SCIENTIFIC MAPPING OF MACHINE LEARNING METHODS IN PREDICTING POWER OUTPUT OF SOLAR PHOTOVOLTAIC POWER SYSTEMS

Elisângela Pinheiro¹
Felipe Martins Muller²

ABSTRACT

Objective: This study aimed to conduct a scientometric mapping of the scientific literature on prediction models in photovoltaic solar energy generation, with a special focus on grid-connected photovoltaic systems (GCPV), aiming to provide important insights for researchers, policymakers, and professionals interested in advancing the integration of photovoltaic solar energy into the current energy distribution system.

Theoretical Framework: In this section, the main concepts and theories underpinning the research are presented, focusing on prediction models in photovoltaic solar energy generation, as well as grid-connected photovoltaic systems (GCPV).

Method: The methodology adopted comprised a bibliometric approach, analyzing publications indexed in the Scopus and Web of Science databases over the last decade, using the Biblioshiny software from RStudio.

Results and Discussion: The results revealed a significant growth in academic production, identifying key authors, leading research countries, and influential journals in the field. Central and emerging themes were also mapped, along with research gaps and opportunities in the field of photovoltaic solar energy.

Research Implications: The practical and theoretical implications of this research include insights into how the results may influence the integration of photovoltaic solar energy into the energy distribution system, impacting areas such as scientific research, policy development, and professional practice.

Originality/Value: This study contributes to the literature by offering a comprehensive mapping of research on prediction models in photovoltaic solar energy generation, highlighting gaps and opportunities to advance the field, as well as providing valuable insights for various stakeholders interested in this area.

Keywords: Photovoltaic Solar Energy, Prediction Models, Grid-Connected Photovoltaic Systems, Scientometric Mapping, Bibliometrics.

MAPEAMENTO CIENTÍFICO DE MÉTODOS DE APRENDIZADO DE MÁQUINA NA PREVISÃO DE POTÊNCIA DE SAÍDA DE SISTEMAS DE ENERGIA SOLAR FOTOVOLTAICA

RESUMO

Objetivo: Este estudo teve como objetivo realizar um mapeamento cienciométrico da literatura científica sobre modelos de previsão na geração de energia solar fotovoltaica, com ênfase nos sistemas fotovoltaicos conectados à rede (SFVCR), visando fornecer insights importantes para pesquisadores, formuladores de políticas e profissionais interessados em avançar na integração da energia solar fotovoltaica no sistema de distribuição de energia atual.

Referencial Teórico: Neste tópico, são apresentados os principais conceitos e teorias que fundamentam a pesquisa, destacando-se os modelos de previsão na geração de energia solar fotovoltaica, assim como os sistemas fotovoltaicos conectados à rede (SFVCR).

1 Universidade Federal de Santa Maria, Postgraduate Department of Production Engineering and Community University of the Chapecó Region, Santa Maria, Rio Grande do Sul, Brasil. E-mail: elisangela.pinheiro@acad.ufsm.br Orcid: https://orcid.org/0000-0003-4109-0949
2 Universidade Federal de Santa Maria, Postgraduate Department of Production Engineering, Santa Maria, Rio Grande do Sul, Brasil. E-mail: felipe@inf.ufsm.br Orcid: https://orcid.org/0000-0003-0062-5863
Método: A metodología adotada compreendeu uma abordagem bibliométrica, analisando publicações indexadas nas bases de dados Scopus e Web of Science ao longo da última década, utilizando o software Biblioshiny do RStudio.

Resultados e Discussão: Os resultados revelaram um crescimento representativo na produção acadêmica, identificando os principais autores, países líderes em pesquisa e periódicos influentes na área. Foram mapeados também os temas centrais e emergentes, assim como lacunas e oportunidades de pesquisa no campo da energia solar fotovoltaica.

Implicações da Pesquisa: As implicações práticas e teóricas deste estudo incluem insights sobre como os resultados podem influenciar a integração da energia solar fotovoltaica no sistema de distribuição de energia, impactando áreas como pesquisa científica, desenvolvimento de políticas e prática profissional.

Originalidade/Valor: Este estudo contribui para a literatura ao oferecer um mapeamento abrangente da pesquisa em modelos de previsão na geração de energia solar fotovoltaica, destacando lacunas e oportunidades para avançar no campo, além de fornecer insights valiosos para diversos públicos interesados nessa área.

Palavras-chave: Energia Solar Fotovoltaica, Modelos de Previsão, Sistemas Fotovoltaicos Conectados à Rede, Mapeamento Cienciométrico, Bibliometria.

MAPEO CIENTÍFICO DE MÉTODOS DE APRENDIZAJE AUTOMÁTICO PARA PREDECIR LA PRODUCCIÓN DE ENERGÍA DE SISTEMAS DE ENERGÍA SOLAR FOTOVOLTAICA

RESUMEN

Objetivo: Este estudio tuvo como objetivo realizar un mapeo cienciométrico de la literatura científica sobre modelos de predicción en la generación de energía solar fotovoltaica, con especial enfoque en los sistemas fotovoltaicos conectados a la red (GCPV), con el objetivo de proporcionar conocimientos importantes para investigadores, formuladores de políticas y profesionales interesados, en avanzar en la integración de la energía solar fotovoltaica en el actual sistema de distribución de energía.

Marco teórico: En esta sección se presentan los principales conceptos y teorías que sustentan la investigación, centrándose en los modelos de predicción en la generación de energía solar fotovoltaica, así como en los sistemas fotovoltaicos conectados a la red (GCPV).

Método: La metodología adoptada comprendió un enfoque bibliométrico, analizando publicaciones indexadas en las bases de datos Scopus y Web of Science durante la última década, utilizando el software Biblioshiny de RStudio.

Resultados y Discusión: Los resultados revelaron un crecimiento significativo en la producción académica, identificando autores clave, países líderes en investigación y revistas influyentes en el campo. También se mapearon temas centrales y emergentes, junto con lagunas y oportunidades de investigación en el campo de la energía solar fotovoltaica.

Implicaciones de la investigación: Las implicaciones prácticas y teóricas de esta investigación incluyen conocimientos sobre cómo los resultados pueden influir en la integración de la energía solar fotovoltaica en el sistema de distribución de energía, impactando áreas como la investigación científica, el desarrollo de políticas y la práctica profesional.

Originalidad/Valor: Este estudio contribuye a la literatura al ofrecer un mapeo completo de la investigación sobre modelos de predicción en la generación de energía solar fotovoltaica, destacando brechas y oportunidades para avanzar en el campo, además de brindar información valiosa para diversas partes interesadas en esta área.

Palabras clave: Energía Solar Fotovoltaica, Modelos de Predicción, Sistemas Fotovoltaicos Conectados a Red, Mapeo Cienciométrico, Bibliometría.
1 INTRODUCTION

In recent years, there have been significant advances in solar photovoltaic modeling and forecasting Hong et al. (2020), driven by improvements in sensor technologies, machine learning algorithms, data analysis techniques, and AI technology (Onwusinkwue et al., 2024). However, the intermittent and variable nature of solar radiation makes prediction a significant challenge. And from the techniques proposed in the scientific literature to address this issue, it is unclear which approaches are most promising, the current research trends, and the main knowledge gaps in the area. This makes it challenging to identify strategic research for future research and develop more accurate and robust prediction models.

Therefore, the research question is: **What has been the evolution of predictive models in the scientific literature to improve the integration of photovoltaic solar energy into electrical grids, considering its inherent variability and dynamics?**

Therefore, the objective of this study is to carry out a scientometric mapping of the scientific literature on photovoltaic solar energy prediction models, with the aim of mapping scientific and technological development in the area. The specific objectives are: Analyze the most used methodologies, the main authors, prominent institutions and leading research countries; Identify and analyze the main models used in the area of photovoltaic solar energy generation and Analyze the most used methodologies, the main authors, prominent institutions and leading countries in research.

2 SCIENTIOMETRIC METHODOLOGY

The research data were obtained from the Web of Science (WOS) and Scopus databases, covering the years 2014 to 2024. The search was carried out using the search keywords “photovoltaic solar energy”, “predic*” and “output power”. These portals were chosen due to the analysis resulting from the qualification criteria of magazines, periodicals and newspapers according to the criteria (QUALIS) of the Coordination for the Improvement of Higher Education Personnel CAPES (2023). Furthermore, the option to use it as the main basis for obtaining data is justified by its credible quality, given that it is made available by the official higher-level personnel information agency.

Duplicates were removed using the Bibliometrix 4.1.3 Aria package; Cuccurullo (2017) implemented in R 3.4.1 (R Core Team, 2023) and following the PRISMA statement, we filtered the articles and assessed them for eligibility according to the research topic proposed in this
study Page et al. (2021). Reviews and meta-analyses were removed from the analyses. The final dataset comprises [1310] publications, as can be seen in Figure 01.

**Figure 1**
*Flow diagram adapted from PRISMA (2020) for the centimetric evaluation of solar photovoltaic energy forecasting models*

From a total database between the Scopus and Web Of Science database of 3,012 articles, with the exclusion of 777 duplicate articles, a number of 2,235 articles remained, of which book chapter, reviewer, conference review, proceeding paper, conference paper, were excluded. Data paper, letter and outside the solar photovoltaic surplus at the end 1310, (Attached) arguably meets the ideal sample size for this analysis as specified by Rogers et al. (2020). This analysis was carried out in the RStudio software in Biblioshiny, it was possible to maintain 29 metadata in the Scopus and WOS junction. The software uses different data formats, from documents with the .csv extension and also specific formats, such as RIS and bib.

**3 RESULTS OF SCIENCIOMETRIC ANALYSIS**

The results presented here consider the direct analysis carried out using the Bibliometrix package in Biblioshiny. And also indirectly in that the works were generated in Excel® software. Considering the variables collected in each article: authors and collaborations, publication trend analysis, institutions, countries, journals, terms and keywords, citations and impact.
3.1 TEMPORAL TRENDS IN PUBLISHING

1,310 articles were found covering the area of photovoltaic solar energy. In the last decade, there has been an increasing trend in the number of publications that employ machine learning methods to predict the output power of photovoltaic solar energy systems. These data indicate a growing interest and significant evolution of research in this field over time. The reduced number is observed in 2024, this being a partial number, until the end of March 2024. The compound annual growth rate of publications on the use of machine learning methods in predicting the output power of solar energy systems photovoltaic energy between 2014 and 2024 is approximately 4.21% per year. This index confirms a sustained and continuous growth in the amount of research carried out in this area over the last decade, driven by the advancement of machine learning technologies and the growing relevance of photovoltaic solar energy as a renewable energy source. See Figure 2.

**Figure 2**

*Annual production of publications in the area of forecasts in the field of photovoltaic solar energy*

![Graph showing annual production of publications in the area of forecasts in the field of photovoltaic solar energy between 2014 and 2024.]

Source: Information generated by Biblioshiny, image generated in Excel with data obtained by searching Scopus and Web Of Science.

We identified six prominent journals in the field of photovoltaic solar energy, as illustrated in Figure 3 (Letters A and B), where we applied Bradford's Law. This law describes the distribution of citations and identifies the most cited journals (the core journals) for a field or subject, suggesting that a restricted number of journals contribute significantly to the literature published on a given topic. The Bradford distribution is represented by a semi-logarithmic graph, which organizes magazines by classes of equivalent productivity (Bradford,
1934). The H index was also calculated for the six most relevant magazines in the area of solar and renewable energy. 'Applied Energy' is ahead with an H-index of 20, indicating a strong influence in the scientific community, with many frequently cited articles. 'Energy' and 'Solar Energy' follow closely, both with an H-index of 19, reflecting their equivalent importance as sources of innovative research in the field. 'Energy Conversion and Management' and 'Renewable Energy' also show significant contributions, with H-indexes of 16 and 13, respectively, while 'Energies' records an H-index of 9, denoting an influential but more moderate presence.

**Figure 3**

*letters A and B – The most relevant magazines and their classification*

Figure 4 reinforces the continuous and differentiated growth of publications in the selected journals, indicating the growing importance of research into renewable energy from solar sources.
Figure 4

_Cumulative Growth of Publications in Selected Energy Journals (2014-2023)_

Source: Image generated by Biblioshiny with data obtained by searching Scopus and Web Of Science

3.2 AUTHORS, COLLABORATIONS AND QUOTES

Identifying key authors, their collaboration networks, and associated institutions is crucial to understanding influential research centers and how collaboration occurs globally. Notably, researcher Zhang Y stands out as a leader, with seven publications, which highlights his central position in the field. He is followed by Zhang X and Li Y, both with five contributions, highlighting his significant contemporary relevance. A consistent group of researchers, including Mekhilef S, Tan Q, and Tan Z, each with four articles demonstrates active engagement in knowledge dissemination. Other notable participants are Ju L, Karthick A, Li L, and Li Q, all contributing three articles each. Visualization using the point scale directly correlates with the volume of publications, offering an intuitive view of research dynamics and suggesting possible centers of influence and collaboration in the area. As illustrated in Figure 5 (Letters A and B), Letter C illustrates the application of Lotka's law to analyze the distribution of scientific productivity between authors (Lotka, 1926). This analysis reveals that a small group of authors produce the majority of documents, suggesting a dominant influence and leadership in the local field. These lead authors often play a crucial role in directing research and establishing collaborative networks. On the other hand, most authors contribute only a single document, indicating a more occasional participation or a specific reach in the area. This pattern highlights the role of frequent authors as pillars of knowledge and innovation, while also recognizing the diverse contribution of less frequent authors to the robustness and diversity of scientific dialogue.
Figure 5

*Letters A, B and C - Distribution of publications by authors and their productions over the years and the distribution of productivity according to Lotka's Law*

![Graph showing author productivity and distribution over years according to Lotka's Law](image)

Source: Image generated by Biblioshiny with data obtained by searching Scopus and Web Of Science

3.3 INSTITUTIONS AND COUNTRIES

North China University of Electric Power stands out as a significant leader in solar photovoltaic energy research, with 12 publications. Wuhan University follows, with 5 contributions, consolidating its position as an important knowledge hub. Imperial College London, along with other institutions such as North China University of Electric Power and Hong Kong Polytechnic University, maintain a robust presence with 4 publications each. Universities such as Oldenburg and Hefei University of Technology, as well as Jijel University, solidify the global solar energy research network with 3 articles each, highlighting the global and collaborative nature of solar energy research, with contributions from a diversity of geographic and academic contexts. See Figure 6 Letters A.

On the other hand, Figure 6 Letters B, analyzes the involvement of countries in photovoltaic solar energy research, highlighting both independent production (Single Country Publications - SCP) and international collaboration (Multiple Country Publications - MCP). China leads with a predominant presence in both SCP and MCP, highlighting its central position in international development and collaboration in this field. Italy and Algeria also make a significant contribution, but with a higher proportion of SCP, indicating a strong core of local research. The United States and Korea exhibit balanced participation between SCP and MCP, reflecting a trend toward international collaborations. This analysis shows that, although research into photovoltaic solar energy is a global industry with diverse international
contributions, some countries stand out both in terms of scientific production and collaborative partnerships.

**Figure 6**

*letters A and B: Scientific Productivity by Institution and Global Contribution in Collaboration in Photovoltaic Solar Energy Research*

![Chart illustrating scientific productivity and global collaboration in photovoltaic solar energy research.](chart.png)

Source: Image generated by Biblioshiny with data obtained by searching Scopus and Web Of Science

Figure 7, Letter A, illustrates the geographical distribution of scientific production in photovoltaic solar energy, highlighting China as global in number of publications in this field. In addition, other regions such as Europe, North America, parts of Latin America and Asia, and some countries in Africa and the Middle East also make notable contributions. Letter B demonstrates the collaboration networks of these researches, displaying global partnerships between countries. The visualized lines represent collaborations between institutions or authors from different nations, highlighting robust connections between China and the United States, as well as between China and Australia, indicating a strong cooperative relationship in research projects. Likewise, collaborations are observed between Spain and Brazil, Malaysia and Iraq, India and Saudi Arabia, and China and the United Kingdom, showing an interconnected network that spans continents. These interactions highlight the truly global nature of scientific research and the collaborative effort in the search for sustainable solutions and innovations in the field of solar energy.
Figura 7

*Letter A and B - Global distribution of scientific production in photovoltaic solar energy and its collaboration networks*

![Map of scientific production and collaboration networks in photovoltaic solar energy](image)

Source: Image generated by Biblioshiny with data obtained by searching Scopus and Web Of Science

Figure 8 illustrates China's exponential growth in the field of photovoltaic solar energy, consolidating its position as a global leader, especially with a significant increase from 2019 onwards. This prominence of China can be attributed to the intensification of its efforts in research and development, the significant expansion of solar energy infrastructure, and strong political support for clean energy. In contrast to Italy, the UK and the US exhibit more moderate but consistent growth, reflecting a continued commitment to research in the area. Similarly, Algeria follows a pattern of gradual growth, parallel to that observed in European and North American countries, demonstrating a growing commitment to the development of photovoltaic solar energy.
**Figura 8**

*Countries with the greatest scientific contribution in the area of photovoltaic solar energy*

As a result of its extensive involvement in research, China has the highest number of citations received for scientific articles related to solar photovoltaics, with a total of 3,758 citations, reflecting the substantial impact and global influence of its investigations. Algeria and the United States also stand out, with 759 and 696 citations, respectively, followed by Italy, Australia and Malaysia, each with more than 450 citations, demonstrating the international relevance of their research.

Table 1 lists the 10 most cited articles in the field of solar photovoltaic energy. Qing X.'s article, published in the magazine 'Energy' in 2018, leads with 639 citations, emphasizing its fundamental role in advancing research in the area. It is accompanied by works by Yang H.T. (2014) and Wang F. (2020), which have accumulated 399 and 362 citations, respectively, reflecting their significant contribution to the understanding and application of photovoltaic technology. Other articles, such as those by Wang K. (2019) and Jang H.S. (2016), also achieved high recognition, with more than 200 citations each, underlining the continued importance of these studies in the international scientific community.
Table 1

The 10 most cited articles in the area of photovoltaic solar energy from 2014 to 2024

<table>
<thead>
<tr>
<th>Articles</th>
<th>DOI</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qing; Niu (2018), Energy</td>
<td>10.1016/j.energy.2018.01.177</td>
<td>639</td>
</tr>
<tr>
<td>Yang et al. (2014), IEEE Trans Sustainable Energy</td>
<td>10.1109/TSTE.2014.2313600</td>
<td>399</td>
</tr>
<tr>
<td>Abdel-Nasser; Mahmoud (2019), Neural Computing Application</td>
<td>10.1007/s00521-017-3225-z</td>
<td>392</td>
</tr>
<tr>
<td>Mirzapour et al. (2019), Ambient Intell Humanized Computer</td>
<td>10.1007/s12652-017-0600-7</td>
<td>315</td>
</tr>
<tr>
<td>Jang et al. (2016), IEEE Trans Sustainable Energy</td>
<td>10.1109/TSTE.2016.2535466</td>
<td>247</td>
</tr>
<tr>
<td>Liu et al. (2015), IEEE Trans Sustent Energia</td>
<td>10.1109/TSTE.2014.2381224</td>
<td>240</td>
</tr>
<tr>
<td>Shongwe; Hanif (2015), IEEE J Fotovoltaica</td>
<td>10.1109/JPHOTOV.2015.2395137</td>
<td>233</td>
</tr>
<tr>
<td>Wu et al. (2015), APPL Energy</td>
<td>10.1016/j.apenergy.2015.03.109</td>
<td>231</td>
</tr>
</tbody>
</table>

Source: Table generated by Biblioshiny with data obtained by searching Scopus and Web Of Science

Figure 9, Letters A and B, highlights the most cited articles, along with their respective authors and established collaboration networks. In Letter A, co-authorship networks are illustrated, showing significant connections between researchers. Zhang Y stands out with 28 publications, followed by Wang J, who contributed 35 publications. Li J and Zhang J subsequently appear, each with 23 publications, demonstrating the intense collaboration and productivity of these authors in the field of solar photovoltaic energy.

Figure 9

The most cited articles in photovoltaic solar energy and their respective co-authors

Source: Image generated by Biblioshiny with data obtained by searching Scopus and Web Of Science
3.4 TERMS AND KEYWORDS

In this subchapter, we present the analysis of the keywords and most frequent terms found in the titles, abstracts and keywords of the articles. These analyzes serve to identify the subtopics and main research foci. Figure 10 highlights the most prominent terms in recent literature on solar PV and its prediction technologies. Terms such as 'solar power generation', 'photovoltaic cells' and 'energy forecasting' are particularly emphasized, indicating that they are the main focuses of research and development in the field. The presence of terms such as 'model', 'optimization' and 'prediction' reflects the priority given to improving the techniques and efficiency of solar energy forecasts. Additionally, the emphasis on 'artificial neural networks' and 'deep learning' suggests an increasing integration of advanced machine learning methods in optimizing the performance of photovoltaic systems.

**Figure 10**

*Frequency of keywords in solar energy and forecasting publications*

Source: Image generated by Biblioshiny with data obtained by searching Scopus and Web Of Science

Figure 11 displays a treemap, providing a visual representation of the most frequent keywords in articles about solar energy and photovoltaic systems. This treemap reinforces the relevance of the terms identified in the word cloud analysis. Notably, 'solar power generation' emerges as the most prominent theme, with 406 occurrences, representing 9% of the total. It is closely followed by 'solar energy' and 'photovoltaic cells', each with 6% of the total, standing out as key areas of focus in research. Terms such as 'forecasting' and 'prediction' are also significant, with 270 and 174 occurrences respectively, emphasizing the interest in forecasting and modeling within the sector. Furthermore, 'optimization', 'solar radiation' and 'performance' are frequent terms, reflecting the ongoing concern with the efficiency and effectiveness of photovoltaic systems. Concepts such as 'machine learning', 'deep learning' and 'neural networks'
are also highlighted, demonstrating the growing interface between solar energy and technological advances, each contributing approximately 1% to the academic dialogue.

**Figure 11**

*Treemap of main Keywords*

![Treemap of main Keywords](image)

Source: Image generated by Biblioshiny with data obtained by searching Scopus and Web Of Science

Analysis of solar energy research trends from 2015 to 2022 highlights the remarkable rise of the term 'deep learning'. This term has demonstrated substantial growth and reached a peak of interest in 2021, reflecting its increasing application in solar energy systems for optimization and forecasting purposes. Terms such as 'forecasting', 'solar energy' and 'solar power generation' have maintained a consistent presence over the years, reinforcing their fundamental importance in the area. Furthermore, the emergence of topics such as 'long short-term memory' and 'wind power' suggests an expansion of the scope of research to include new methodologies and renewable energy sources. The visualization not only captures the frequency of terms over time, but also illuminates the dynamics of innovation and changes in research foci within the solar energy industry.
Figure 12

*Trending Topics in Solar Energy Research (2015-2022)*

![Thematic Map of Solar Energy Research Topics](Image)

Source: Image generated by Biblioshiny with data obtained by searching Scopus and Web Of Science

Figure 13 presents a thematic map that provides a strategic analysis of the topics covered in solar photovoltaic energy research. On the map, the horizontal axis reflects the centrality or relevance of the themes, while the vertical axis indicates their density or degree of development. Fundamental themes such as 'solar power generation', 'solar energy' and 'forecasting' are located in the upper right corner, demonstrating that they are well-developed and central themes in scientometric mapping. On the other hand, themes such as 'modules' and 'accumulation' are positioned at the bottom left, signaling areas that are emerging or losing focus. Motor themes such as 'photovoltaic system' and 'wind', despite their high centrality, have relatively lower density, suggesting that they are areas that drive research in the field, but still have significant room for development."
4 FINAL CONSIDERATIONS

This study highlights a significant evolution in predictive models for the integration of photovoltaic solar energy into electrical grids, with emphasis on the increasing adoption of advanced technologies that face the variability and dynamics inherent to solar energy. Using comprehensive scientometric mapping, we identify the most impactful developments in the field, which are reflected in the methodologies, models and significant contributions of leading authors and institutions from different countries. The search covered the keywords “photovoltaic solar energy”, “predict*” and “output power” from 2014 to March 2024, providing a detailed analysis of the last decade. The results obtained highlight the increase in publications and technological innovations, as well as the importance of international cooperation for advancing research in this area. It is clear that advanced models based on machine learning, especially those using neural networks and machine learning techniques, are increasingly essential to effectively predict solar energy generation, crucial for the efficient integration of this renewable source into electrical grids. The accuracy of these models is vital to optimizing the use of solar energy, minimizing grid impacts and maximizing efficiency. The study also highlights robust international collaboration, with significant contributions from leading countries such as China, the United States and Germany. These collaborations are essential for the rapid development of innovative solutions and the dissemination of technical knowledge, facilitating the challenges of solar variability. It is recommended that future research continues to explore the development of new predictive models and the application of advanced artificial intelligence techniques.
intelligent techniques, as well as expanding international cooperation. Specific case studies could provide further insights into the effectiveness of models in different regional and technological contexts, allowing for better adaptation to local needs. It is concluded that scientometrics played a crucial role in this study, offering a detailed view of advances in research on photovoltaic solar energy. Thus, this work not only maps the state of the art, but also directs future research efforts, aiming for a more efficient and sustainable integration of solar energy into global energy infrastructures.

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