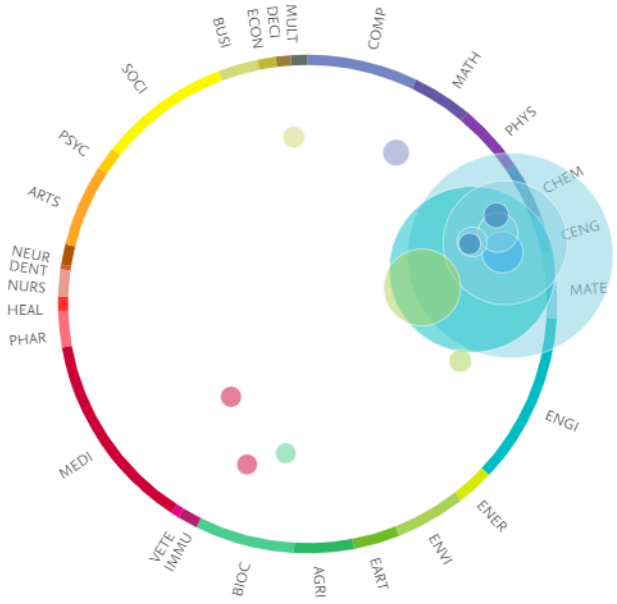

Figure 6. Distribution according to categories.

3. Discussion

A similar study, developed by García-Lillo et al. [24], with the aimed to establish the key trends and academic contributions made in the field of renewable energies and sustainable development in Web of Science. The results show that research on renewable energy and its effect on sustainable development remains insufficient in the literature. Although research on these topics is still insufficient, in recent years, research focused on the study of sustainability and renewable energy has increased exponentially. There is an increase in interest in the subject, with 2015 being the year where this growth occurs with greater intensity, with 2017 being the year that generates a turning point in the number of publications.

García-Lillo et al. [24] concludes that research trends seem to be directed towards managing the transition to a new, more sustainable energy model composed of renewable energy production systems, in addition to the adoption of new technologies to increase the efficiency of products and power transmission systems. The transition towards a new, more sustainable energy model seems to be a fundamental step to guarantee the sustainability of human action.[25–28]

On the other hand, Zhang et al. (2022) provides a comprehensive bibliometric analysis of the evolution of Artificial Intelligence in Renewable Energy (AI&RE) research from 2006 to 2022. The study is based on the Web of Science Core Collection Database show that China is the most productive and influential country/region, with the widest range of collaborative partners. The study reveals that AI-related technologies can effectively solve issues related to integrating renewable energy with the power system, such as solar and wind forecasting, power system frequency analysis and control, and transient stability assessment. In addition, future research trends are discussed.[29]

Hache y Palle (2019) [30] provides insights into the integration of variable renewable energy sources (RES) into power networks. It identifies potential research leads and unresolved challenges regarding technical aspects, markets and financing issues, and social aspects. The paper advocates the need for a systemic vision, for both research and policymakers that goes beyond the sole power system. The results of this paper can be useful for policymakers, researchers, and industry professionals who are interested in renewable energy integration and can help them to understand the current state of research and identify potential areas for future research.[31,32]

The analysis of quartiles reveals an unequal distribution of publications, with a significant concentration in the Q1 quartile, representing the top 25%. This quartile shows higher research activity and scientific production compared to the lower quartiles. As we move towards the lower quartiles, there is a progressive decrease in the number of publications. This pattern suggests a potential disparity in resources and attention dedicated to research in the studied field.[33] It is crucial to promote a more balanced approach to foster research and scientific production across all quartiles and achieve broader and sustainable advancement.[34,35]

Mukoro et al. (2022) [36] highlights the need for research in this area to integrate environmental sustainability for a more holistic approach to informing decision-making. The paper provides insights into the types of business models, why they are adopted, and factors affecting their viability, which can be useful for entrepreneurs and investors in the renewable energy sector in Africa. The authors identifies

common challenges to energy access in Africa, such as unaffordability, unmet energy needs, low demand for electricity, lack of finance, business models that are unfamiliar to customers, and market immaturity, which can inform the development of policies and strategies to address these challenges.

It is important to encourage the adoption of energy-using products to increase the average consumption and revenue per user and, hence, the viability of mini-grids.[37,38]

In relation to the analysis at the level of countries and regions, we found a wide distribution of scientific production and intensity of international scientific collaborations, with a lower participation of the African region, which in some countries was nil.[39–41] It is not surprising to find that the G-20 countries are the most productive in this regard, perhaps this is determined by the greater possibility of investment not only in concrete strategies but also in research and innovation. Countries with emerging economies such as Brazil, Malaysia, Turkey, and South Africa have considerable scientific output, and extensive collaborative networks.

In this regard, Gupta y Vegelin, 2016 [16] conducting case studies to examine how the three dimensions of inclusive development can be integrated into the implementation of the SDGs. The authors suggests several future works that can be undertaken to further explore the concept of inclusive development and its application to the sustainable development goals (SDGs). These include developing indicators to measure progress on the three dimensions of inclusive development and incorporating them into the SDG monitoring framework; examining the role of power relations and governance structures in shaping the implementation of the SDGs and the achievement of inclusive development. Exploring the potential of new technologies and innovations to support the achievement of inclusive development and the SDGs; examining the implications of the COVID-19 pandemic for the achievement of inclusive development and the SDGs. These future works can help to further refine the concept of inclusive development and provide guidance for policymakers and implementers on how to achieve sustainable development in a way that is socially, ecologically, and relationally inclusive.[42]

Following the pandemic, the scientific literature has been profoundly distorted by COVID-19, which has been reported by several authors. However, in our study we did not find COVID-19 as a relevant issue. However, Shulla et al. (2021) [43] states that the COVID-19 pandemic has significant implications for the achievement of the SDGs, particularly regarding SDG3 (Health & Well-Being), SDG4 (Quality Education), SDG8 (Decent Work & Economic Growth), SDG12 (Consumption & Production), and SDG13 (Climate Action).

The pandemic has also highlighted the interdependencies between the SDGs, and additional spillover effects can be obstacles for achieving certain SDGs, such as SDG5 (Gender Equality), SDG9 (Infrastructure & Innovation), SDG10 (Reducing Inequalities), SDG11 (Sustainable Cities), and SDG17 (Partnerships for the Goals). The paper suggests that the interdependent implications and recent trends in international development related to sustainability can be a useful framework in the post-pandemic recovery period.

Shulla et al. (2021) [43] argues for a potential policy response in the form of green recovery, which can help to address the challenges and opportunities of sustainable development in the context of the COVID-19 pandemic.[44,45] Therefore that policymakers and practitioners need to develop more integrated and holistic approaches to sustainable development that take into account the interdependencies between the SDGs and the challenges and opportunities of the COVID-19 pandemic.

Limitations and future research

The results of the research conducted have several limitations. First, bibliometrics is a comprehensive and quantitative method for assessing the structure of the knowledge base, but the emphasis on quantitative information related to publications in a given area is not a substitute for review methods that qualitatively analyze the substantive content of scientific publications. Therefore, the review presented in the article is only a general overview of research on green and renewable energy innovations and thus a starting point for future in-depth research in this area. Moreover, the interpretation of the maps produced with the VOSviewer software is subjective,[46] despite this it should be noted that the co-occurrence of the author's keywords shows some similarities and links between innovation and green and renewable energy, which calls for future research with a more qualitative approach.

3. Conclusions

Scientific production in the field of affordable and clean energy has experienced steady growth, reflecting an increasing interest in research and development of sustainable energy solutions. However, it is important to recognize that this increase in the number of published papers has not translated into greater impact and recognition in the scientific community. Although more knowledge is being generated, its influence seems to be diminishing.

International collaboration has proven to be fundamental in the scientific production on affordable and clean energy. Countries that participate in joint research obtain a higher number of citations, indicating the importance of establishing international linkages to maximize the visibility and impact of research. However, national collaboration and exclusively institutional collaboration also play a relevant role in knowledge generation.

When analyzing the distribution of publications in different quartiles, a concentration of papers in the Q1 quartile is observed, suggesting greater research activity in that group. This raises the need to encourage greater diversity and equity in scientific production, promoting research in lower quartiles.

A detailed analysis of scientific output by country reveals the existence of prominent leaders, such as China, the United States and India, which show a strong commitment to sustainable energy research. However, it is encouraging to note the active participation of emerging countries, such as Brazil, Malaysia, Turkey and South Africa, which demonstrate a growing global interest in affordable and clean energy solutions.

A survey of key research areas within the field reveals a focus on solar energy, hydrogen production, consideration of environmental and economic aspects, energy efficiency, the use of renewable resources, and the development of lithium-ion batteries and electrode materials. These themes reflect a search for innovative and sustainable solutions in energy generation, storage and use.

This research is important in terms of improving the knowledge about the relationship between chain efficiency and renewable energy and especially determining the future directions in this research.

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