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SOLAR PHOTOVOLTAIC ENERGY IN FAMILY DWELLINGS: A BIBLIOMETRIC STUDY OF ISSUES EXPLORED, TRENDS, AND CHALLENGES

ENERGÍA SOLAR FOTOVOLTAICA EN VIVIENDAS FAMILIARES: ESTUDIO BIBLIOMÉTRICO DE TEMAS EXPLORADOS, TENDENCIAS Y RETOS

ENERGIA SOLAR FOTOVOLTAICA EM RESIDÊNCIAS FAMILIARES: ESTUDO BIBLIOMÉTRICO DE TEMAS EXPLORADOS, TENDÊNCIAS E DESAFIOS

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RESUMEN

Este estudio analiza la evolución científica sobre energía solar fotovoltaica en viviendas familiares mediante un análisis bibliométrico basado en Scopus y herramientas como Bibliometrix y VOSviewer. Se examinaron 414 documentos publicados entre los años 2000 y 2024, se aplicó un enfoque cuantitativo y técnicas de visualización de redes. Los hallazgos evidencian un crecimiento sostenido desde el año 2008 y un auge desde 2016, impulsado por el interés global en energías renovables. Las principales contribuciones provienen de áreas como energía, ingeniería y ciencias ambientales, consolidándose "Applied Energy" y "Energies" como revistas clave. Conceptos como "solar energy" y "energy efficiency" dominan el campo, destacándose temas motores como almacenamiento de energía e integración de redes inteligentes, y emergentes como simulaciones energéticas. Se recomienda ampliar las fuentes de datos y explorar enfoques comparativos para mejorar la comprensión de los factores que afectan la adopción de esta tecnología.

Palabras clave
energía solar, tecnología fotovoltaica, viviendas familiares, sostenibilidad

ABSTRACT

This study analyzes the scientific evolution of solar photovoltaic energy in family dwellings using a bibliometric analysis based on Scopus and tools such as Bibliometrix and VOSviewer. 414 papers published between 2000 and 2024 were reviewed, employing a quantitative approach and network visualization techniques. The findings indicate sustained growth since 2008 and a notable surge since 2016, driven by global interest in renewable energies. The main contributions come from energy, engineering, and environmental sciences, with "Applied Energy" and "Energies" consolidated as key journals. Concepts such as "solar energy" and "energy efficiency" dominate the field, with topics like energy storage and smart grid integration standing out, as well as emerging areas like energy simulations. It is recommended that data sources be expanded and comparative approaches be explored to improve the understanding of the factors influencing the adoption of this technology.

Keywords
solar energy, photovoltaic technology, family housing, sustainability

RESUMO

Este estudo analisa a evolução científica da energia solar fotovoltaica em residências familiares por meio de uma análise bibliométrica baseada no Scopus e ferramentas como Bibliometrix e VOSviewer. Foram examinados 414 documentos publicados entre os anos 2000 e 2024, aplicando-se uma abordagem quantitativa e técnicas de visualização de redes. Os resultados evidenciam um crescimento sustentado desde 2008 e um auge desde 2016, impulsionado pelo interesse global em energias renováveis. As principais contribuições provêm de áreas como energia, engenharia e ciências ambientais, com a consolidação de "Applied Energy" e "Energies" como revistas-chave. Conceitos como "energia solar" e "eficiência energética" dominam o campo, com destaque para temas catalisadores como o armazenamento de energia e a integração de redes inteligentes, e temas emergentes como as simulações energéticas. Recomenda-se ampliar as fontes de dados e explorar abordagens comparativas para melhorar a compreensão dos fatores que afetam a adoção desta tecnologia.

Palavras-chave:
energia solar, tecnologia fotovoltaica, residências familiares, sustentabilidade

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INTRODUCTION

Solar photovoltaic energy has emerged as a primary solution to address the growing demand for clean and sustainable energy worldwide. In a context marked by the transition to decarbonized economies, photovoltaic technologies have shown enormous potential to reduce greenhouse gas emissions and mitigate the effects of climate change. In particular, applications in family homes have become relevant due to their ability to promote energy self-sufficiency, optimize electricity consumption, and contribute to the economic well-being of households (Maghrabie et al., 2021; Cillari et al., 2021; Nykyri et al., 2022; Vahabi Khah et al., 2023). However, these initiatives face significant challenges related to technological limitations, high initial investment costs, and regulatory barriers that hinder mass adoption (Liu et al., 2021b; Herrando et al., 2023; Shabbir et al., 2022).

At a global level, climate and energy policies have played a crucial role in promoting solar photovoltaic energy projects in dwellings. The implementation of strategies such as energy communities and distributed generation in European Union countries has promoted the integration of photovoltaic systems in residential environments, which has achieved promising results in terms of efficiency and sustainability (Gallego-Castillo et al., 2021; D'Agostino et al., 2022; Gamaleldine & Corvacho, 2022; García-Gáfaro et al., 2022). Nevertheless, regional inequalities in terms of infrastructure and access to renewable technologies underscore the need to design approaches tailored to the local specificities and socio-economic capacities of each region (Nematchoua et al., 2021; Hu et al., 2021; Cerezo-Narváez et al., 2021; Xue et al., 2021).

The research question is posed in this context: What are the patterns and trends of the scientific approach to photovoltaic solar energy in family homes over time? This question seeks to elucidate not only the evolution of scientific production, but also the priority areas of research, the predominant methodological approaches and the factors that drive or limit progress in this field; and specifically: 1): How many studies have been published over the years?, 2) Who are the most active authors in the area?, 3) What are the most important journals related to the topic?, 4) Which areas of knowledge have been researched, 5) What is the semantic development of the phenomenon under study?, 6) What are the driving topics, perspectives, niches, and emerging themes of the phenomenon under study?, 7) What are the historical roots of the central concept or construct of the topic under study? The current literature presents a wide variety of perspectives that address aspects such as efficient energy management, storage technologies, and interactions between users and photovoltaic systems (Liu et al., 2021b; Alqahtani & Balta-Ozkan, 2021; Mascherbauer et al., 2022; Padovani et al., 2021).

In this sense, the main objective of the study is to know the patterns and trends of the scientific approach over time and also to evaluate the impact of academic sources, determine the main authors, identify the areas of knowledge from which they have been investigated, explore the most pertinent topics, evaluate methodological approaches, identify potential areas for future research, and establish the origin of the main construct of the topic to be investigated. This study is justified by the need to understand how research in solar photovoltaics for family homes has evolved, which identifies patterns, trends, and areas of opportunity for future explorations. By providing a comprehensive bibliometric analysis, it is hoped that this contribution will enhance knowledge in this field, offering valuable tools for researchers, policymakers, and professionals seeking to accelerate the transition to sustainable renewable energies.

Several studies have highlighted the impact of complementary technologies on improving the performance of photovoltaic systems. For example, Liu et al. (2021a), Bakthavatchalam et al. (2022), and Heinz and Rieberer (2021) underline the importance of energy storage using batteries and the use of hydrogen vehicles to guarantee a continuous energy supply in residential communities. Similarly, Maghrabie et al. (2021), Forrousso et al. (2024), Sadeghibakhtiar et al. (2024), and Sohani et al. (2023) highlight the innovative applications of photovoltaic systems integrated in buildings, which not only improve energy efficiency but also reduce operating costs and promote long-term sustainability. These investigations underscore the need for a multidisciplinary approach that integrates technological, economic, and social perspectives.

On the other hand, studies such as those of Gallego-Castillo et al. (2021) and Masip et al. (2023) mention that the success of solar photovoltaics in housing depends on striking an appropriate balance between political regulations and social acceptance. The establishment of autonomous energy communities and the exchange of energy between users have been key proposals to promote collaboration and reduce implementation costs. In addition, recent research highlights the need to consider future climate changes and their impact on the viability of photovoltaic systems, which reinforces the relevance of long-term strategic planning (Nematchoua et al., 2021; Neves et al., 2021).

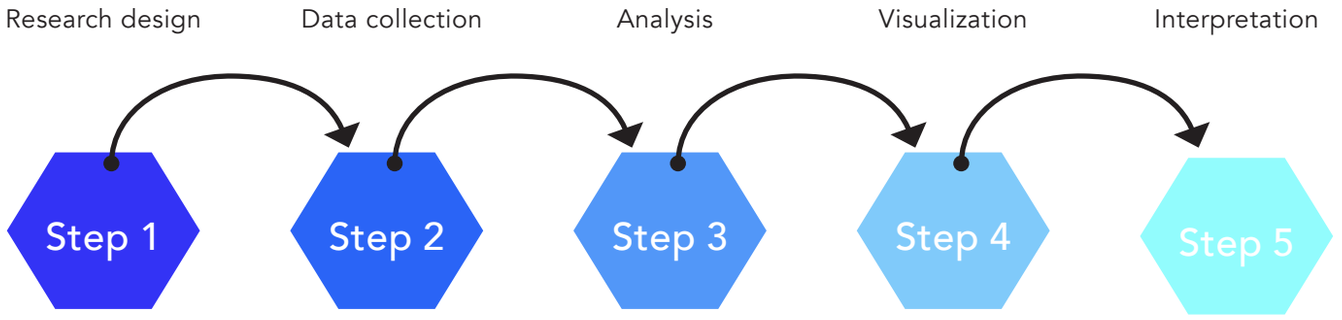


Figure 1. Steps of the proposed methodological model. Source: Prepared by the authors.

METHODOLOGY

This quantitative research is a bibliometric analysis, the same that has been used in different fields of study among researchers (Aria & Cuccurullo, 2017). The methodological model proposed by Zupic and Čater (2014) was used, which consists of five steps: i) research design; ii) collection of bibliometric data; iii) analysis; iv) visualization, and v) interpretation (Figure 1).

RESEARCH DESIGN

This research, examining photovoltaic solar energy in family homes, analyzed a series of academic articles collected up to 2024. The research design is a non-experimental longitudinal study, incorporating studies conducted since 2000. For this reason, this study offers significant perspectives that can help make well-informed decisions about solar photovoltaics and family homes in a complex and constantly evolving landscape.

COLLECTION OF BIBLIOMETRIC DATA

In this bibliometric analysis, the internationally recognized Scopus database was used, which contains approximately 28 million abstracts (Burnham, 2006), making it the most comprehensive database available. At the same time, the search parameters were determined from the information contained in the title, the abstract and the keywords of the publications, introducing several search terms related to the topic of study, such as "photovoltaic solar energy;" "solar panels;" "photovoltaic systems;" "solar power generation;" "photovoltaic technology;" "distributed solar energy"; and "family homes;" "residential homes;" "single family homes;" "family residences;" "domestic homes;" or "residential buildings". The words selected were chosen to improve accuracy, relevance, and clarity, while catering to a broad range of audiences and perspectives. They facilitate obtaining more relevant results and allow exploring various facets of solar photovoltaic energy in family homes. The initial search yielded a total of 4,656 documents spanning from 2000 to November 2024. It is worth noting that the search strategy was limited to open-access resources, as it sought to provide access to research articles.

Filters were then applied to improve the results. For this, the search was carried out in the titles for the key terms: TITLE-ABS-KEY ("Photovoltaic solar energy" OR "Solar Panels" OR "Photovoltaic systems" OR "Solar power generation" OR "Photovoltaic technology" OR "Distributed Solar Energy") AND TITLE-ABS-KEY ("Family homes" OR "Residential homes" OR "Single family homes" OR "Family residences" OR "Domestic homes" OR " Residential buildings"), which resulted in a total of 414 records relevant to this research. Additionally, the necessary bibliometric data were obtained from the Scopus platform in CSV file format, which includes all available information, such as the number of citations, authors, year of publication, journal titles, and other relevant details. This data was used in the study to obtain relevant conclusions and results.

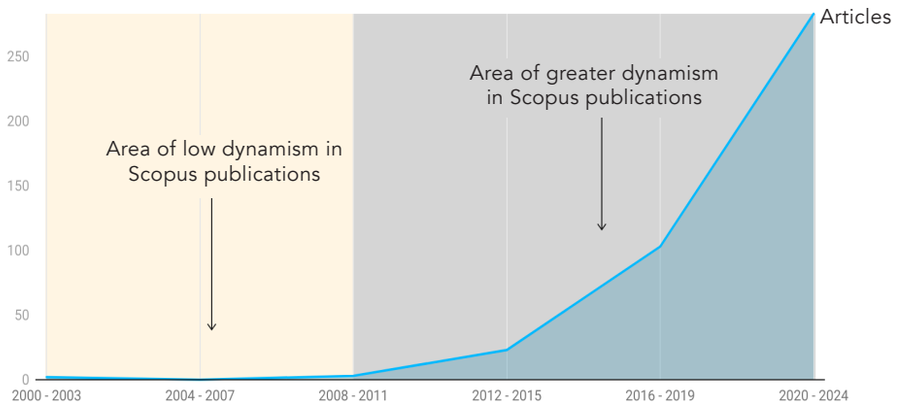
RESULTS

This section presents the results of the bibliometric analysis regarding the research questions posed, related to photovoltaic solar energy in family homes (Table 1).

Throughout the analyzed period, from 2000 to 2024, a total of 414 documents were published, according to the provided data. This number reflects the continuous effort in generating knowledge related to the subject of study. In addition, the average annual growth rate of 18.84% indicates a consistent increase in scientific production, suggesting a growing interest in the academic community to explore and address related thematic areas. The information reflects a solid research activity with a collaborative approach,

Table 1. General information. Source: Metadata was used, analyzing the indicators in Bibliometrix to 2024

Description	Results
MAIN INFORMATION ABOUT THE DATA	
Period	2000:2024
Sources (Journals, Books, etc.)	151
Documents	414
Annual growth rate %	18.84
Average age of the document	3.57
Average number of citations per document	18.19
References	16240
CONTENTS OF THE DOCUMENT	
Keywords plus (ID)	2588
Author's keywords (DE)	1302
AUTHORS	
Authors	1444
Authors of single-author documents	20
COLLABORATION BETWEEN AUTHORS	
Documents by a single author	21
Co-authors by document	3.86
International co-authorships %	27.29



Evolution of photovoltaic solar energy in family homes
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Figure 2. Changes over time in the number of publications. Source: Prepared by the authors.

as evidenced by the average of 3.86 co-authors per document and a notable proportion of international co-authors, which accounts for 27.29%. This shows a trend towards greater integration and global cooperation in the studies published during the analyzed period.

The evolution of publications related to photovoltaic solar energy in family homes shows an interesting pattern over time (Figure 2). Between 2000 and 2007, a period of low dynamism was observed, characterized by slow growth in the number of published articles. This period reflects a limited initial interest or the early stage of research in this field. From 2008 to 2015, a more sustained increase is observed, marking a transition to an area of greater dynamism. However, it is between 2016 and 2024 that an accelerated growth is experienced, reaching a significant peak in publications. This increase suggests a growing global

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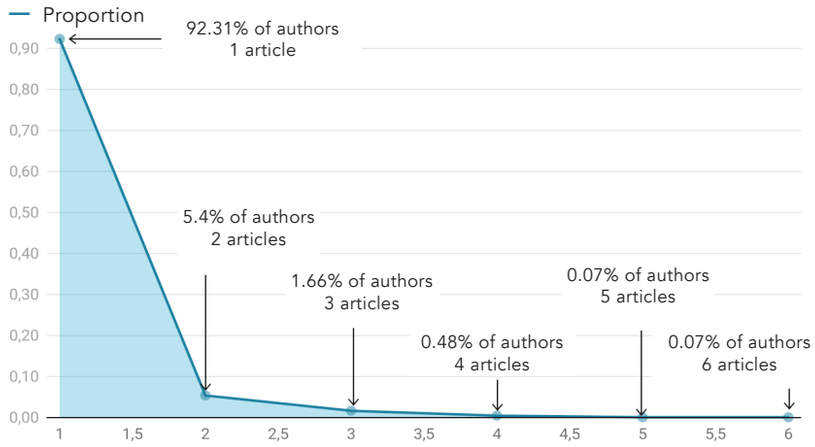


Lotka's Law. A large proportion of authors contribute one article, and only a minimal proportion contribute more than two articles
Created with Datawrapper

Figure 3. Observance of Lotka's Law Source: Prepared using metadata obtained from Scopus, indicators analyzed in Bibliometrix, and presented through Datawrapper.

Table 2. Performances of the top 10 authors in the collection. Source: Prepared using metadata obtained from Scopus, the indicators were processed in Bibliometrix.

Author	h-index	m-index	Total citations	Publications	First publication
ABDALLAH R	4	1.00	92	4	2021
ALBATAYNEH A	4	1.00	94	6	2021
ASIF M	4	0.40	164	4	2015
JUAIDI A	4	1.00	92	4	2021
MANZANO-AGUGLIARO F	4	1.00	92	4	2021
ABANDA FH	3	0.33	82	3	2016
CHRISTOFORIDIS GC	3	0.38	105	3	2017
DONG J	3	0.27	25	3	2014
ENONGENE KE	3	0.33	82	3	2016
KURUGANTI T	3	0.43	24	3	2018

Top 10 authors, measured by h and m index, since the first year of publication

interest in the topic, likely driven by heightened environmental awareness, sustainability policies, and technological advancements in solar photovoltaics. In this sense, the graph also highlights that this field of study has gained popularity in recent years, with an exponential increase in academic production between 2020 and 2024, which reflects its relevance as a critical issue within the debates on renewable energy and sustainability.

Figure 3 and Table 2 reinforce the analysis based on Lotka's Law, which states that most authors contribute with a single article, while a small percentage make multiple contributions. In this case, the distribution shows that 1,333 authors (92.31%) have published only one article, which confirms that the research effort in this field is concentrated on specific contributions. This could be due to the emerging or interdisciplinary nature of the topic, which has attracted researchers from different areas who make a single publication related to this field. Also, a significantly smaller number of authors, 78 (5.4%), have published two articles, while only 24 authors (1.66%) have contributed with three publications. This decreasing pattern continues, with only seven authors publishing four articles, and marginal figures for those who have published five or six articles, each representing 0.07% of the researchers.

This behavior suggests that, although the field of study has a broad scope in terms of participation, few researchers specialize in depth and make recurring contributions. Such a distribution not only reflects the

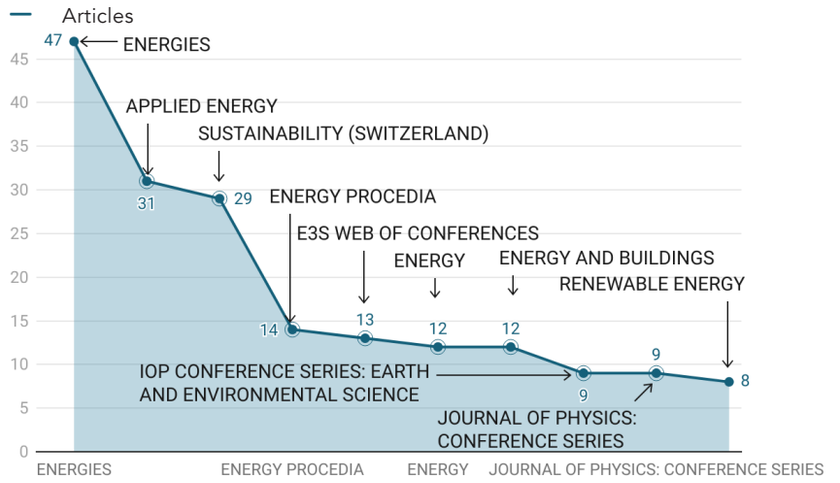


Figure 4. Observance of Bradford's Law concerning the productivity of journal publications. Source: Prepared by the Authors, using metadata obtained from Scopus, indicators analyzed in Bibliometrix, and presented through Datawrapper.

dynamic nature of the topic but also its capacity to engage researchers from diverse contexts. However, the low number of authors with multiple publications could indicate a need to consolidate research communities more dedicated to the topic, which could further enhance the accumulated knowledge and innovations in this field.

The analysis of the productivity of the top 10 authors in the field of solar photovoltaic energy for family homes, based on the h and m indices, as well as total citations and publications, evidences significant contributions within a relatively recent timeframe. Most of these authors started publishing between 2014 and 2021, reflecting that this field of study is relatively new and has gained traction in recent years. Among the authors, Albatayneh A. stands out as the most prolific, with six publications and 94 total citations, achieving an h-index of 4 and an m-index of 1.00, indicating a consistent and sustained impact since 2021. Other authors, such as Abdallah R., Juaidi A., and Manzano-Aguilaro F., also exhibit similar performance, with an h-index of 4 and an m-index of 1.00, accompanied by four publications each, all published since 2021. This group of authors represents a recent and concentrated contribution in terms of academic impact.

On the other hand, authors such as Asif M. and Dong J. have a more extensive career, having begun publishing in 2015 and 2014, respectively. Asif M. stands out with 164 citations in total, the highest number among the authors analyzed, suggesting that his publications have had a significant impact on the field. Nonetheless, his m-index of 0.40 indicates a more moderate pace of citation, considering the elapsed time. Furthermore, authors like Abanda FH and Enongene KE, with an h-index of 3 and an m-index of 0.33, have made a notable contribution with three publications each since 2016, accumulating 82 citations. Meanwhile, Dong J. and Kuruganti T. have a more limited impact in terms of total citations (25 and 24, respectively), suggesting that their influence in the field could be more specific or still in development. In general, the data reflect an expanding field, with significant contributions coming from authors who, for the most part, have begun to publish in recent years. This suggests a trend toward the growth and consolidation of knowledge about solar photovoltaic energy in family homes, driven by a group of key researchers who lead academic production.

Figure 4 illustrates the application of Bradford's Law to the productivity of journals related to solar photovoltaic energy in family homes, with a focus on journals in Zone 1, which are considered core sources. According to this law, a small number of journals concentrate the majority of publications in a specific subject area, as evident in the graph. In this case, Energies is positioned as the primary source, with 47 published articles, making it the core line of scientific dissemination in this field. Its predominance reflects its high specialization and relevance for researchers working in this area. Other journals, such as Applied Energy and Sustainability (Switzerland), are also part of this core, with 31 and 29 articles, respectively.

However, although their contribution is less than that of Energies, these journals are still essential sources, representing reliable and high-impact publishing platforms for studies related to the subject. As one moves towards the following journals on the list, such as Energy Procedia (14 articles) and E3S Web of Conferences (13 articles), productivity decreases,

Table 3. Productivity of the top 10 journals, linked to the collection. Source: Preparation by the Authors. The table was created using metadata obtained from Scopus, and the indicators were processed in Bibliometrix.

Fuente	Índice h	Índice m	Total citas	Publicaciones	Año inicio publicaciones
APPLIED ENERGY	23	2.30	1817	31	2015
ENERGIES	13	1.08	537	47	2013
SUSTAINABILITY (SWITZERLAND)	13	1.30	498	29	2015
ENERGY PROCEDIA	9	0.90	212	14	2015
ENERGY	8	0.50	281	12	2009
ENERGY AND BUILDINGS	8	0.80	270	12	2015
RENEWABLE AND SUSTAINABLE ENERGY REVIEWS	7	0.88	289	7	2017
RENEWABLE ENERGY	7	0.70	425	8	2015
ENERGY REPORTS	5	0.56	263	7	2016
IEEE ACCESS	5	0.71	159	7	2018

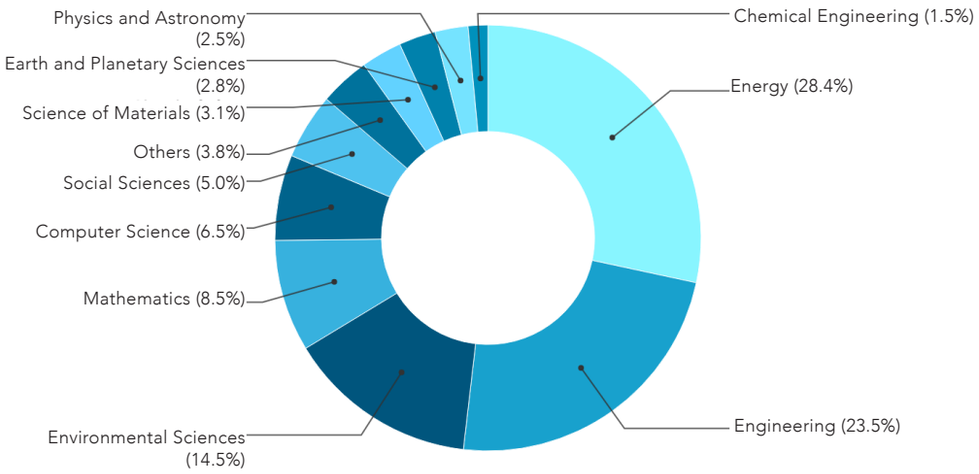
Top 10 most important journals, measured by the h and m index, since they started publication

which follows the pattern expected by Bradford's Law. These journals, although relevant, do not reach the same density of publications as the first three, but they continue to be significant within the core zone. In conclusion, the observation of Bradford's Law in this collection reaffirms that a small number of journals concentrate the majority of relevant publications. This suggests that researchers tend to prefer these core sources to maximize the visibility and impact of their work, consolidating their role as key players in the dissemination of knowledge in the field of solar photovoltaic energy.

The analysis of the productivity of the top 10 journals linked to the collection (Table 3) shows an evident heterogeneity in terms of impact and volume of publications. Applied Energy is positioned as the most influential journal, with an h-index of 23—the highest on the list—reflecting its ability to accumulate a large number of citations (1,817 in total) from 31 publications since 2015. Its m-index of 2.30 indicates a constant impact over time. On the other hand, Energies stands out for its volume, with 47 publications, the most significant number among the journals analyzed. Although it has an h-index of 13 and a total of 537 citations, this suggests a more moderate impact compared to its number of articles. Its m-index of 1.08 reflects a significant but less consistent contribution in terms of citations per year since 2013. Journals such as Sustainability (Switzerland) and Energy Procedia have h-indices of 13 and 9, respectively, with a start of publications in 2015. Although Sustainability (Switzerland) has more publications (29 vs. 14) and a higher relative impact (m-index of 1.30 vs. 0.90), both journals have proven to be important for the field.

The case of Energy is notable for being the oldest journal on the list, which started its publications in 2009. With an h-index of 8 and a total of 281 appointments, its productivity is consistent, although its m-index of 0.50 reflects a lower rate of impact accumulation. On the other hand, Renewable and Sustainable Energy Reviews and Renewable Energy have h-indices of 7. Nevertheless, the former accumulates fewer publications (7 versus 8) and a slightly lower total of citations (289 versus 425). This could indicate a more targeted specialization of the articles published in these journals. Finally, journals such as Energy Reports and IEEE Access, with h-indices of 5 each, represent sources of lower volume and age (since 2016 and 2018, respectively). However, their inclusion on this list reflects their emerging relevance to the topic. Together, these journals represent a mix of consolidated and emerging platforms that, collectively, contribute to the development and dissemination of knowledge in solar photovoltaic energy for family homes. The variability in their h and m indices, as well as the number of citations, reflects differences in scope, specialization, and impact within the field.

Figure 5 illustrates the distribution of research on photovoltaic solar energy in family homes across various areas of knowledge, reflecting its multidisciplinary nature. The most significant focus comes from the Energy area, which accounts for 28.4% of the analyzed documents. This data is consistent with the nature of the topic, since solar photovoltaic energy is a technology directly related to the energy sector, both in terms of generation and efficiency. The second highest represented area is Engineering, with 23.5% of the studies. This approach emphasizes the importance of



Documents by thematic area, which researched photovoltaic solar energy in family homes
Created with Datawrapper

Figure 5. Areas of knowledge that scientifically investigate photovoltaic solar energy in family homes. Source: Prepared by the Authors using metadata obtained from Scopus and presented through Datawrapper.

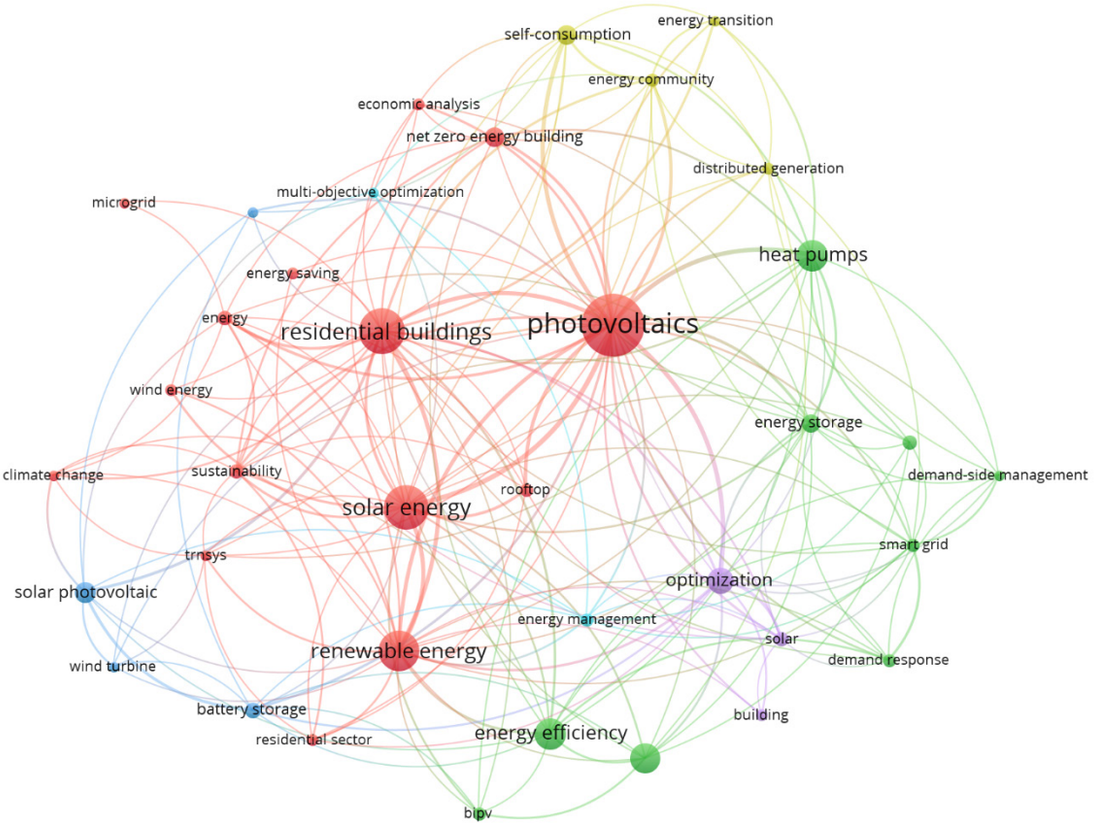


Figure 6. Diagram of a semantic network that is linked to photovoltaic solar energy in family homes. Source: Prepared by the Authors using metadata obtained from Scopus, processed in Vosviewer.

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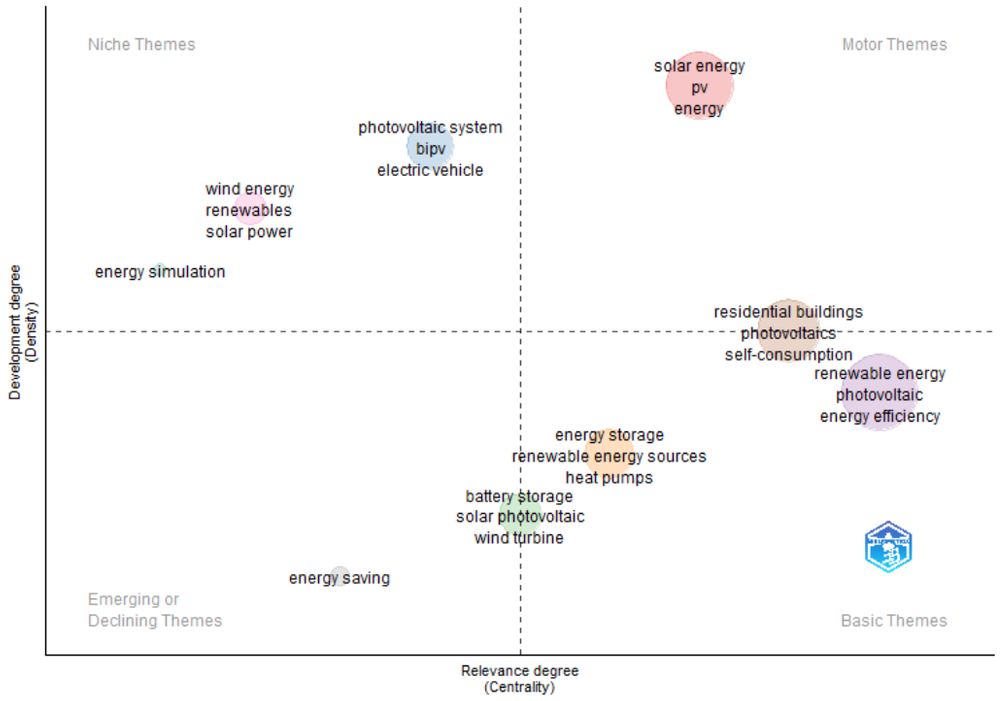


Figure 7. Thematic map. Source: Prepared by the Authors using metadata obtained from Scopus, and the indicators have been analyzed with Bibliometrix.

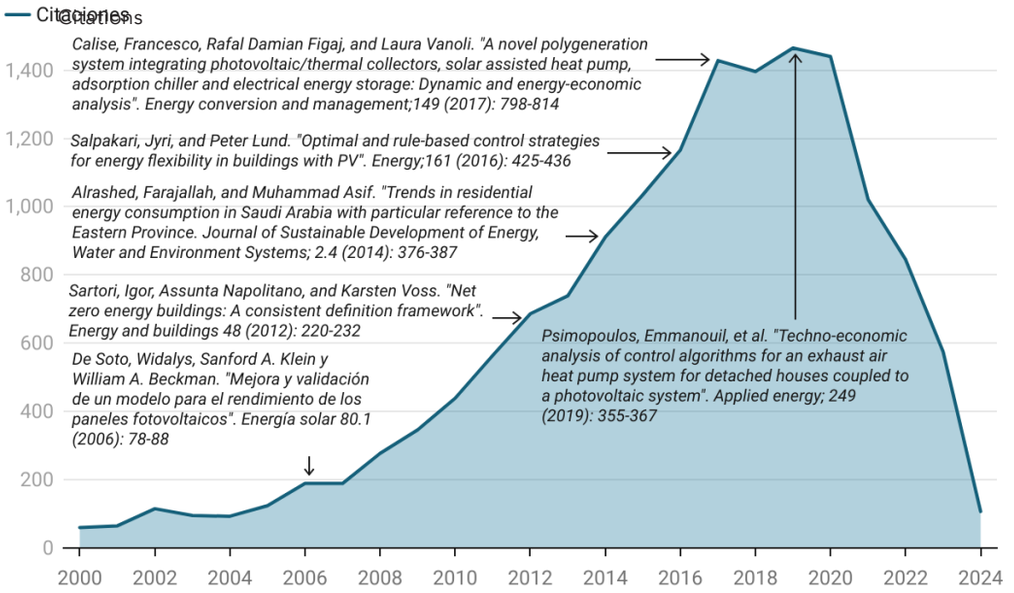
designing, implementing, and optimizing the technical aspects of photovoltaic systems, which are crucial for their effective application in family homes.

Environmental sciences occupy the third place, with 14.5% of the research. This underlines the interest in assessing the environmental impact of adopting this technology, as well as its role in the transition to more sustainable and environmentally friendly energy systems. Other areas, such as Mathematics (8.5%) and Computer science (6.5%), also have a relevant participation, which reflects the use of mathematical models and computational tools to optimize the performance of photovoltaic systems and analyze data related to their implementation. Social sciences (5%) provide a valuable perspective by considering factors such as social acceptance, user behavior, and public policies that encourage the adoption of this technology.

More specific areas, such as Materials Science (3.1%) and Earth and Planetary Sciences (2.8%), focus on the development of new materials for solar panels and the analysis of geographical and climatic conditions that influence their performance. Finally, Physics and astronomy (2.5%) and Chemical engineering (1.5%) are less represented, but their contributions are key to understanding the fundamental principles and chemical processes involved in the conversion of solar energy. In general, the diversity of knowledge areas involved evidences the complexity of the topic and its ability to attract the interest of technical, social, and environmental disciplines, which is fundamental to comprehensively address the challenges and opportunities presented by solar photovoltaic energy in family homes.

The semantic diagram presented in Figure 6 offers a detailed overview of the main thematic areas and conceptual connections related to research on photovoltaic solar energy in family homes. The clusters differentiated by colors reflect thematic groupings that represent the key trends and predominant approaches in this field of study. The central term "photovoltaics" is at the center of the diagram, with a strong connection to areas such as "residential buildings," "solar energy," and "renewable energy." This suggests that much of the research focuses on integrating photovoltaic technologies into residential buildings, with an emphasis on their role within the broader framework of transitioning to renewable energies.

The red cluster, which encompasses terms such as "residential buildings," "solar energy," and "renewable energy," indicates a predominant focus on integrating solar energy into the residential sector and its contribution to energy sustainability. The connection with terms such as "sustainability" and "climate change" underlines the environmental and social relevance of these investigations. In the green cluster, terms such as "energy efficiency," "heat pumps," and "optimization" highlight a technical focus on improving the performance and efficiency of solar photovoltaic energy systems. This group reflects the interest in optimizing both energy resources and



Evolution of the references in the field of study, cited by year of publication. Prepared using Bibliometrix.
Created with Datawrapper

Figure 8. Spectroscopy of the year of the mentioned source - Historical origins of the solar photovoltaic energy approach in family homes. Source: Prepared by the Authors, using metadata obtained from Scopus, indicators analyzed in Bibliometrix.

costs, along with the incorporation of complementary technologies such as heat pumps and smart grids. The more peripheral blue cluster encompasses terms such as "solar photovoltaic," "microgrid," and "wind energy," indicating an interdisciplinary exploration that combines various renewable energy sources and their integration into microgrids. This approach highlights the importance of energy diversity and decentralization in energy generation.

The terms "energy storage," "smart grid," and "demand-side management" suggest an emerging trend toward advanced energy management, including storage and consumption optimization. This is essential for maximizing the use of solar energy and addressing challenges such as intermittency and grid stability. In general, the semantic map evidences an expanding field of research that combines technological, environmental, and social aspects. The connections between the terms and clusters indicate a trend towards the integration of photovoltaic technologies in residential contexts, supported by advances in efficiency, storage, and energy management. Furthermore, the inclusion of terms related to sustainability and climate change underscores the global and strategic significance of these investigations.

Figure 7 provides a clear view of the research dynamics on solar photovoltaic energy in family homes, categorizing the topics by their relevance (centrality) and level of development (density). This organization allows identifying the predominant approaches, emerging research areas, and those that are in decline. Such is the case that, in the upper right quadrant, which includes the driving topics, there are concepts such as solar energy, photovoltaics, and energy efficiency. These topics are highly relevant and in development, as they indicate that they are central to research and drive progress in the field. Their position reflects their role as pillars of scientific discussion by highlighting the integration of photovoltaic technologies with energy efficiency approaches and their implementation in residential buildings.

Similarly, the lower right quadrant, which groups the basic topics, includes terms such as renewable energy, energy storage, and wind turbine. These topics are fundamental to the field, but are less developed, suggesting that they serve as a conceptual basis for future research. Their centrality suggests that they are closely connected to other topics, although they could benefit from further in-depth exploration and specialization. In the upper left quadrant, where niche topics are located, concepts such as photovoltaic systems, BIPV (Building Integrated Photovoltaics), and electric vehicles are found. These topics have a high degree of development, but low central relevance, suggesting that they are specialized areas with the potential to become broader trends if they achieve a greater connection with the central problems of the field.

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Finally, in the lower left quadrant, which represents emerging or declining issues, terms such as "energy saving" and "energy simulation" are included. Their low centrality and density suggest that these areas, although they may be relevant in specific contexts, are not currently the primary focus of research. This could indicate a decrease in interest or the need to reformulate their connection with motor subjects. In general, the thematic map reflects an evolving field, where driving topics such as energy efficiency and photovoltaic technologies lead research. In contrast, areas related to energy storage and renewable energies offer bases for new explorations. On the other hand, niche topics present opportunities for advancement in specialized areas while emerging or declining ones might require re-evaluation to maintain their relevance.

Figure 8 shows a historical evolution of citations related to key research on solar photovoltaic energy in family homes. Seminal documents that have marked milestones in the development of this field are highlighted. These studies reflect the consolidation of knowledge over time and its increasing relevance in the academic field. In this sense, the work of Calise et al. (2017) leads the citations due to its innovative approach to poly-generation systems, which include photovoltaic/thermal collectors, solar heat pumps, and energy storage. This study stands out for offering dynamic and economically viable solutions for energy management in buildings, by setting a standard for further research in optimization and sustainability.

Thus, the paper by Salpakari and Lund (2016) focuses on rule-based control strategies to improve energy flexibility in buildings with photovoltaic systems. This work has been widely cited due to its significant contribution to the development of practical and scalable approaches for integrating solar technologies into residential infrastructure. The article by Alrashed and Asif (2014), which analyzes residential energy consumption in Saudi Arabia, focuses on the challenges and opportunities for implementing renewable energy systems. Its relevance lies in providing a reference framework for the energy transition in regions with high levels of solar irradiance. The study by Sartori et al. (2012) establishes a consistent framework for defining zero-energy buildings, a key concept for moving towards more sustainable housing. This work is fundamental for the design and planning of infrastructures that minimize dependence on non-renewable energy sources.

Moreover, the work of De Soto et al. (2006) focused on the development and validation of models to evaluate the performance of photovoltaic panels. As one of the first efforts in this field, their findings have served as the basis for more advanced research in the simulation and optimization of solar systems. The article by Psimopoulos et al. (2019) performs a techno-economic analysis of control algorithms for heat pumps coupled to photovoltaic systems in single-family homes. This study combines technical and economic perspectives, highlighting its practical applicability in real-life scenarios. In other words, the upward trend of citations until 2019 reflects a growing interest and the consolidation of these investigations as essential references. The subsequent decline may indicate a transition towards new areas of focus or the emergence of more recent research that is beginning to redefine the field. These works have been fundamental pillars in the evolution of solar technologies applied to family homes, as they lay the foundations for a more sustainable energy future.

DISCUSSION

The results obtained in this research on photovoltaic solar energy in family homes reflect consistent patterns and some divergences in comparison with the previous studies cited in the analyzed literature. Regarding the leading indicators, the average annual increase of 18.84% in scientific production observed from 2000 to 2024 aligns with the global trend reported by Gallego-Castillo et al. (2021), Hamed Banirazi Motlagh et al. (2023), Mustafa et al. (2022), and Rinaldi et al. (2021). These authors also identified an exponential growth in academic interest towards sustainable systems, particularly in regions with high solar potential. However, while these studies highlight the geographical context as a key factor, the analysis carried out in the following research emphasizes the importance of greater international collaboration, with 27.29% being the main driver of this growth.

Regarding the evolution of publications, the productivity peaks since 2016 coincide with a global increase in sustainability policies and emerging technologies, as observed in Fina et al. (2021) and Wu et al. (2022). The distribution by areas of knowledge reaffirms the multidisciplinary nature of the field, with energy (28.4%) and engineering (23.5%) leading the research. This aligns with the trends identified by De Soto et al. (2006), who emphasize the integration of engineering and energy concepts in the development of photovoltaic technologies.

The principal authors, such as Abdallah R. (Albatayneh et al., 2021; Albatayneh et al., 2022; Monna et al., 2022) and identified journals, such as Applied Energy (Bayer & Pruckner, 2024; Johari et al., 2024; Ramadhani et al., 2024) and Energies (Constantinides et al., 2024; Ollas et al., 2024; Zaboli et al., 2024), stand out as key platforms, confirming the application of Bradford's Law. This finding coincides with the analysis of Sartori et al. (2012), which highlights these journals as pillars in the dissemination of knowledge. Nevertheless, differences in impact indices, such as the Energies h-index (13 vs. 23 for Applied Energy), suggest disparities in academic relevance between publication channels.

The semantic development of the topic reveals thematic clusters integrating "residential buildings" and "renewable energy", aligning with the approaches of Psimopoulos et al. (2019). This study also explores interdisciplinary connections, although in less depth, compared to the broad thematic range that our analysis highlights. The results of this study, which analyzes the patterns and trends in research on solar photovoltaic energy in family homes, find convergences and divergences with recent research. These comparisons allow us to contextualize our findings within the broader scope of the discipline and derive key implications.

First, the driving topics identified in the developed thematic map, such as "solar energy", "photovoltaics," and "energy efficiency", are aligned with the global emphasis on the integration of renewable technologies in family homes. This is consistent with the analysis of Sarker et al. (2023), which highlights the implementation of residential photovoltaic systems in Malaysia as a key strategy to reduce electricity costs and carbon emissions; similarly, the importance of energy storage to maximize the self-consumption of the energy produced is highlighted (Ali Yildirim et al., 2023). Both studies underline the role of these technologies as pillars in the energy transition. However, the findings about emerging topics, such as "energy saving" and "energy simulation", lack robust theoretical integration, which contrasts with studies such as that of Soomar et al. (2022), which explore emerging trends in photovoltaic energy optimization to address economic and environmental constraints. This highlights an opportunity to deepen these issues through more advanced methodological approaches.

In terms of technical challenges, investigations such as those by Bandaru et al. (2021), which review photovoltaic-thermal technology (PVT) in residential applications, highlight structural and financial limitations that coincide with the obstacles identified in our results. In that sense, the costs and planning of storage infrastructure and the grid are important financial and technical challenges (Nordgård-Hansen et al., 2022). These findings underscore the importance of technological innovation in overcoming critical barriers. Thus, the analysis of collaborative density in scientific production reflects the interdisciplinary nature of the field. This result is complemented by the discussion of Tawalbeh et al. (2020), who evaluate the environmental impacts of photovoltaic systems and propose sustainable designs to mitigate greenhouse gas emissions; which is related to the application of metaheuristic optimization algorithms, such as the Multi-Objective Gray Wolf Algorithm (MOGWO), to determine the optimal size of building-integrated photovoltaic systems (BIPV) and battery capacity, to minimize the Levelized Cost of Energy (LCOE) in different climates, which demonstrates the convergence of solar energy engineering with computer science and mathematical optimization (Behzadi et al., 2023). Both studies emphasize the relevance of collaborative approaches to tackling complex problems.

The convergence of these results with recent studies underscores the central role of solar photovoltaics in the transition toward sustainable residential energy models. However, the identification of divergences evidences areas that require greater academic and technical attention, which strengthens the bases for future research in this dynamic field. Finally, the historical roots of the concept align with the seminal findings of Calise et al. (2017), who established standards in the optimization and economic viability of solar systems. This analysis reinforces these antecedents by identifying a sustained growth in citations until 2019, indicating that their role is fundamental in the consolidation of the field.

The main contributions of this study include a comprehensive view of the patterns and trends in research on solar photovoltaic energy in family homes. Key areas, such as international collaboration, multidisciplinarity, and the identification of driving topics, are highlighted. These perspectives are helpful for researchers and policymakers when outlining strategies for the adoption of renewable technologies. However, the study's limitations include its reliance on a single database, which may bias the results in favor of articles indexed in Scopus. In addition, the analysis of metadata, although rigorous, could benefit from triangulation with other databases, such as Web of Science, to validate and enrich the findings. Future research could investigate the impact of emerging technologies, such as smart grids and energy storage systems, on the adoption of photovoltaic systems in homes. In addition, comparative studies between countries or regions with different degrees of technological maturity and public policies could provide additional insights into the factors that drive or limit the adoption of this technology.

CONCLUSIONS

The bibliometric analysis conducted in this research allows comprehensively answering the posed questions, providing a clear overview of the patterns and trends in research on solar photovoltaic energy in family homes. Firstly, a significant and sustained growth in scientific production has been observed since 2000, driven by an increasing focus on sustainability and the transition to clean energy sources. This trend reflects a global interest that has been particularly concentrated over the last two decades, coinciding with the advancement of photovoltaic technologies and international environmental policies.

The stand-out authors in this field present recent contributions, with the majority of their publications dating back to the last decade. This indicates that the topic is in a phase of growth and consolidation, attracting researchers from diverse contexts and disciplines. Nonetheless, most authors have a limited participation in terms of the number of publications, which could suggest a lack of sustained specialization in this specific field.

The most influential magazines, such as Energies and Applied Energy, play a central role in disseminating knowledge about solar photovoltaic energy in homes. These platforms concentrate most of the relevant publications, which reinforces the application of Bradford's Law in the field. The diversity of impact indices among these journals reflects differences in scope and specialization, which provides options for researchers with diverse approaches.

The multidisciplinary nature of the field is evident in the distribution of the areas of knowledge that address it, where energy, engineering, and environmental sciences stand out. This diversified approach allows addressing the complex technical, social, and environmental challenges posed by the implementation of photovoltaic technologies in homes. In addition, the semantic development reflects the interconnection of key terms, such as "sustainability" and "energy efficiency", with emerging perspectives integrating storage and smart grids.

Ultimately, the historical analysis reveals that seminal studies have laid a solid foundation for the field's development, particularly in areas such as system optimization and economic viability. These works have guided subsequent research, which marks milestones in the understanding and application of solar technologies in family homes. This legacy, combined with the continuous generation of knowledge, ensures the relevance of the topic in current debates on renewable energies.

Although the findings of this research are significant, some limitations should be recognized. Reliance on a single database, Scopus, can limit the breadth of analysis and exclude valuable insights from other sources. In addition, the focus on metadata leaves out more in-depth qualitative analyses that could enrich the interpretation of the results. In the future, it is recommended to expand the analysis to additional databases, such as Web of Science, to improve the representativeness and robustness of the results. Similarly, future research could focus on studying the impact of emerging technologies, such as smart grids and energy storage, in the residential context. Cross-country comparative studies would also provide unique insights into how local policies and socioeconomic conditions influence the adoption of these technologies. Together, these actions could strengthen global understanding and foster effective strategies to accelerate the transition to clean energy.

CONTRIBUTION OF AUTHORS CREDIT

Conceptualization, A.E.M.L.; Data curation, J.G.R.; Formal analysis, J.G.R.; Acquisition of financing; Research, A.E.M.L.; Methodology, J.G.R.; Project management, G.M.H.B., M.U.U; Resources, L.P.A.; Software. A.E.M.L.; Supervision, G. of the P.P.A.; Validation, J.G.R.; Visualization, G.M.H.B., M.U.U, L.P.A.; Writing - original draft, A.E.M.L.; Writing - revision and editing, J.G.R.

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