BIBLIOMETRIC ANALYSIS OF THE IMPACTS OF CLIMATE CHANGE ON PHOTOVOLTAIC ENERGY PRODUCTION

Nícolas Matheus da Fonseca Tinoco de Souza Araújo[a*,b], Raphael Abrahão[a]

[a]Federal University of Paraíba, Presidente Castelo Branco Avenue, s/n, Campus I, CEP 58051-970, João Pessoa, PB, Brazil. raphael@cear.ufpb.br
[b]Rural Federal University of Semi-Arid, Avenue Francisco Mota, 572, Central Campus, CEP 59625-900, Mossoró, RN, Brazil. nicolas.araujo@ufersa.edu.br

ARTICLE INFO

***Keywords**: scientific mapping; greenhouse effect, renewable energy, energy generation, forecasting, review.*

Received: Feb 02, 2024
Reviewed: Mar 03, 2024
Accepted: Mar 04, 2024

ABSTRACT

Higher concentrations of greenhouse gases, resulting from anthropogenic actions associated with energy generation, are one of the causes of climate change. In view of this, several efforts have been undertaken in the search for more sustainable alternatives, and photovoltaic (PV) technology has stood out among the different possibilities. However, PV generation is highly sensitive to future climate variability, which is a source of uncertainty that can complicate energy planning and compromise the viability of systems. This theme has received attention from the academic community, but some challenges to mapping and identifying the relevant literature have been encountered. Therefore, this study was conducted to analyze and identify relevant aspects of international scientific production focused on the impacts of climate change on the potential of photovoltaic production, CC-PVP, through bibliometric techniques. For this purpose, 3900 articles from the Web of Science and Scopus databases, published between 1960 and 2021, were retrieved and analyzed through a bibliometric approach, using the SciMAT v1.1.04 tool. Among the results obtained, it is worth pointing out that the CC-PVP research field has moderate maturity, and it is concentrated in the areas of energy, fuels, and technology, as well as environmental sciences and meteorology. It was concluded that key themes revolve around global energy, forecasting photovoltaic energy production, and electrical energy consumption, especially concerning climate change. Furthermore, it was found that researchers from China, North America, and Australia contribute significantly to this area compared to researchers from other countries.

1. INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC) (2021), average global temperatures are rising due to the higher concentrations of greenhouse gases in the atmosphere, due to human activities such as fossil fuel combustion and rapid urban population growth (Da Guarda et al., 2020). There has been a surge in discussions concerning the causes and effects of this trend, particularly linked to energy demand and consumption issues. These discussions have garnered increased attention in global debates. Various solutions exist to decrease greenhouse gas emissions while satisfying the energy needs of society (Pérez et al., 2019). In addition, it should also be considered that climate change is likely to in-crease future energy demand (Van Ruijven et al., 2019).

Given this scenario, renewable energy fills the gap between climate and energy sciences, playing a very important role in strategies for decarbonization and mitigation of the adverse effects of climate change (Bush, 2020) and its possible consequences on societies and on the environment (IPCC, 2021). The reduction in the cost of the photovoltaic (PV) energy-production system and the improvement in energy-production efficiency (Polman et al., 2016) – combined with easy implementation, modularity, low maintenance, and, mainly, a fast-learning curve – has been responsible for an increase in the number of panels installed (Baurzhan et al., 2016). Hence, initiatives utilizing photovoltaic solar systems possess the capability to aid in mitigating climate change (Feron et al., 2017). Yet, the susceptibility to atmospheric conditions and potential variations in future climate poses uncertainty, potentially

* Corresponding author: Nícolas Matheus da Fonseca Tinoco de Souza Araújo. Rural Federal University of Semi-Arid, Avenue Francisco Mota, 572, Central Campus, CEP 59625-900, Mossoró, RN, Brazil. nicolas.araujo@ufersa.edu.br

complicating energy planning and undermining investments in this sector (Craig et al., 2019; Feron et al., 2021).

Therefore, when contemplating the establishment of a PV plant, it is vital to assess not solely the current renewable resources but also the ramifications of climate change (CC) on the future of photovoltaic energy production (PVP), especially in cases of long-term usage and financial commitment (Pérez et al., 2019).

1.1 Justification and Objectives

The research described in this article focuses on the analysis of the impacts of CC on PVP. This study utilizes a bibliometric methodology applied to the available literature within the Web of Science (WoS) and Scopus (Sco) databases.

This type of study uses scientific concepts and technical elements to measure the aspects of scientific production of a given area of knowledge, based on statistical instruments that enable a better analysis of 'scientific publications', as presented in the literature on bibliometric indicators (Todeschini and Baccini, 2016), a combination of scientific mapping and citation analysis (Noyons and Moed, 1999), measurement of academic research (Andrés, 2009), mechanisms used to measure the recording of information and the dissemination of knowledge (Vanti, 2002), and scientometric indicators (Spinak, 1998).

This research holds an original and exploratory element. To the best of the authors knowledge, no studies with similar characteristics, specifically focusing on the bibliometric review of documents concerning the impacts of climate change on photovoltaic energy-production potential, exist in the literature. The research delves into an analysis of its own performance while conducting a scientific mapping (López-Belmonte et al., 2020) of works associated with this domain. The study combines a unique focus on climate change's influence on photovoltaic energy and a comprehensive scientific mapping, making it distinct within the field. This study identifies emerging themes and collaborative networks. It assesses the evolution of scientific production and its degree of maturity (Moreno-Guerrero et al., 2020). Additionally, it defines the institutions concentrating the largest number of publications and the most active networks or research groups. Furthermore, it synthesizes the titles of the journals commonly used for publication, lists the most productive authors, and identifies the most cited authors. These findings can demonstrate the relevance of these authors within the theme (Todeschini and Baccini, 2016). Hence, this study aims to attract researchers' interests in this concept, offering a comprehensive view of CC-PVP's significance, its associated research trajectories, and potential future trends it encompasses.

This study adhered to procedural guidelines outlined in prior research (Emodi et al., 2019; Marín-Marín et al., 2021), aiming to employ an established study model endorsed, compared, and validated within the scientific community. Thus, this study aimed to achieve the subsequent goals:

- Establishing the importance of CC-PVP;
- Presenting the evolution of CC-PVP in scientific articles;
- Determining the most relevant approaches of CC-PVP in scientific articles; and
- Determining the authors of the most relevant research on CC-PVP in scientific articles.

1.2 Research Question

This review is driven by the query: "What are the features, scope, and entities involved in research pertaining to the impacts of climate change on the potential of photovoltaic production (PVP)?"

1.3 Identification of Relevant Studies

In this type of research, a thorough procedure should be followed to avoid biases. For this purpose, guidelines established in other studies (Emodi et al., 2019; Marín-Marín et al., 2021) were followed in order to perform all the necessary actions optimally. Concretely, this research conducted the sub-sequent procedures (Montero-Díaz et al., 2018): (i) selection of study databases (WoS and Sco); (ii) delineation of the focal concept for analysis (CC-PVP); and (iii) formulation of the search equation encompassing all terms linked to the primary construct (Table 1). The selection of these databases was based on their comprehensive coverage of energy and meteorology-related fields. Their inclusion was particularly influenced by their recognition as prestigious repositories hosting publications listed in the Journal Citation Reports (JCR) (Zhu and Liu, 2020). These databases were chosen for their expansive scope across multiple disciplines connected to energy and meteorology, aligning with the breadth and prestige required for this study. Therefore, WoS and Sco are postulated as relevant databases for retrieving documents pertinent to the examined state of the art in this study.

The bibliographic research aimed to utilize bibliometrics in identifying peer-reviewed literature regarding evidence of CC-PVP. The search query incorporates terms deemed relevant by the authors, encompassing variability, climate change, impacts, and energy production in relation to PV technology. The preliminary search was implemented on 11 December 2021, at the aforementioned platforms, which are databases of world prestige (Zhu and Liu, 2020) with records from 1965 (for WoS) and 1960 (for Sco) to the present date (Emodi et al., 2019). Although the limitation of year of publication is used

by some authors (Emodi et al., 2019), it was not adopted in this study because the aim was to identify the entire history of articles within the analyzed theme.

Table 1 - Search strings used to search for articles for the review.

Search String		Web of Science (1965–2021)	Scopus (1960–2021)
Title	**Title-Abstract-Keywords**		
Photovoltaic OR PV	impact AND power * AND (weather * change * OR climat* change* OR global warming)	243	235
Photovoltaic OR PV	impact AND *lectric* AND (weather * change * OR climat * change * OR global warming)	187	201
Photovoltaic OR PV	impact AND energy * AND (weather * change * OR climat * change * OR global warming)	327	289
Photovoltaic OR PV	? ffect * AND power * AND (weather * change * OR climat * change * OR global warming)	421	454
Photovoltaic OR PV	? ffect * AND *lectric * AND (weather * change * OR climat * change* OR global warming)	261	337
Photovoltaic OR PV	? ffect * AND energy * AND (weather * change * OR climat * change * OR global warming)	470	475
	Subtotal	1909	1991
	Total	3900	

Legend: the asterisk (*) denotes any grouping of characters, including no characters, while the question mark (?) represents any single character.

The search criteria outlined in Table 1 were employed within both the WoS and Sco databases, resulting in 1909 and 1991 articles retrieved, correspondingly. The exact description of the strings used in each database is shown in Tables S1 and S2 of Supplementary File S1.

2. METHODOLOGY

2.1 Research Scope

The research methodology used in this study was bibliometric (Moreno-Guerrero et al., 2020). This approach was selected due to its capability to precisely quantify and analyze the publications indexed within the two databases under examination (Carmona-Serrano et al., 2021). In this context, the design of development research allows the search, recording, analysis, and forecast of documents that revolve around a theme (Carmona-Serrano et al., 2021).

In addition, a co-word analysis was conducted (Herrera-Viedma et al., 2020). In this type of analysis, the focus lies in examining the keywords within the plethora of documented literature. Particularly, this examination allows connections to be made between the themes investigated in various publications concerning the construct being analyzed. Additionally, co-word analysis allows the themes that may soon present themselves as potentially relevant to be predicted. This analysis also involves creating maps with nodes that indicate achievements, positions within specific language domains, and the evolution of a subject. Similarly, another indicator, the h index, was taken into account for the analyses in the present study (López-Robles et al., 2019).

The review was conducted in the following five main steps: (i) definition of scope, (ii) identification of the research question, (iii) identification of relevant studies, (iv) selection of the study, and (v) data treatment.

2.2 Study Selection Process

The selection process of this study is similar to that used by Emodi et al. (2019) and by Marín-Marín et al. (2021). Initially, duplicates and irrelevant articles were removed. In the filters of the respective databases, only articles, conference articles, and review articles were maintained, as performed by Marín-Marín et al. (2021). Each article underwent independent review, applying the selection criteria to titles and abstracts. The initial selection was comprehensive, aiming to encompass all literature pertaining to the influence of CC over PVP.

The selection process utilized criteria (outlined in Table S3 of Supplementary File S1) to filter through a diverse array of articles based on their titles and abstracts, narrowing down the focus to studies that specifically address the effects of climate change on energy systems utilizing PV technology, whether in the past, present, or future. As the articles were handled separately according to their source database, a new exclusion of duplicates was necessary to finish the eligibility step and determine which ones would be included in the quantitative analyses.

In addition, the PRISMA flow diagram (LIBERATI et al., 2009), in Figure 1, was used to review the publications.

During the screening process, reviewers frequently convened to resolve discrepancies and address any concerns pertaining to the selected articles for this review.

2.3 Data Treatment

Data processing was performed in Excel 2013 software (Microsoft, 2013), feeding it information to create graphs and tables that assisted in the quantitative and qualitative analyses of the studies. The necessary data were provided by the WoS and Sco databases, such as: title, authors, keywords, number of citations, abstract, year, country, and journal of publication.

Moreover, SciMAT v1.1.04 (Cobo et al., 2012) was employed to longitudinally analyze the dynamic and structural development of the entire literature, involving the examination of how a keyword evolved within a predefined series of time periods (Herrera-Viedma et al., 2020). SciMAT orchestrates the following procedures:

• Identification: Analysis of the publication's keywords (n = 735) involves the creation of co-occurrence maps using nodes, generating a network of co-words. Identification of the most crucial keywords (n = 587) occurs, followed by the clustering of significant terms and topics using an algorithm.

• Representation: Strategic diagrams are crafted to organize terms based on their progression within the literature. These diagrams are structured into four quadrants (Q) (Figure 2a): upper right corner (Q1) = pivotal and significant themes; upper left corner (Q2) = extensively developed or isolated themes; lower left corner (Q3) = emerging or waning themes; and lower right corner (Q4) = overarching or fundamental themes. These visualizations are generated by considering density (internal strength) and centrality (connections between networks) principles (Herrera-Viedma et al., 2020). Additionally, thematic networks (Figure 2b) depict the primary theme linked to other terms.

• Specification: Timeframes are established to categorize publications and facilitate the examination of node development across time. These intervals are determined based on establishing a volume of publications sharing certain similarities. For this study, three periods were defined (P1 = 2005–2015; P2 = 2016–2018; P3 = 2019–2021). However, concerning the analysis of articles' authors, only one period—spanning from the beginning to the end (PX = 2005–2021)—was established. The strength of connections between periods is computed by considering the number of shared keywords or themes.

• Evaluation: The evolution of themes is scrutinized across the established timeframes (Figure 2c). Additionally, production indicators aligned with the inclusion criteria are outlined (Table 2).

3. RESULTS

3.1 Analysis of Bibliometric Performance

The PRISMA flow diagram (Figure 1) showed that the bibliographic research resulted in a total of 3900 articles—with 1909 and 1991 articles returned from the WoS and Scopus databases, respectively—which were reduced to 788 and 709 after eliminating duplicates. Following the review of titles and abstracts, an additional 1349 were removed.

In the eligibility phase, as the articles were handled separately according to their source database, a new removal of duplicates (35 in all) was necessary.

After that, 113 articles were chosen, spanning from 2005 to 2021; these publications were utilized for quantitative synthesis to delineate the scope of the studies regarding the impacts of CC on the potential for photovoltaic production (labeled as #1 to #113 in Supplementary File S2).

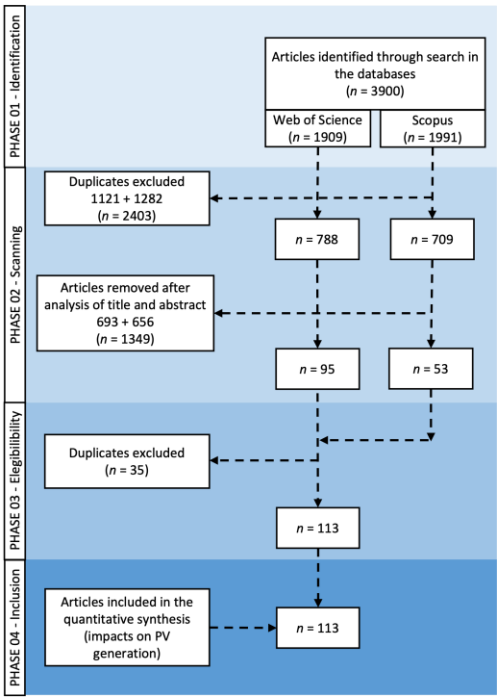
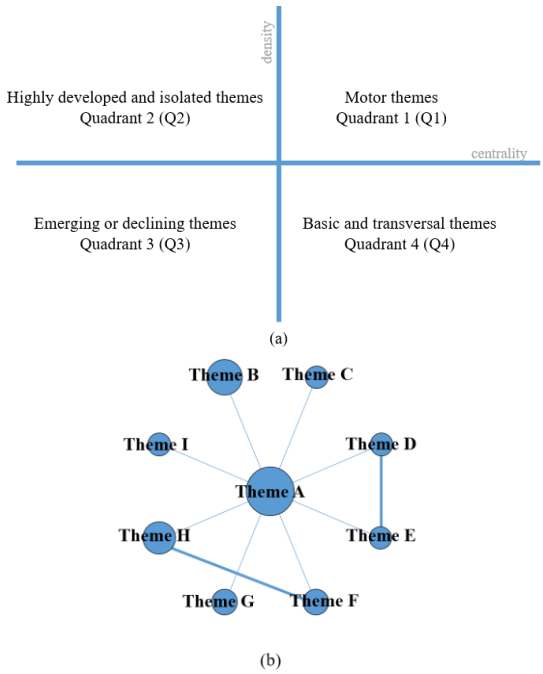
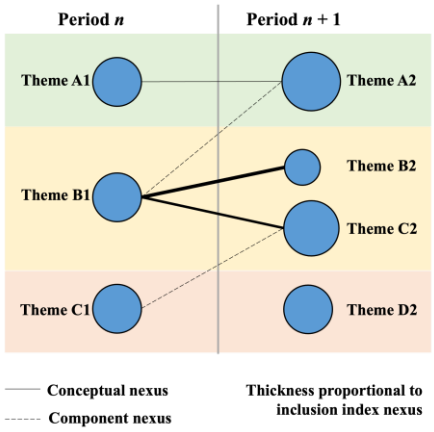


Figure 1 - PRISMA flow diagram of the study in the bibliometric review and reasons for exclusions.





(c)

Figure 2 - Format and data of co-word analysis with SciMAT: (a) strategic chart, (b) thematic mesh and (c) evolution of themes. Source: Marín-Marín et al., 2021.

Figure 3 represents the chronology of the number of articles published annually and number of the publications accumulated over the years on CC-PVP. The progression has been uneven, marked by three distinct phases. The initial phase spans from 2005 to 2015, inclusive. Throughout this period, scientific output typically did not surpass five manuscripts per year.

Table 2 - Production indicators and inclusion criteria adopted in this study.

Configuration	Values
Analysis unit	Keywords: keywords, Web of Science (WoS) and Scopus (Sco)
Frequency threshold	Keyword: $P_1 = (2)$, $P_2 = (2)$, $P_3 = (2)$
Type of network	Co-ocurrence
Co-occurrence union value threshold	Keyword: $P_1 = (2)$, $P_2 = (2)$, $P_3 = (2)$
Normalization measure	Equivalence index
Clustering algorithm	Simple center algorithm Maximum size: 9; minimum size: 2
Type of document selection	Core mapper
Quality measure	h index and number of citations
Evolution measure	Jaccard index
Overlap measure	Inclusion index

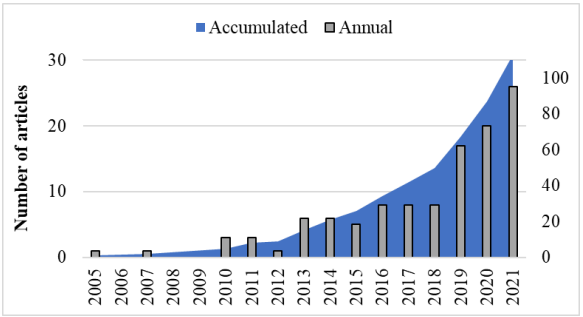


Figure 3 - Articles published per year and the accumulated quantity.

The second phase witnesses a marginal rise in scientific output spanning from 2016 to 2018, averaging approximately nine articles per year with consistent production. The subsequent phase, encompassing 2019 to 2021, experienced a substantial increase in output, which demonstrates the relevance of the theme in the current context.

Undoubtedly, English serves as the predominant language in scientific publications concerning CC-PVP (Figure 4). Other languages have significantly less production com-pared to English in the scientific literature on CC-PVP.

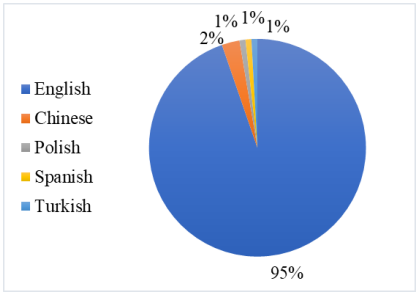


Figure 4 - Languages used in the articles.

The multiple research areas described by the WoS, in which the articles are included, confirmed the interdisciplinarity of the study involving climate change and PV technology, as described in Figure 5. Although the focus of the publications was the changes in the energy supply, with 74 articles in “Energy” and 57 in “Fuels”, other categories were also relevant, such as “Technology” and “Sustainable Science”, with 46 and 45 articles, respectively. The topics found included electronics, meteorology, thermodynamics, engineering, environmental sciences, (with respect to the ecologically friendly alternative source), computer science, materials science, and economy, among others.

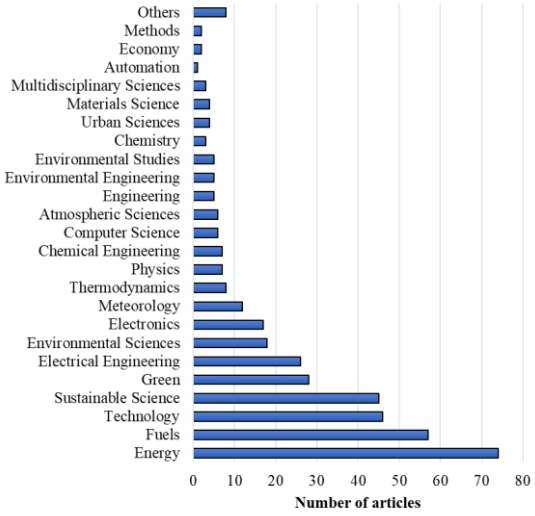


Figure 5 - Division of articles per research area. (During this construct, articles considered interdisciplinary, according to the division established by the WoS and Sco databases, could be classified in more than one research area).

The scientific community favored research articles presenting the most significant findings on CC-PVP (82 articles). Additionally, it is notable that there was a relatively small quantity of conference articles (26 articles) and review articles (5 articles) in this field of study.

In the realm of CC-PVP studies, no particular scientific institution exhibited notably higher production volumes than the rest. The number of articles was uniform when analyzing the institutions occupying the first positions (Figure 6). A total of 206 institutions had at least one article published in the area.

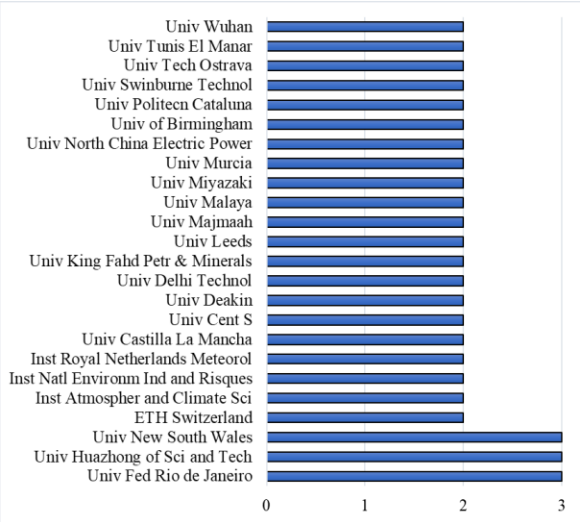


Figure 6 - Institutions of origin of the articles.

Figure 7 highlights the authors with more than one publication, a total of 32 com-pared to the total of 431 authors. There is no author standing out from the others. A limited number of authors displaying slightly higher productivity than others was noticed. Through a comparative analysis using Lotka's ideal model (Lotka, 1926), it becomes evident that the production related to CC-PVP approaches a moderate level of maturity.

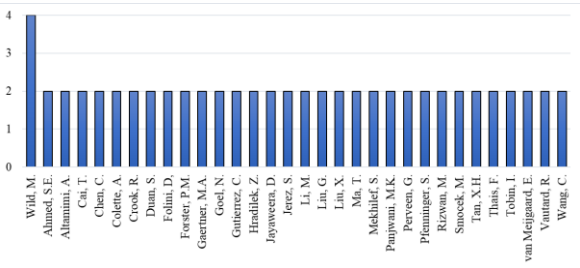


Figure 7 - Authors with two or more published articles.

In Figure 8, it is possible to observe the relationship between the main authors. Wild M. is the one with the most relationships, which would justify his greater number of publications (four). Several scientific groups that had no correlation with the others were found, which presumably compose distinct research groups.

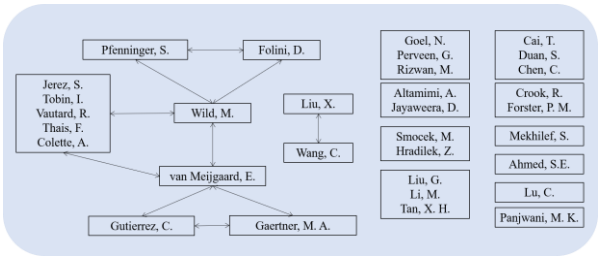


Figure 8 - Correlation between the most prolific authors. Lines indicate joint publication.

The articles were published in 69 scientific bases, most with a focus on energy, while others were in the areas of sustainability, meteorology, information technology, automation, thermodynamics, infrastructure, engineering, and economics. However, only 10 bases had three or more articles published (Figure 9). The "IEEE Conferences" journal, which brings together articles published in conferences of the IEEE entity was the most representative, with 12 publications, followed by the journals "Energy", "Renewable Energy", and "Renewable and Sustainable Energy Reviews", with 6, 5, and 5 publications, respectively. All journals reported have relevant impact factors, which points to the importance of the articles on the theme.

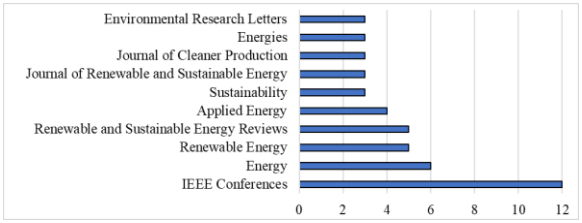


Figure 9 - Bases that had published two or more articles. Articles published by each base.

Figure 10 explains the territorial arrangement referring to the location where the studies were conducted and the number of authors per territory. Among these countries, China emerges prominently in the ranking with a staggering 17 publications, surpassing the second and third positions—held by the United States and Australia—by more than 50%. Notably, the majority of published articles are authored by researchers from developed nations like the USA, Australia, Spain, Switzerland, and the United Kingdom. However, the study also underscores substantial contributions from developing countries such as China and India, signifying their noteworthy impact on the subject matter.

The citation volume for manuscripts centered on CC-PVP research stands at a moderate level compared to other research domains. Notably, the article by Pfenninger et al. (2016) emerges as the most cited, accumulating a total of 388 citations,

followed by Das et al. (2018), which has garnered 300 citations. It is interesting to note that, among the six most cited articles, only one is a review article and one is a conference article (Table 3).

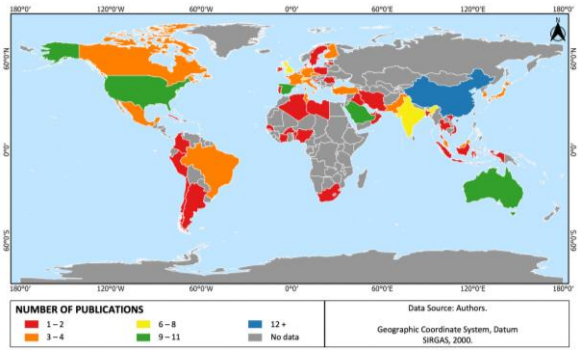


Figure 10 - Countries of researchers who conducted the studies and their quantities. (The construct was obtained from the nationality of all authors of each article, and not only of the first (main) author. Thus, a single article may have been assigned to more than one country).

Table 3 - The six most cited articles according to the Web of Science and Scopus databases.

Reference	Type	Citations	
		Web of Science	Scopus
Pfenninger et al. (2016)	Article	388	-
Das et al. (2018)	Review article	248	300
Jerez et al. (2015)	Article	117	123
Cai et al. (2010)	Conference article	-	122
Crook et al. (2011)	Article	112	111
Smith et al. (2014)	Article	103	109

3.2 Structural and Thematic Development

Figure 11 portrays the evolution of keywords across different periods, resembling an X-ray image. It reveals several pertinent details essential for analysis. The ascending arrows denote the count of keywords not utilized in subsequent periods. Descending arrows signify the addition of new keywords within a specific timeframe. Horizontal dates represent the quantity of overlapping keywords between two periods. Circles indicate the number of keywords employed by authors in each period.

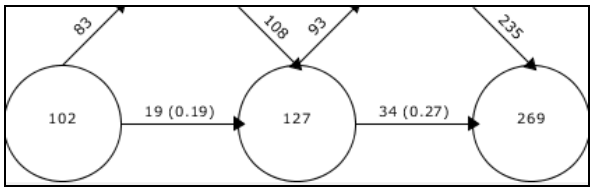


Figure 11 - Continuity of keywords between contiguous intervals.

In this instance, these data indicate the absence of a clearly defined research trajectory over time. This is evidenced by the overlap percentages between consecutive periods, which reach 19% between 2005–2015 and 2016–2018, and 27% between 2016–2018 and 2019–2021—both below 30%. However, the comparison between the last two periods shows an increase in percentage. This trend might suggest the emergence of a research trajectory in the foreseeable future, albeit still in a formative stage.

The thematic evolution of research related to CC-PVP was generated from the Jaccard index (Real and Vargas, 1996). This metric establishes associations between themes, considering whether the linkage between themes relies on keywords or other themes. A continuous line on the chart signifies a thematic connection, representing a conceptual linkage. Conversely, a dashed line indicates a link based on keywords, denoting a non-conceptual connection. Moreover, the thickness of the connecting line is noteworthy, signifying the volume of overlapping keywords or themes. A greater thickness signifies a higher number of shared elements between adjacent themes.

Figure 12 highlights several notable aspects.

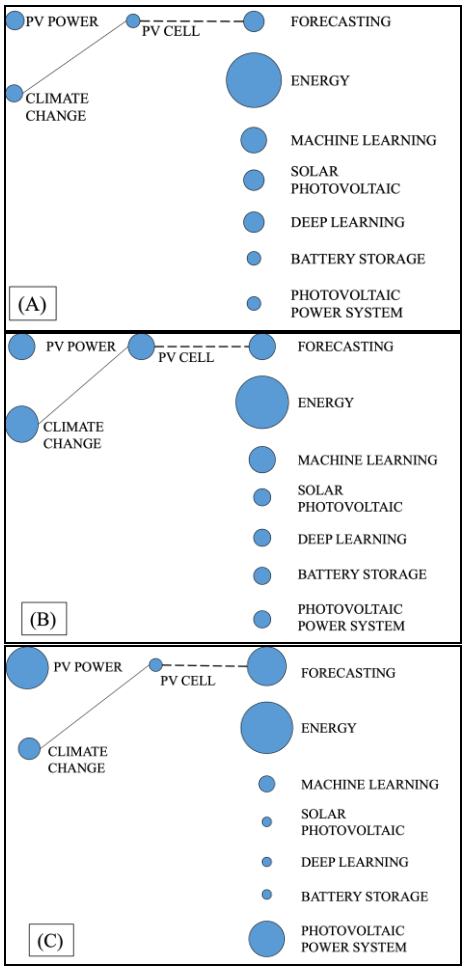


Figure 12 - Thematic evolution by different quality measures: (A) number of documents, (B) h index, and (C) number of citations.

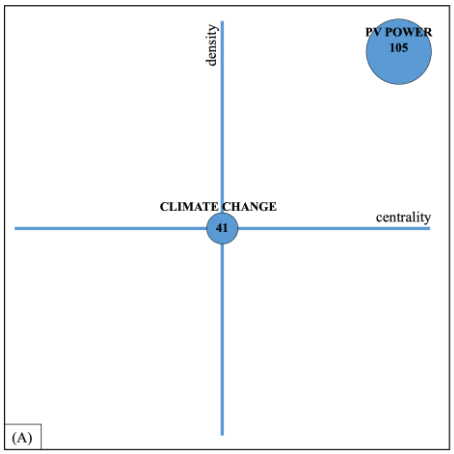
Primarily, there is a strikingly low number of connections between adjacent themes, signifying the absence of links among the diverse research trajectories within the CC-PVP studies. Second, there is only one line of research indicating continuity in the three periods, represented by "Climate Change", "PV cell", and "Forecasting", respectively.

Also, it is possible to observe that the term "Energy" is relevant, regardless of the quality measure, while the terms "PV power", "Forecasting", and "Photovoltaic Power System" stand out when considering the number of citations, and the term "Climate change" is evident when considering the h index.

To analyze the most outstanding themes of CC-PVP, the strategic diagrams of each selected period, constructed by SciMAT based on the density and centrality measures of Callon, Courtial, and Laville (1991), will be presented, as conducted previously. The volumes of the spheres that will be presented in these diagrams are equivalent to the number of citations received by the themes they represent.

3.2.1 First Period (2005 to 2015)

According to the strategic diagram presented in Figure 13A, it was observed that scientific production focuses on two themes: "Climate change" and "PV power". As part of the quadrant of motor themes, which are those highly developed or essential to build the research area, the theme "PV power" stands out as the most important of this period. The theme "Climate change", due to being at the center, appears as an emerging, transversal theme and driving force for research.



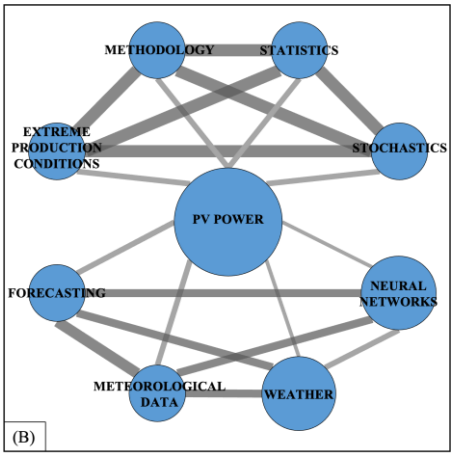


Figure 13 - Bibliometric data of the period from 2005 to 2015: (A) strategic diagram and (B) cluster network of the theme "PV power".

As the most relevant theme of the period, "PV power" has a cluster network (Figure 13B) that is divided into two major areas: evaluation of PV energy production using statistical methods and evaluation using artificial intelligence methods associated with the use of meteorological data.

Table 4 shows data on the number of publications for the themes that stood out in this period, the citations obtained by these publications, and the values of the h index. It is observed that both themes reached significant numbers of citations, although the h index values were low.

Table 4 - Performance of themes in the period from 2005 to 2015.

Theme	Publications	Citations	h Index
Climate change	3	41	3
PV power	4	105	2

3.2.2 Second Period (2016 to 2018)

According to the strategic diagram presented in Figure 14A, the scientific production focuses on only one theme: “PV cell”. This is in the quadrant of the motor themes, which are those highly developed or essential to build the research area, being the most important of this period.

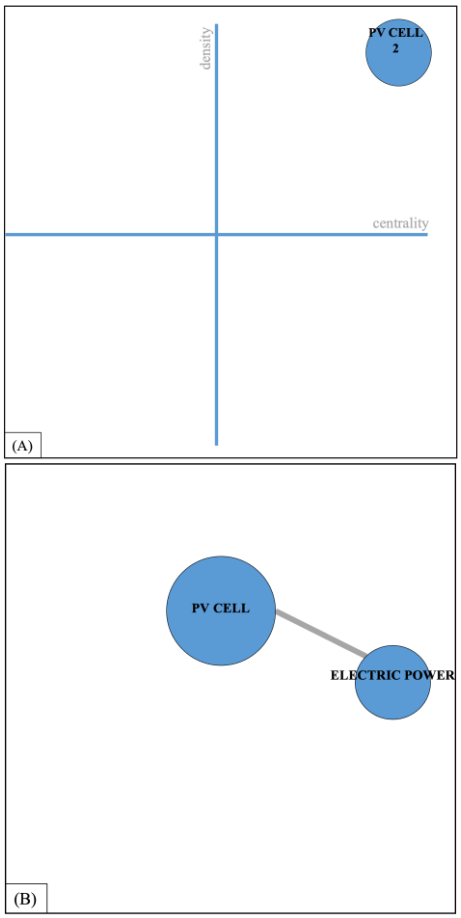


Figure 14 - Bibliometric data of the period from 2016 to 2018: (A) strategic diagram and (B) cluster network of the theme “PV cell”.

The “PV cell”, despite being the most relevant theme of the period, has a greatly reduced network of clusters (Figure 14B), having only one additional cluster, “Electric Power”. Thus, it is understood that the period was characterized by the concentration of studies in a single line focused on the electrical characteristics of PV technology.

Table 5 shows low values for the number of publications, citations, as well as for the h index of the most relevant theme for the period from 2016 to 2018. Thus, it is concluded that the scientific productivity was low and without much impact when compared to the previous period.

Table 5 - Performance of themes in the period from 2016 to 2018.

Theme	Publications	Citations	h Index
PV cell	2	13	2

3.2.3 Third Period (2019 to 2021)

According to the strategic diagram presented in Figure 15A, the scientific production of this period is concentrated in seven themes. As part of the quadrant of the motor themes, which are those that are highly developed or essential to build the research area, the themes “Forecasting” and “Deep learning” stood out. As part of the quadrant of basic and transversal themes, considered as important for the scientific field, the themes “Machine-learning” and “Energy” also presented themselves as relevant. The current period exhibits a notable expansion in the scope of study areas, particularly emphasizing the application of machine learning techniques in evaluating photovoltaic systems. This period surpasses its predecessors in terms of the diversity and depth of research areas, focusing notably on the integration of machine learning methods within photovoltaic system assessments.

The theme “Energy” has a highly interdisciplinary network of clusters (Figure 15B) that mainly relates themes of energy, climate change, and solar energy. The theme “Forecasting” has, in its network of clusters (Figure 15C), themes such as “Electric Power”, “Smart Power Grids”, and “Photovoltaic Generation”, which indicate that researchers are looking at how photovoltaic production and electric energy consumption will behave in the world, especially when considering climate change. In general, the densities of the themes indicate that it is not a completely consolidated area, but an area in continuous expansion.

Table 6 shows data on the number of publications of the themes that stood out in the period from 2019 to 2021, the citations obtained by these publications, and the respective values of the h index. It is observed that the theme “Energy” stands out, in the number of publications, the number of citations, and impact factor obtained by the h index, highlighting its transversality.

4. CONCLUSIONS

This study was conducted to analyze and highlight relevant aspects of the international scientific production on CC-PVP published between 1960 and 2021 and retrieved from the bibliographic collections Web of Science and Scopus. From 3900 articles that were filtered up to the 113 articles published in 69 scientific bases, produced by 431 different authors from 206 institutions and 56 countries, it was found that the production on this theme has increased significantly in the last three years, especially in 2021, which produced 26 articles, the largest number of the analyzed period.

This evolution allowed an increase in the degree of maturity of this field of research, which was observed when comparing the publications per author with what is expressed by Lotka’s Law. As for the

authors who produced the most, it was found that thirty-two published two or more articles. Martin Wild from the Institute for Atmospheric and Climate Science (Switzerland), with four publications, stood out among them. In relation to the countries, four had 10 or more publications, with China standing out with the largest number of publications, 17 articles, followed by Australia and the United States, both with 11.

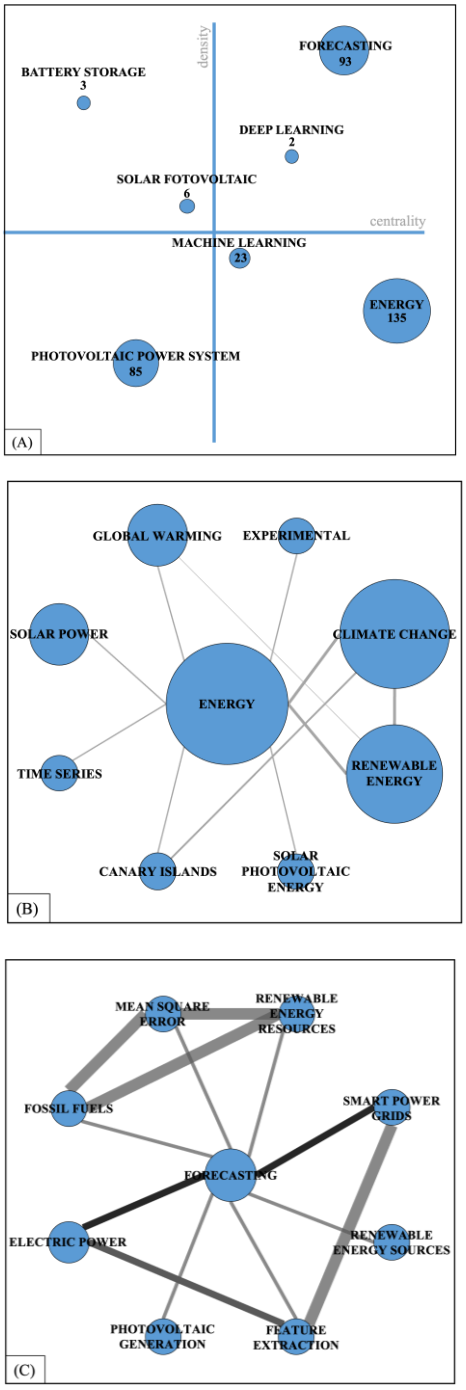


Figure 15 - Bibliometric data of the period from 2019 to 2021: (A) strategic diagram, (B) cluster network of the theme “Energy”, and (C) cluster network of the theme “Forecasting”.

Table 6 - Performance of themes in the period from 2019 to 2021.

Theme	Publications	Citations	h Index
Energy	17	135	5
Forecasting	4	93	2
Photovoltaic power system	2	85	1
Machine learning	6	23	2
Solar photovoltaic	4	6	1
Battery storage	2	3	1
Deep learning	4	2	1

With regard to scientific bases, the “IEEE Conferences” journal, which brings together articles published in conferences of the IEEE entity, was the one that concentrated the largest number of publications, 12 articles, followed by the journals “Energy”, “Renewable Energy”, and “Renewable and Sustainable Energy Reviews”, with 6, 5, and 5, respectively. All journals reported have relevant impact factors, which shows the importance of the articles on the theme. Among them, Applied Energy stands out with the highest index (SJR2019 = 3.607), as well as four articles published between 2005 and 2021.

The most productive institutions, with three articles each, were Universidade Federal do Rio de Janeiro (Brazil), University of Huazhong of Science and Technology (China), and University of New South Wales (Australia).

As for the articles considered as the possible elite of this field of research, the two with the most citations were those of Pfenninger et al. (2016) and Das et al. (2018), both published in high-impact journals: “Energy” and “Renewable and Sustainable Energy Reviews”, respectively.

The area that concentrates the largest number of publications on CC-PVP is “Energy”, with 74 articles, followed by “Fuels” and “Technology” with 57 and 46, respectively, which demonstrates the importance of CC-PVP in interdisciplinary areas.

Through observing the consistent keywords across consecutive intervals, it became evident that there is not a defined research trajectory evolving over time. This lack of continuity stems from the overlap percentage between contiguous periods, consistently remaining below 30%. However, in the comparison between the last two periods, there is an increase in this percentage, indicating a potential emergence of a research trajectory in the foreseeable future. Nonetheless, this direction seems to be in an incipient stage of development.

The strategic diagrams, obtained by SciMAT, show the topics predominantly addressed in the periods analyzed. Thus, it was possible to determine that in the period between 2005 and 2015, the publications on CC-PVP focused on two themes: “Climate change” and “PV power”. Of these themes, the only one identified as highly developed or essential to build the research area was “PV power”, which received 105 citations, the largest amount of this period.

The second period was characterized by the concentration of studies in a single line focused on the electrical characteristics of PV technology.

In the third period the focus was on seven themes, among which two stood out: “Energy” and “Forecasting”. The theme “Energy” has a very interdisciplinary network of clusters that mainly relates the topics of energy, climate change, and solar energy. “Forecasting” appears with a network of clusters that indicates that researchers are looking into how photovoltaic production and electric energy consumption will behave in the world, especially when considering climate change. The highlight of citations for this third period was the theme “Energy”, with 135 records, followed by “Forecasting”, with 93.

The limitations of this study are the use of only two databases, Web of Science and Scopus, and the possibility that articles dealing with the subject did not include the terms used here to identify studies on CC-PVP. For future research, it is suggested to expand the scope of this analysis, comparing its results with the sample of other bibliographic collections, following the same procedures.

5. ACKNOWLEDGEMENTS

The authors thanks support from the Brazilian National Council for Scientific and Technological Development (CNPq) (project 308753/2021-6), the Paraíba State Research Foundation (FAPESQ) (Project 3063/2021 and Grant 18/2020) and PROPESQ/UFPB (project PVK13163-2020).

6. REFERENCES

Andrés, A. *Measuring Academic Research: How to Undertake a Bibliometric Study*; Chandos Publishing: Cambridge, UK, 2009.

Baurzhan, S.; Jenkins, G.P. Off-grid solar PV: Is it an affordable or appropriate solution for rural electrification in Sub-Saharan African countries? *Renew. Sustain. Energy Rev.* **2016**, *60*, 1405–1418.

Bush, M.J. *Climate Change and Renewable Energy: How to End the Climate Crisis*, 1. ed.; Springer International Publishing: Cham, Switzerland, 2020; p. 525.

Cai, T.; Duan, S.; Chen, C. Forecasting power output for grid-connected photovoltaic power system without using solar radiation measurement. In Proceedings of the 2nd International Symposium on Power Electronics for Distributed Generation Systems, Hefei, China, 16–18 June 2010; Volume 10, pp. 773–777.

Callon, M.; Courtial, J.P.; Laville, F. Co-word analysis as a tool for describing the network of interactions between basic and technological research: The case of polymer chemistry. *Scientometrics* **1991**, *22*, 155–205.

Carmona-Serrano, N.; Moreno-Guerrero, A.J.; Marín-Marín, J.A.; López-Belmonte, J. Evolution of the autism literature and the influence of parents: A scientific mapping in Web of Science. *Brain Sci.* **2021**, *11*, 74.

Cobo, M.J.; López-Herrera, A.G.; Herrera-Viedma, E.; Herrera, F. SciMAT: A new Science Mapping Analysis Software Tool. *J. Am. Soc. Inf. Sci. Technol.* **2012**, *63*, 1609–1630.

Craig, M.; Losada Carreño, I.; Rossol, M.; Hodge, B.-M.; Brancucci, C. Effects on power system operations of potential changes in wind and solar generation potential under climate change. *Environ. Res. Lett.* **2019**, *14*, 034014.

Crook, J.A.; Jones, L.A.; Forster, P.M; Crook, R. Climate change impacts on future photovoltaic and concentrated solar power energy output. *Energy Environ. Sci.* **2011**, *4*, 3101–3109.

Da Guarda, E.L.A.; Domingos, R.M.A.; Jorge, S.H.M.; Durante, L.C.; Sanches, J.C.M.; Leão, M.; Callejas, I.J.A. The influence of climate change on renewable energy systems designed to achieve zero energy buildings in the present: A case study in the Brazilian Savannah. *Sustain. Cities Soc.* **2020**, *52*, 101843.

Das, U.K.; Tey, K.S.; Seyedmahmoudian, M; Mekhilef, S.; Idris, M.Y.I.; Van Deventer, W.; Horan, B.; Stojcevski, A. Forecasting of photovoltaic power generation and model optimization: A review. *Renew. Sustain. Energy Rev.* **2018**, *81*, 912–928.

Emodi, N.V.; Chaiechi, T.; Beg, A.B.M.R.A. The impact of climate variability and change on the energy system: A systematic scoping review. *Sci. Total Environ.* **2019**, *676*, 545–563.

Feron, S.; Cordero, R.R.; Damiani, A.; Jackson, R.B. Climate change extremes and photovoltaic power output. *Nat. Sustain.* **2021**, *4*, 270–276.

Feron, S.; Cordero, R.R.; Labbe, F. Rural electrification efforts based on off-grid photovoltaic systems in the Andean region: Comparative assessment of their sustainability. *Sustainability* **2017**, *9*, 1825.

Herrera-Viedma, E.; López-Robles, J.R.; Guallar, J.; Cobo, M.J. Global trends in coronavirus research at the time of Covid-19: A general bibliometric approach and content analysis using SciMAT. *El Prof. De La Inf.* **2020**, *29*, e290322.

IPCC. Climate Change 2021: The Physical Science Basis. In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2021.

Jerez, S.; Tobin, I.; Vautard, R; Montávez, J.P.; López-Romero, J.M.; Thais, F.; Bartok, B.; Christensen, O.B.; Colette, A.; Déqué, M.; et al. The impact of climate change on photovoltaic power generation in Europe. *Nat. Commun.* **2015**, *6*, 10014.

Liberati, A.; Altman, D.G.; Tetzlaff, J.; Mulrow, C.; Gøtzsche, P.C.; Ioannidis, J.P.; Clarke, M.; Devereaux, P.J.; Kleijnen, J.; Moher, D. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. *PLoS Med.* **2009**, *6*, e1000100.

López-Belmonte, J.; Moreno-Guerrero, A.J.; López-Núñez, J.A.; Hinojo-Lucena, F.J. Augmented reality in education. A scientific mapping in Web of Science. *Interact. Learn. Environ.* **2020**, *31*, 1860–1874.

López-Robles, J.R.; Otegi-Olaso, J.R.; Porto, I.; Cobo, M.J. 30 years of intelligence models in management and business: A bibliometric review. *Int. J. Inf. Manag.* **2019**, *48*, 22–38.

Lotka, A.J. The frequency distribution of scientific productivity. *J. Wash. Acad. Sci.* **1926**, *16*, 317–323.

Marín-Marín, J.A.; Moreno-Guerrero, A.J.; Dúo-Terrón, P.; López-Belmonte, J. STEAM in education: A bibliometric analysis of performance and co-words in Web of Science. *Int. J. STEM Educ.* **2021**, *8*, 41.

MICROSOFT. Excel. 2013. Available online: https://www.microsoft.com/ (accessed on 13 July 2021).

Montero-Díaz, J.; Cobo, M.J.; Gutiérrez-Salcedo, M.; Segado-Boj, F.; Herrera-Viedma, E. Mapeo científico de la Categoría «Comunicación» en WoS (1980–2013). *Comunicar* **2018**, *26*, 81–91.

Moreno-Guerrero, A.J.; Gómez-García, G.; López-Belmonte, J.; Rodríguez-Jiménez, C. Internet addiction in the Web of Science database: A review of the literature with scientific mapping. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2753.

Noyons, E.C.M.; Moed, H.F. Combining Mapping and Citation Analysis for Evaluative Bibliometric Purposes: A Bibliometric Study. *J. Am. Soc. Inf. Sci.* **1999**, *50*, 115–131.

Pérez, J.C.; González, A.; Díaz, J.P.; Expósito, F.J.; Felipe, J. Climate change impact on future photovoltaic resource potential in an orographically complex archipelago, the Canary Islands. *Renew. Energy* **2019**, *133*, 749–759.

Pfenninger, S.; Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy* **2016**, *114*, 1251–1265.

Polman, A.; Knight, M.; Garnett, E.C.; Ehrler, B.; Sinke, W.C. Photovoltaic materials: Present efficiencies and future challenges. *Science* **2016**, *352*, aad4424.

Real, R.; Vargas, J.M. The probabilistic basis of Jaccard's index of similarity. *Syst. Biol.* **1996**, *45*, 380–385.

Smith, C.J.; Forster, P.M.; Crook, R. Global analysis of photovoltaic energy output enhanced by phase change material cooling. *Appl. Energy* **2014**, *126*, 21–28.

Spinak, E. Indicadores cienciométricos. *Acimed* **1998**, *9*, 42–49.

Todeschini, R.; Baccini, A. *Handbook of Bibliometric Indicators: Quantitative Tools for Studying and Evaluation Research*; Wiley-VCH: Weinheim, Germany, 2016.

Van Ruijven, B.J.; De Cian, E.; Sue, I. Wing amplification of future energy demand growth due to climate change. *Nat. Commun.* **2019**, *10*, 2762.

Vanti, N.A.P. Da bibliometria à webometria: Uma exploração conceitual dos mecanismos utilizados para medir o registro da informação e a difusão do conhecimento. *Artículo* **2002**, *31*, 152–162.

Zhu, J.; Liu, W. A tale of two databases: The use of Web of Science and Scopus in academic papers. *Scientometrics* **2020**, *123*, 321–335.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.