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Review

Integration of Solar Photovoltaic Systems into Power Networks: A Scientific Evolution Analysis

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Abstract: Solar photovoltaic (PV) systems have drawn significant attention over the last decade. One of the most critical obstacles that must be overcome is distributed energy generation. This paper presents a comprehensive quantitative bibliometric study to identify the new trends and call attention to the evolution within the research landscape concerning the integration of solar PV in power networks. The research is based on 7146 documents that were authored between 2000–2021 and downloaded from the Web of Science database. Using an in-house bibliometric tool, Bibliometrix R-package, and the open-source tool VOSviewer we obtained bibliometric indicators, mapped the network analysis, and performed a multivariate statistical analysis. The works that were based on solar photovoltaics into power networks presented rapid growth, especially in India. The co-occurrence analysis showed that the five main clusters, classified according to dimensions and significance, are (i) power quality issues that are caused by the solar photovoltaic penetration in power networks; (ii) algorithms for energy storage, demand response, and energy management in the smart grid; (iii) optimization, techno-economic analysis, sensitivity analysis, and energy cost analysis for an optimal hybrid power system; (iv) renewable energy integration, self-consumption, energy efficiency, and sustainable development; and (v) modeling, simulation, and control of battery energy storage systems. The results revealed that researchers pay close attention to "renewable energy", "microgrid", "energy storage", "optimization", and "smart grid", as the top five keywords in the past four years. The results also suggested that (i) power quality; (ii) voltage and frequency fluctuation problems; (iii) optimal design and energy management; and (iv) technical-economic analysis, are the most recent investigative foci that might be appraised as having the most budding research prospects.

Keywords: renewable energy; solar photovoltaic (PV); power networks; bibliometric analysis; science mapping

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1. Introduction

With global energy demand on the rise [1], the utilization of renewable energy is increasing continuously, although at a slower rate than the energy consumption. Renewable energy sources (RESs) strive to improve their technical and economic integration into power networks.

For the last two decades, there has been a big effort to integrate RESs into the energy and electricity mix, both to provide energy security within the context of energy transition policies and to address the impacts of climate change. Among all the various RESs, solar energy is commonly used for generating clean electricity and reducing greenhouse gas emissions [2]. Solar photovoltaic (PV) in particular, is currently regarded as the most essential and promising renewable energy technology [1]. In order to make solar PV more efficient, a grid-connected PV system is required and has become the most popular solar PV application [3]. It provides long-term cost reductions, a reliable system with low maintenance requirements, and fast technological progress [4].

Grid-connected PV installations are growing exponentially at the global level, as illustrated in Figure 1. Solar PV had another record-breaking year in 2020, with new installations comprising an estimated 126 GigaWatts (GW); this brought the worldwide total to an estimated 705 GW in terms of on-grid capacity [5], and the number is growing steadily. According to the International Renewable Energy Agency [6], the total number of installations will rise to 2840 GW by 2030 and 8519 GW by 2050. PV installations have historically outperformed expectations.

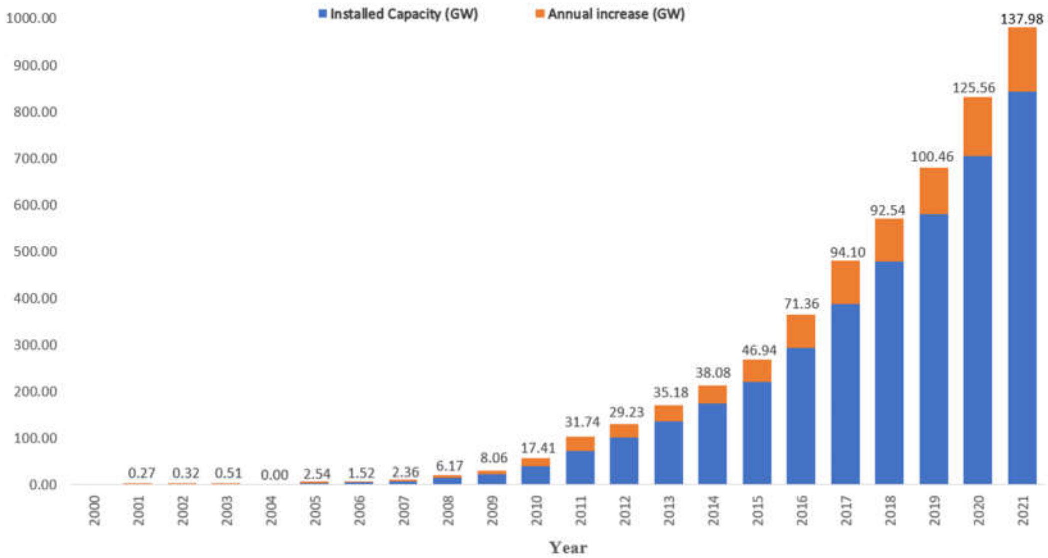

Figure 1. Evolution of solar PV accumulated installed capacity over the last two decades, including the annual increase (orange).

Due to its randomness and intermittent nature, the integration of RESs in power networks will present various challenges. The higher the penetration level of grid-connected PV systems in the medium voltage network, the more stability and reliability issues will arise [7–9]. In addition, with high PV penetration, more harmonics are injected into the system, leading to an increase in the total harmonic distortion (THD) [10]. Studies have also been conducted on the impacts of PV penetration in power networks; the most affected system parameters are voltage and frequency stability, notably at penetration levels above 20% [11–15].

Furthermore, high PV penetration may create a reverse power flow in the network when PV power exceeds the demand [16]. Reverse power flow can create grid instabilities, including frequency and voltage level variations, by allowing more power to flow from the distribution to the transmission system. Due to the continuous increase in PV installations [17,18], new control strategies for the convenient operation and management of new power grids that are integrated with PV systems will be required.

Several studies within the scientific literature have contributed to identifying the main findings in different research fields. Essentially, the reviews concentrated on summarizing the key results based on an extensive search of the current literature. Another complementary approach is a bibliometric analysis, and its primary focus is based on extracting the most noteworthy data from scientific databases such as the Web of Science (WoS) or Scopus [19,20].

Many review papers deal exclusively with solar PV integration such as, Hudson and Heilscher [21] who presented the issues and utility concerns of the system management for PV grid integration. In other investigations, an overview of solar PV integration into power networks has been discussed [22–24]. A comprehensive review of PV inverters on grid-connected PV applications is given in [25–29]. Haque and Wolfs [30], and

Karimi et al. [31] provide a detailed study of the technical impacts of the high PV penetrations in the power networks.

Several bibliometric studies have been conducted, such as solar energy technologies [4,32], solar energy management [33], thermal energy storage [34–36], concentrating solar power development [37], solar cooling [38,39], and solar pumping irrigation. The last ten-year period has witnessed a yearly increase in the number of studies concerning the integration of solar PV into power networks. Nonetheless, to the authors' best knowledge, there are no studies that have been published to date that assess the scientific evolution of the literature quantitatively and qualitatively, referring to the theory and practice of integrating solar PV systems into power networks from a bibliometric perspective, which is our main objective and motivation for carrying out this work.

Based on this literature gap, we formulated the following research question, which guided the construction of this article: How does the bibliometric analysis regarding the integration of solar PV systems into power networks help to create and explore future research?

This study attempts to fill this gap and aims to determine the characteristics of the worldwide literature regarding the integration of solar PV systems into power networks within the field of interest by analyzing the scientific works that were published in WoS from 2000 to 2021. The following are the main expected contributions of this study: (i) summarize the status quo of the global research on the integration of solar PV power plants into power networks; (ii) identify and analyze the scientific publication growth, the most influential authors, institutions, countries, journals, and the degree of existing academic collaboration between researchers, institutions, and countries; and (iii) provide scientific mapping, which includes: word clustering, frequency, and co-occurrence analysis of keywords, which was used to examine the intellectual structure, emerging and hot research lines, as well as a historical trend. Therefore, this work's results have the potential to benefit the larger academic community by drawing attention to the gaps and revealing opportunities and a roadmap for possible future research that may be performed to improve the knowledge [29,40]. The structure of the paper is organized as follows: After this introduction section, the materials and methods are described in Section 2, including data source and data processing. Section 3 presents the results and discussions, and finally, Section 4 summarizes the main conclusions and highlights the gaps, hot topics, and future trends.

2. Materials and Methods

A scientific evolution analysis is a systematic approach that uses statistical tools to examine scientific publications and the variety of documentation types they represent (quantitative analysis of publications) [41,42].

The traditional method for researching and analyzing scientific literature is to conduct an in-depth analysis of the corresponding literature using a structured literature review. This strategy has significant drawbacks. It takes time and the number of publications that can be analyzed is limited. Compared to the traditional review approach, the bibliometric study presents the trending one. It is advantageous in subjects with vast volumes of literature that are difficult to summarize by employing traditional review methods [35,43].

Bibliometrics is a collection of methodologies for analyzing bibliometric parameters and document systems as a research object [32,44], and it is an effective tool for dealing with hundreds, even thousands of publications, of related literature. It permits measuring the provided scientific production in a given region and a specific period [45–48].

The main three indicators of productivity are impact (measuring how productive the units are on other units), the integration of productivity, and its impact using several bibliometric indicators. Some examples of bibliometric indicators are the following: publication and citation count, the cites per paper, and citation thresholds [49]; the h-index [50,51]; the g-index [52]; and the m-quotient [53]. Any of these indexes have their own advantages and, therefore, can be used to complement each other [54]. The most commonly used metrics are the number of publications, citation count, and h-index (defined as the number of publications of an author/journal that has received at least h-times citation).

There are several indicators as mentioned above together with the average number of citations, the division of the h one by the same scientific number gives insights into the duration of each scientist's career [53,55]. The reader is also referred to Norouzi et al. [56] to see a brief explanation of each index.

The methodology that was employed in the present study is based on a similar approach, as the ones that are proposed by Aria and Cuccurullo [57], and Zupic and Čater [54]. An approach with five phases, as shown in Figure 2, includes (i) conceptualization of research, (ii) collection of bibliometric data, (iii) analysis of the collected data, (iv) visualization, and (v) interpretation.

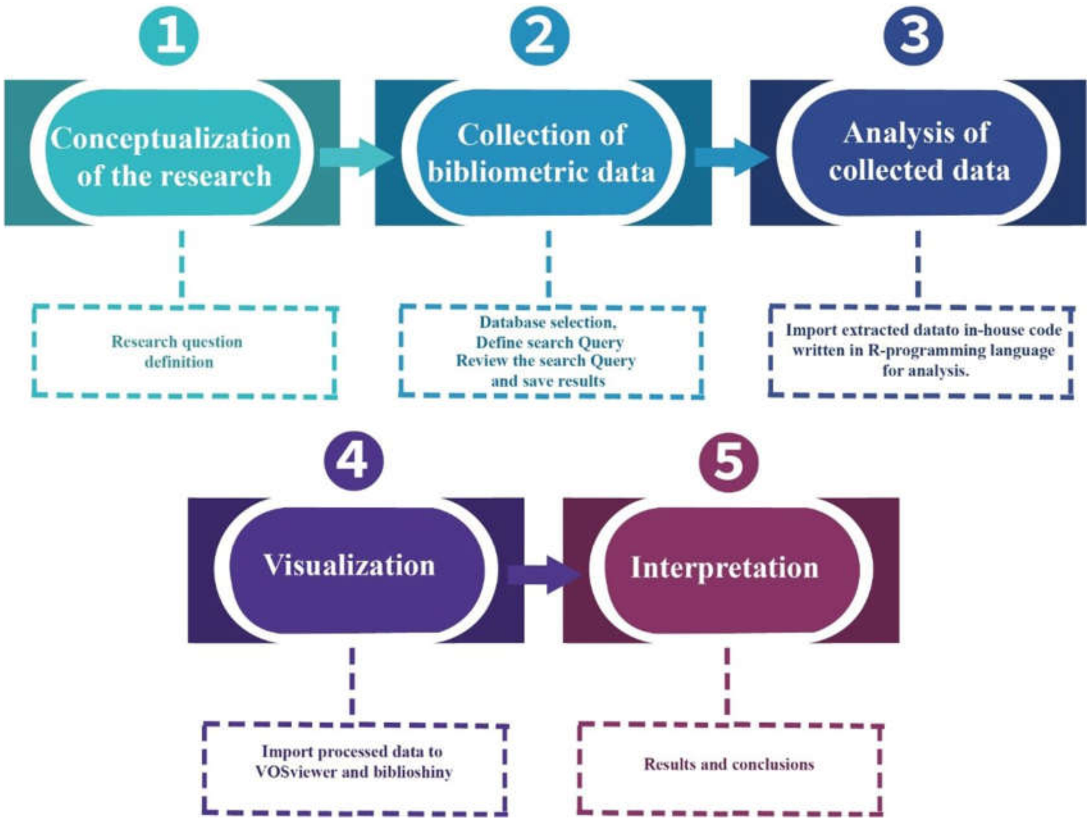

Figure 2. The methodological framework of the bibliometric analysis.

2.1. Database Selection

The first step of the methodology, as presented in Figure 2, is the research topic definition, which is followed by the data selection as the second step. Web of Science and Scopus are two of the most important citation databases. The Scopus database uses three main evaluation indicators: Source Normalized Impact per Paper (SNIP), Impact per Publication (IPP), and SCImago Journal Rank (SJR), while the WoS database uses two main evaluation indicators: impact factor (IF) and 5-year IF. Furthermore, the WoS database contains SCI and SSCI documents. It includes more than 8700 core academic journals that have the most influence in various fields [58]. Moreover, the WoS database was used similarly to the previous bibliometric study analyses that showed the WoS database contains widely accepted high-quality data in various disciplines [59,60]. Considering the features of the WoS database, this study employs WoS as a database for examining the literature on the topic that was analyzed.

2.2. Search Query

The search query is one of the most important stages and significantly influences the study results. Therefore, to obtain the most consistent results concerning the central topic of this study, the authors defined all keywords that describe the topic adequately. Secondly, wildcards are also used to map different combinations of characters in the composition of the query (e.g., "Photovoltaic*"). An extensive collection of keywords is identified by applying expert-driven semantically-related terms [61].

Equation (1). Search query used in WoS database.

$$\text{TS} = (TS_1\ AND\ TS_2\ AND\ TS_3)\ AND\ (TS_4\ OR\ TS_5) \quad (1)$$

To define the logic of the query, the first part of it ($TS_A = TS_1 + TS_2 + TS_3$), is used to capture topics that are related to RES, especially the solar PV ones. The second component ($TS_B = TS_4$) aims to collect topics that are related to the integration of PV plants into power networks. The third part ($TS_C = TS_5$), is to capture energy storage technologies. The complete list of terms that were used in the search query (TS) can be consulted in Appendix A.

In data cleaning, non-relevant categories (i.e., biology, medicine, etc.) were removed from the results. Additionally, an exhaustive effort was made to verify the congruence of the findings by means of skimming the titles and abstracts.

2.3. Research Tools

In this study, the Bibliometrix R package [54] was used to carry out the bibliometric citation analysis and comprehensive scientific mapping analysis. Moreover, VOSviewer, a free software package that was developed by Van Eck and Waltman [62] was employed to create and visualize the citation density networks and collaboration networks for scientific publications, authors, journals, countries, institutions, and keywords [63].

In addition to the Bibliometrix R package and the VOSviewer software, an in-house bibliometric tool was used to carry out the following tasks: Firstly, the repetitive terms that are written in different ways (such as singular and plural forms, abbreviations) were standardized, and merged. For example, "Photovoltaic", "Photovoltaics", "Solar PV", and "PV", were merged into "Photovoltaic". Secondly, the authors' keywords are visualized in Figure 9 using an R programming in-house tool to see the research content evolution in the topic analyzed.

3. Results

In this bibliometric study, the WoS Core Collection database for the period 2000–2021 was employed to extract data, the language was selected as "English", and the document type was limited to scientific articles, proceeding papers, and reviews. The search query in Equation (1) was used for the topic field. The data were collected on the 14th of July 2021. The following subsections present and discuss the findings of this study.

3.1. General Trends

The search criteria that was used in this bibliometric study summarized a total of 7146 documents that were published between 2000 and 2021. The publications were retrieved from 2074 scientific journals. The most frequently used document type was "Article", which accounted for 49.9% (3566 records) of total publications, followed by "Proceeding papers" with 44.4% (3174 records), and followed far behind by "Review" with 5.7% (406 records). The keyword plus, author's keywords, average citations per document, collaboration index, and annual growth rate are also provided in Table 1.

Table 1. General information about the dataset collection of integration of solar PV systems into power networks during 2000–2021.

Description	Results
Type of documents	
Journal articles	3566
Proceedings papers	3174
Review papers	406
Sources (Journals)	2074
Keywords plus	3631
Author's keywords	14,242
Average citations per document	15.49
Collaboration index	2.52
Annual growth rate	20.4%

According to the data that were collected, the total of publications per year regarding the topic under analysis is summarized and shown in Figure 3. The overall period can be split into two phases, before and after 2011. As shown in Figure 3, growth was slower until 2011, this evolution is then accelerated, with an annual growth rate of 20.4%.

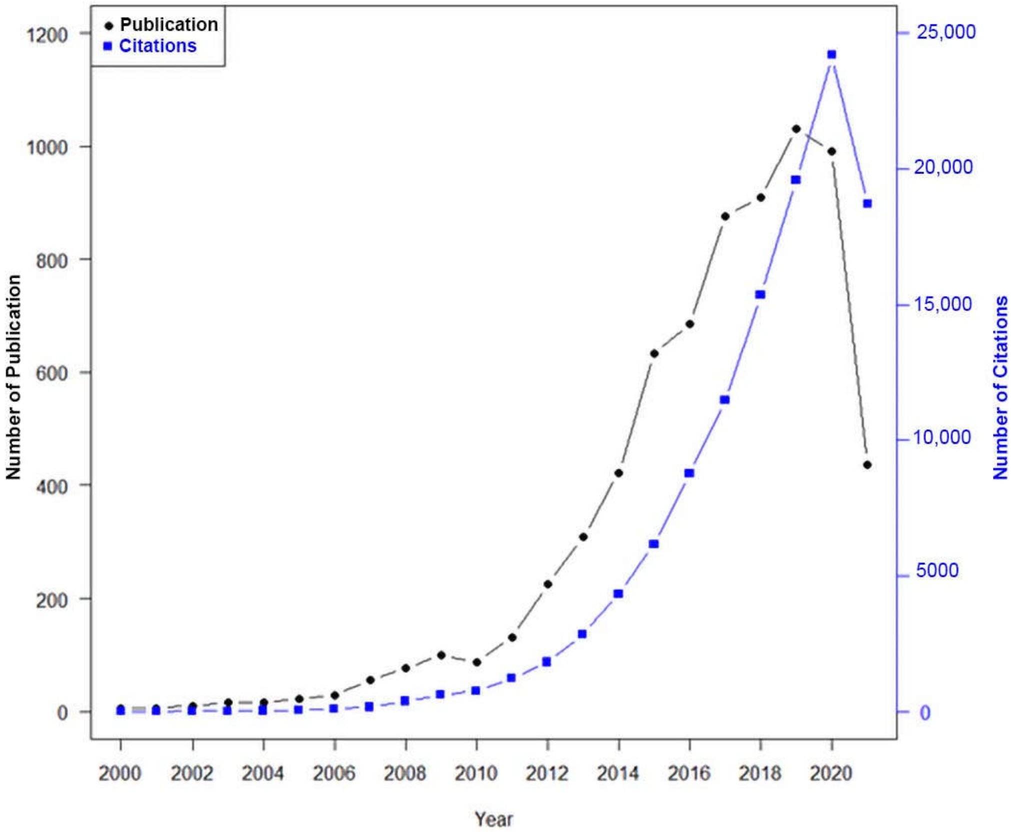

Figure 3. Evolution in the number of publications and the number of citations related to the integration of solar PV systems into power networks during 2000–2021.

This field has been growing in the last 10 years in the scientific sector, as shown in Figure 3. This fact indicates that this field is in significant growth, which is supposed to become a vast market deployment in the near future. Besides this, 95.3% of the publications (6808 out of 7146 publications) were published within 2010–2021 and 71.8% of the total publications (5129 out of 7146 publications) were published since 2015.

The annual distribution of the number of citations follows the publication trend, as depicted in Figure 3; the total number of citations accumulated attained a maximum of 24,201 around the year 2020. As expected, the citations are reduced in the last year that is not complete yet and does not include more recent publications. This demonstrates the uniqueness of this research concerning the integration of solar PV systems into power networks.

The number of publications in 2021 is 505, which is significantly less than the previous year. The reason behind this is that the data collection extends until the 14th of July 2021; thus, the later publications that should be categorized in the year 2021 are not yet included in our dataset.

3.2. Country/Area Statistics

From 2000 to 2021, 133 countries have contributed to publishing on the topic that was analyzed. In Table 2, the top 15 productive countries are ranked concerning the total number of publications.

The top 15 countries are responsible for more than 67% of the world's total publications. There were six Asian countries, five European countries, two from North America, one country from Oceania (Australia), and one from Africa (South Africa) that appeared as the most productive countries concerning this topic and its analysis.

Table 2. Top 15 publishing countries in the integration of solar PV systems into power networks during 2000–2021.

Country	TP	TC	SCP	MCP	TC/TP
India	992	9804	918	74	9.88
China	754	10,067	600	154	13.35
USA	592	11,943	495	97	20.17
Italy	324	6065	260	64	18.72
Spain	282	8573	206	76	30.40
Germany	268	4612	197	71	17.21
Australia	257	3974	193	64	15.46
Iran	222	5815	173	49	26.19
Malaysia	172	4271	108	64	24.83
Canada	171	3561	121	50	20.82
Japan	171	1507	132	39	8.81
United Kingdom	155	2714	103	52	17.51
France	133	1622	96	37	12.20
South Africa	130	1074	102	28	8.26
Korea	117	1907	83	34	16.30

TP = Total number of publications, TC = Total number of citations, TC/TP = Average citations per document, SCP = Single country publications, MCP = Multiple country publications.

As shown in Table 2, India is the leading country in total publications (992), mainly due to the government's strategic and long-term industrial policy [64,65]. India's government adopted a policy of 175 GW of grid-connected renewable energy capacity in 2022 and 450 GW in 2030 [66,67].

Regarding the number of publications, China (754) and the United States (592) come in second and third, respectively. It is worth mentioning that China ranks second for the number of publications that are produced by a single country, while China remains at the top of the list of the number of international collaborative publications. The top 3 are also the biggest emitters of carbon dioxide. Also, other countries, such as Italy, Spain, Germany, Australia, and Iran, show relevant production. The massive amount of scientific publications demonstrate the EU's growing interest and investment. This is mainly due to the adoption of two essential strategies to support the Green Deal's energy [68]: the 'EU Strategy for Energy System Integration' and the 'EU Hydrogen Strategy', with the goal of bringing the entirety of Europe's energy generation to 100% renewable sources by 2050 [69,70].

To further understand the collaboration pattern between the countries, the software (VOSviewer) is used to generate the countries' academic interactions based on joint publications related to author affiliation as well as an analysis of their interactions. Note that "UK" refers to England, Scotland, Wales, and Northern Ireland as members of the European Union (EU-28), whereas "China" refers to mainland China, Hong Kong, Macao, and Taiwan.

The thickness of the links and the node size corresponds to the number of documents that were published and the number of publications that the countries jointly issued, respectively, and the distance between two nodes reflects the intensity of their relationship. A shorter distance represents a higher degree of similarity, and the color indicates the cluster into which an item is entered [71]. In order to be included in the co-authorship network, a country must have 35 publications.

It can be seen from Figure 4 that the EU has a strong collaboration with China, the USA, India, and Australia, followed by remarkable collaborations between China and the USA, Australia, Japan, and Iran. Three main clusters were identified in Figure 4. The first cluster (in red) led by the EU, includes Australia, Canada, Malaysia, Brazil, Switzerland, and others. The second cluster (in green) led by India comprises of China, the USA, Iran, Japan, etc. The third cluster (in blue), led by South Africa, includes Turkey, Norway, Algeria, Morocco, and the United Arab Emirates (UAE).

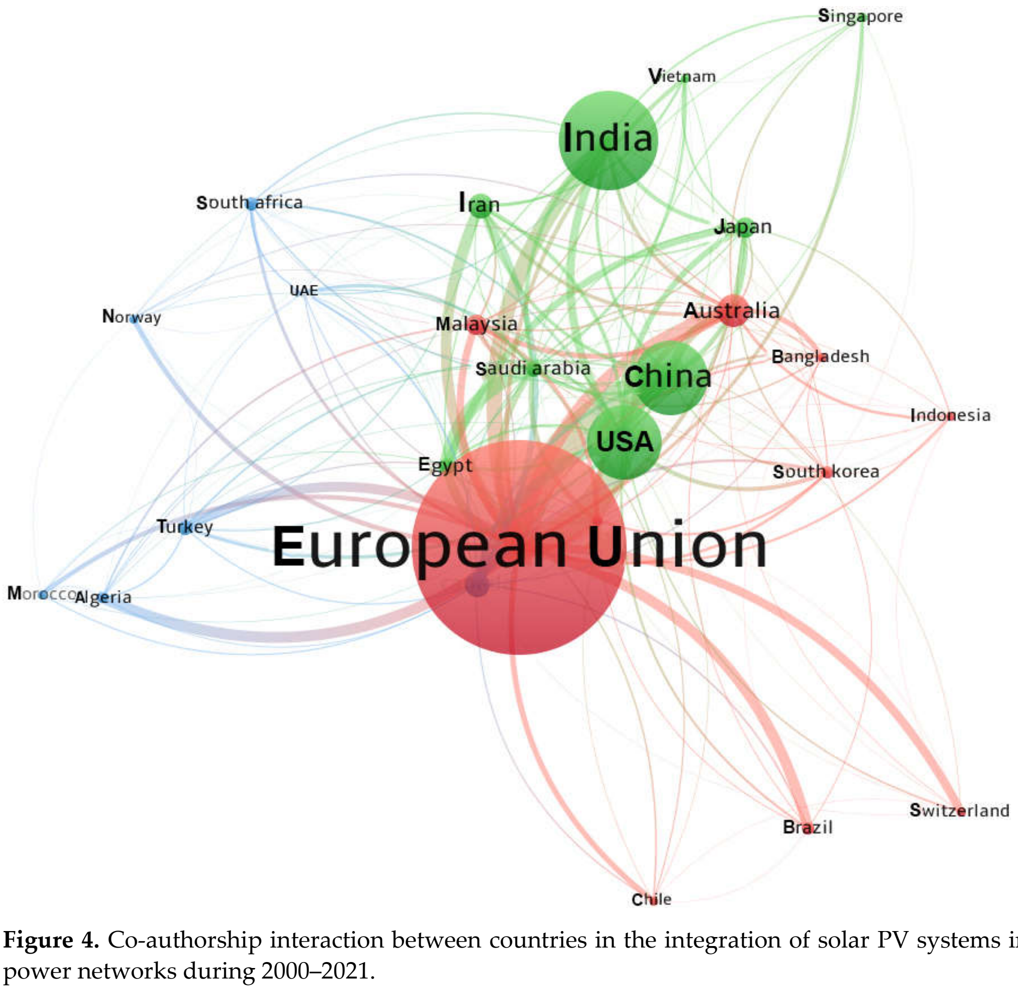

Figure 4. Co-authorship interaction between countries in the integration of solar PV systems into power networks during 2000–2021.

Figure 5 complements Figure 4 and illustrates the interaction of the European countries' publications on the topic that was analyzed. It is clear that there are five major publishing countries in Europe: Italy, Spain, Germany, the United Kingdom, and France. All of them are ranked among the top 15 most productive countries concerning the topic under analysis (Table 2). As seen in Figure 5, there is a high level of interaction among them as well as sharing authorship with all the remaining countries.

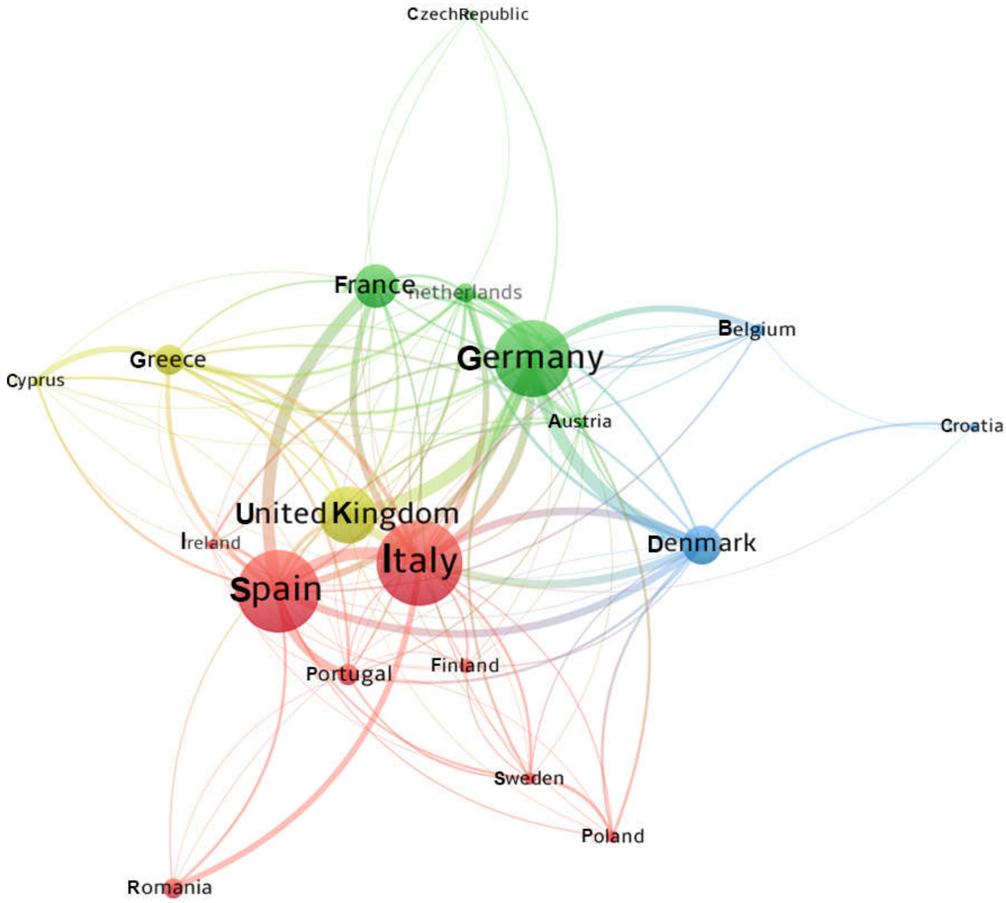

Figure 5. Co-authorship interaction of the European countries in the integration of solar PV systems into power networks during 2000–2021.

3.3. Institution and University Statistics

Information from the authors' institutional affiliations showed that they were distributed among a total of 4890 institutions. Table A1 provides a list of the top 15 productive institutions regarding the publication amount. Among them, three are from China; two from Iran, Spain, and Malaysia; and one each from Denmark, India, the USA, Italy, Portugal, and Singapore.

The university with the highest number of research contributions was Aalborg University in Denmark with nearly 2% of the field's entire global publications. (126 publications), followed by North China Electric Power University in China (109 publications), and then Iran's Islamic Azad University (93 publications).

The corresponding cooperation network diagram between the leading research organizations is shown in Figure 6. In order to facilitate the analysis, the minimum number of publications for an institution to appear in the cooperation network was set to 25. A total of 40 institutions matched these criteria, with five clusters identified in Figure 6. Concerning the number and width of the links in the figure, the strongest co-authorship links can be observed between Aalborg University (Denmark) and Islamic Azad University (Iran), National Renewable Energy Laboratory (USA), and Polytechnic University of

Milan (Italy), Indian Institute of Technology Delhi (India) and Nanyang Technological University (Singapore), and North China Electric Power University (China) and Tsinghua University (China). These universities are ranked among the top 15 most productive institutions concerning the topic under analysis (Table A1).

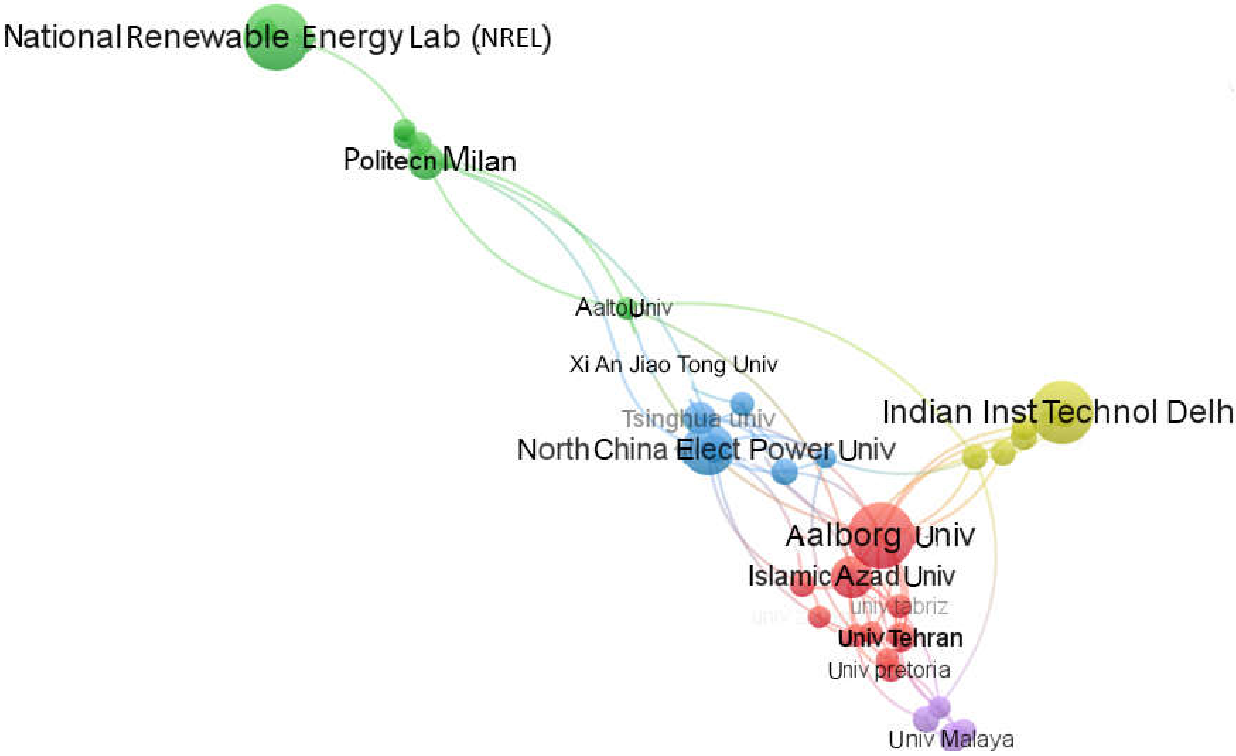

Figure 6. Collaboration network of institutions in the integration of solar PV systems into power networks during 2000–2021.

3.4. Journals Statistics

A total of 7146 studies were published in 2074 journals and/or conference proceedings. These journals are classified in various research areas: i.e., engineering, energy fuels, computer science, mathematics, environmental science, science and technology, and economics. This indicates that the topic under analysis has piqued the interest of a wide range of scholars in a variety of sectors as a viable approach for promoting other areas, both economically and environmentally.

Table 3 consists of a list of the top 15 most productive journals based on the number of their publications. These 15 journals account for 28.5% of the world's publications in this field. We analyzed several factors that were reported in Table 3 to identify the most significant journals concerning the topic under analysis.

Among them, Energies was the journal with the most publications, 328 publications (4.58%) and an impact factor (IF) of 3.00. Regarding the number of publications, Renewable & Sustainable Energy Reviews (IF = 14.98) with 237 records (3.31%), and Renewable Energy (IF = 8.00) with 234 publications (3.27%) came in second and third position, respectively.

Table 3. Top 15 source journals of the study in the integration of solar PV systems into power networks during 2000–2021.

Sources	TP	TC	TC/TP	Local h-Index	IF (2020)	IF (5 Years)	Best Quartile
Energies	328	2529	7.71	23	3.00	3.09	Q1
Renewable & Sustainable Energy Reviews	237	15,829	66.79	64	14.98	14.92	Q1
Renewable Energy	234	8543	36.51	53	8.00	7.44	Q1
Applied Energy	208	7945	38.20	46	9.75	9.95	Q1
Energy	193	5785	29.97	46	7.15	6.85	Q1
Energy Conversion and Management	137	5153	37.61	43	9.71	8.95	Q1
International Journal of Hydrogen Energy	112	3642	32.52	35	5.82	5.24	Q1
IEEE Access	97	658	6.78	15	3.37	3.67	Q1
Sustainability	88	552	6.27	14	3.25	3.47	Q1
Solar Energy	74	3044	41.14	27	4.67	5.62	Q1
Journal of Cleaner Production	71	1246	17.55	21	7.25	9.44	Q1
International Journal of Electrical Power & Energy Systems	67	2088	31.16	25	4.63	4.85	Q1
Iet Renewable Power Generation	66	1425	21.59	18	3.93	4.24	Q2
International Journal of Renewable Energy Research	66	361	5.47	10	–	–	Q3
Energy Policy	62	1884	30.39	25	6.14	6.58	Q1

TP = Total number of publications, TC = Total number of citations, TC/TP = Average citations per document, Local h-index = h-index calculated from our dataset, IF (2020) = Impact Factor (2020 Journal Citation Reports®).

As shown in Table 3, Renewable & Sustainable Energy Reviews with the highest impact factor (IF = 14.98), was ranked first. In accordance with the h-index (h = 64) and total citations (TC = 15,829), followed by Renewable Energy (h = 53, TC = 8543) and Applied Energy (h = 46, TC = 7945).

According to the average number of citations per document (TC/TP), Renewable & Sustainable Energy Reviews, Solar Energy, and Applied Energy are the top three journals although they are ranked 2nd, 10th, and 4th regarding the number of records, indicating these journals are of the highest quality.

3.5. Author Statistics

According to the findings, 17,471 authors have contributed to publishing on the integration of solar PV systems into power networks. Where necessary, duplicated author profiles have been removed from the database, which is especially common among Chinese authors. Table A2 provides some bibliometric indicators, such as the number of author's publications, the number of citations, the h-index, the g-index, as well as the m-quotient, which facilitated the identification of the most relevant authors.

Table A2 shows the 15 most productive authors in terms of the number of publications. Among them, three are from Denmark, three are from China, and one is from each of the following countries: Australia, Canada, India, Japan, Malaysia, Portugal, Spain, Saudi Arabia, and the United Arab Emirates.

Amongst these authors, Bhim Singh is the most productive one, with 44 publications and a local h-index equal to 8, from the Indian Institute of Technology Delhi, India. According to the number of publications, Frede Blaabjerg, with 37 publications, and a local h-index equal to 15, has the highest number of citations (3762) and an average number of citations per document (TC/TP) of 101.7 that is the highest one within the top 15 most productive authors. Meanwhile, Josep Guerrero, with 34 records, has the second-highest number of citations (1702), with an average number of citations per document (TC/TP) of 54.9. In addition, he holds the highest local h-index (16) among the top 15 authors. Both are from the Aalborg University in Denmark, and they are ranked second and third, respectively.

Furthermore, as indicated in Table A2, Francisco Jurado from the University of Jaén in Spain is the top-ranked author in terms of the m-quotient parameter, indicating his emergence as an author. His publication output has been steadily increasing over time and accounts for this author's rise to prominence.

Figure 7 illustrates these top authors' productivity in the integration of solar PV systems into power networks over the past two decades. It is worth noting that the author with the most extended trajectory in this field was Frede Blaabjerg from the Aalborg University in Denmark. Moreover, other authors from the same University (Josep Guerrero and Yongheng Yang) have been actively working in this field since 2008 and 2012, respectively. The author Bhim Singh, from the Indian Institute of Technology Delhi, has recently produced a significant amount of research output within this domain.

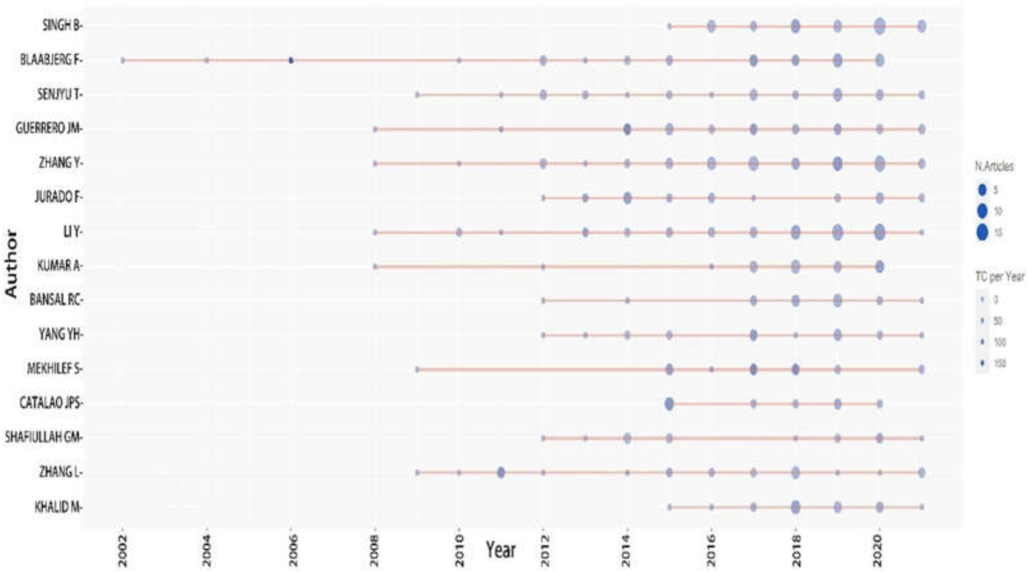

Figure 7. Time evolution of the top 15 authors in the integration of solar PV systems into power networks during 2000–2021.

3.6. Research Hotspots and Evolution

Keywords summarize research articles and highlight and refine the research's main topic. We focused on the author's keywords instead of all the keywords in order to obtain a more precise pattern identification analysis in this study [72].

With the help of VOSviewer, the keywords co-occurrence network with the authors' keywords in the integration of solar PV systems into power networks during 2000–2021 is illustrated in Figure 8. In order to create this knowledge map (network), groups of keywords that relate to the same subject were merged (for example, "photovoltaic", "PV", and "photovoltaic systems" are given as "photovoltaic").

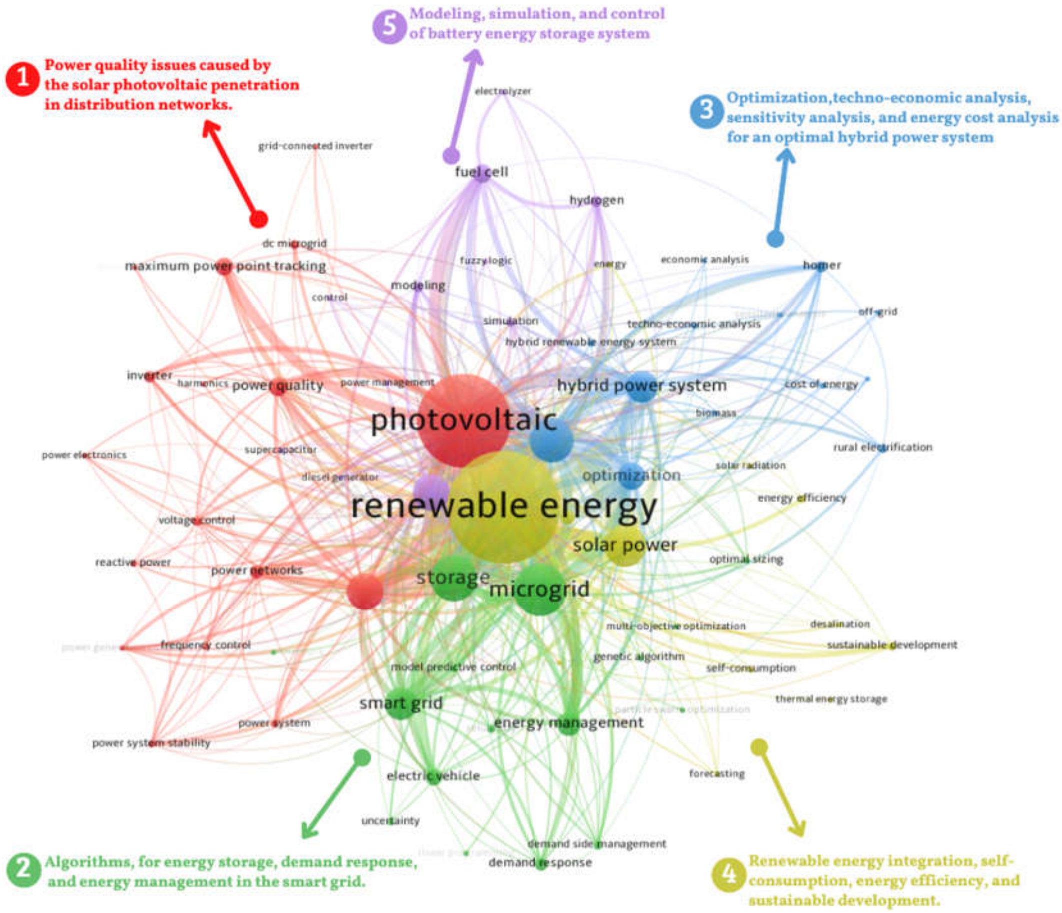

Figure 8. Map based on the co-occurrence of the authors' keywords in the integration of solar PV systems into power networks during 2000–2021.

The node's size reveals the keywords frequency. The co-occurrence frequency of the keywords is represented as an edge between two nodes, with a thicker line corresponding to a higher frequency. The minimum number of keyword occurrences is limited to 30 in order to facilitate the analysis. There are 69 nodes and 24,380 links in total, divided into five clusters:

1. Power quality issues that were caused by the solar PV penetration in distribution networks (red color).
2. Algorithms, for energy storage, demand response, and energy management in the smart grid (green color).
3. Optimization, techno-economic analysis, sensitivity analysis, and energy cost analysis for an optimal hybrid power system (blue color).
4. Renewable energy integration, self-consumption, energy efficiency, and sustainable development (yellow color).
5. Modeling, simulation, and control of battery energy storage system (purple color).

As shown in Figure 8, the most significant cluster is cluster 1 (in red color). Analysis of the data revealed that this cluster's main concept surrounds power quality-related issues that are caused by the solar PV penetration in distribution networks, as can be gathered from the terms such as: "photovoltaic", "power electronics", "power quality", and "power system stability", "frequency control", "grid-connected inverter", "harmonics", and "reactive power". The impact of PV installations on power systems is becoming more noticeable as the number of PV installations is growing worldwide. Several studies [73–75] have been performed to measure the PV systems' penetration impact in power networks. Power quality, the power imbalance between generation and load demand, and voltage and frequency fluctuation are the operational and safety issues that have arisen due to the high penetration of the PV systems [76–78]. According to Karimi et al. [31], voltage and harmonics are the primary challenges for PV integration. On the other hand, Haque and Wolfs [30] emphasized overvoltage and voltage imbalance issues.

The "maximum power point tracking" (MPPT) technique for the PV system under partially shaded conditions (PSCs) has been studied extensively. In order to mitigate the negative effects of PSCs on PV power generation, one solution is to change the hardware circuit of the PV array, such as incorporating the switch matrix to reorganize the PV system configuration [79].

Modifying the tracking algorithms is another option. The global maximum power point tracking (GMPPT) approach [80,81] refers to a collection of updated algorithms. The GMPPT approach is less expensive, has less circuit complexity, and is more flexible than hardware-based improvements. "Particle swarm optimization" and "fuzzy" algorithms are among the intelligent algorithms that are presented in [82–84]. This leads to another cutting-edge research area which is the dynamic reconfiguration of PV module interconnections within a PV array.

As can be seen in Figure 8, the most repetitive nodes in Cluster 2 (in green color) are: "microgrid", "smart grid", "storage", "energy management", "demand response", "multi-objective optimization", "genetic algorithm", and "particle swarm optimization". These keywords reflect that the applications of the advanced algorithms to optimize the problem of energy storage and energy management in the microgrid and the smart grid have piqued researchers' interest. One or more objective functions may be involved in energy management and control optimization in a microgrid [85]. These may include reducing costs (fuel, operating, and maintenance costs), and the cost of deteriorating storage elements such as batteries or capacitors.

With regard to this cluster, the authors in reference [86], provide a generalized framework for intelligent energy management of a microgrid using artificial intelligence algorithms with multi-objective linear programming optimization. Marzband et al. [87] presented an enhanced real-time energy management system for microgrid systems; this technique uses genetic algorithms to minimize carbon dioxide emissions and energy costs while maximizing the potential of existing renewable energy sources.

Zhao et al. [88] employed a genetic algorithm that was combined with particle swarm optimization to find the most probable capacity model of a solar PV-wind hybrid renewable energy system with quick global convergence. Ben et al. [89] employed a fuzzy adaptive genetic algorithm to identify the optimal number of PV panels, and storage units.

Cluster 3 (in blue color) presented aspects that are related to the optimization of techno-economic analysis and energy cost analysis for an optimal hybrid power system, which can be inferred from the terms "optimization", "hybrid power system", "wind power", "techno-economic analysis", "HOMER", and "cost of energy", and these keywords reflect that the researchers are very interested in these topics. Concerning these terms, Celik [90] conducted an optimization analysis on a hybrid power system that included both solar PV and wind power. Similarly, Markvart [91] studied a PV and wind power hybrid system optimization. Diaf et al. [92] investigated a PV and wind power system from a techno-economic standpoint. Laterra et al. [93] described the procedure to develop a fuzzy logic based on multi-objective optimization to build the unit size of a grid-connected solar PV and wind power system.

Besides the aforementioned mathematical methods, HOMER (Hybrid Optimization Model for Electric Renewables) is a popular software that can handle a variety of technologies for both steady and transient simulation. HOMER has been used in several case studies to model, simulate, and optimize hybrid power systems [94–97].

Cluster 4 (in yellow color), with central nodes "renewable energy", "energy efficiency", "self-consumption", and "sustainable development", illustrates that researchers focus on sustainable development by integrating renewable energy and energy efficiency as stated in [98–103].

As shown in Figure 8, the main objective of the publications within cluster 5 (in purple color) is the modelization, simulation, and control of battery energy storage systems, especially hydrogen technologies for grid-connected applications, as can be concluded from the following keywords: "hydrogen", "fuel cell", "electrolyser", "modeling", "simulation", and "control", as mentioned in [104–107].

The application of "deep learning" has become more and more promising in the energy domain, with a huge potential for renewable energy prediction challenges, especially in the field of "photovoltaic" systems for "power forecasting". Son et al. [108], for instance, used a deep neural network approach to anticipate PV power in a "microgrid" environment, and they provided an "energy management" approach to balance between the amount of energy that was generated and the amount of energy that was required. Moreover, another study [109], presented an innovative "fuzzy logic" system for "forecasting" the output power of two "photovoltaic" power plants in Milan and Catania, Italy. Furthermore, in Wang et al. [110], PV power prediction was done using a hybrid "deep learning" model (Long Short-Term Memory—Convolutional Network).

In addition, the authors' keywords are visualized in Figure 9 using an R programming in-house tool to see the research content evolution in the topic that was analyzed. A frequency threshold of five has been defined as a minimum. From a general perspective, and according to Figure 3, the topic's number of publications is vast, with many further and deeper investigation opportunities.

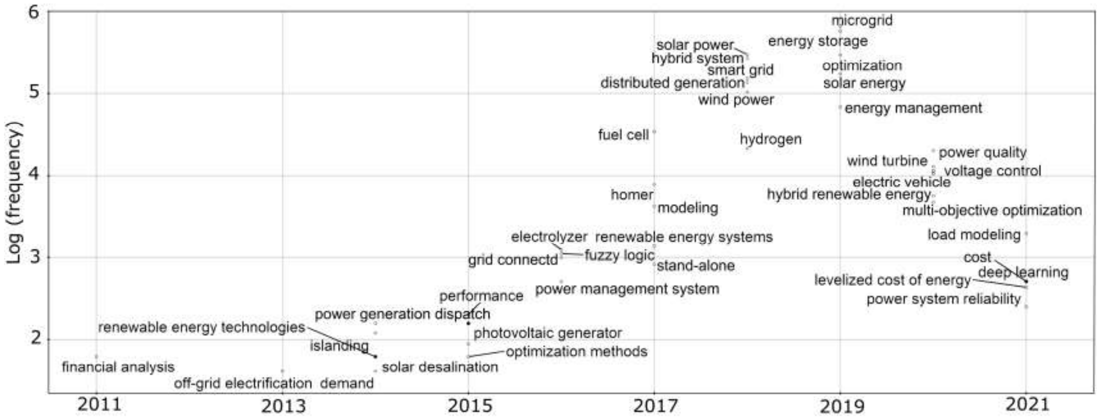

Figure 9. Map based on authors' keywords for trending topics in the integration of solar PV systems into power networks during 2000–2021.

Since there were few publications in this field between 2000 and 2012, as shown in Figure 3, the study concerns were dispersed, and the research context evolution path was unclear. However, various research areas, such as photovoltaic generators, financial analysis, solar radiations forecasting, and several PV cell materials, were prominent topics of study currently.

During 2013–2018, in Figure 9, the researchers focused on the challenges that were related to the optimization methods that applied to the integrations of PV systems into smart grids. In the same period, the performance evaluations of the hybrid renewable energy system using HOMER, and the optimization of the hydrogen storage system with the PV gained much interest.

In 2019–2021, several emerging topic research areas could be detected in Figure 9. It can be summarized as follows: (i) power quality issues due to PV system integrations in power networks, such as voltage control, current imbalance, and harmonic distortion; (ii) optimization of PV systems and energy management using advanced algorithms, including particle swarm, genetic algorithms, and fuzzy logic; (iii) techno-economic analysis for hybrid power systems (PV-wind); and (iv) optimization of battery energy storage systems, especially hydrogen technologies for grid-connected applications. As discussed in the next paragraphs, these four challenging perspectives should be considered in future development studies to improve the current knowledge that has been achieved and developed so far, thus individuating opportunities for future contributions.

In recent years (2019–2021), the concepts of "power quality", "voltage control", "power system reliability", "uncertainty", and the integration of "photovoltaic" systems in "microgrid" are found to be the top keywords for authors as can be seen in Figure 9 and Figure 8's cluster 1 (in red), and as highlighted in [74,75]. Moreover, Metwaly and Teh [111] presented two approaches; (i) to determine the different combinations of "battery energy storage system power" ratings, and energy capacity, as well as their implications on the "power system reliability"; and (ii) an adoption technique to evaluate a "battery energy storage system" that includes "demand response" and dynamic thermal ratings.

Emad et al. [112] presented an optimal "techno-economic" design of "hybrid renewable energy" sources, which include "photovoltaic", "wind", and a "battery energy storage system" for a "microgrid". Their research is based on an optimization process to meet load demand while minimizing "energy costs" using "HOMER" software, "particle swarm optimization", and a "genetic algorithm".

Another topic of recent interest includes the optimization of PV systems and energy management using advanced algorithms, including particle swarm, genetic algorithms, and fuzzy logic as can be concluded from cluster 2 (in green) in Figure 8 and Figure 9's authors' keywords, as well as highlighted in [86,93,113,114]. Furthermore, another hot topic is techno-economic analysis for hybrid power system (PV-wind) using mathematical techniques and HOMER, as can be seen from the following authors' keywords "techno-economic", "hybrid renewable system", and "HOMER" in Figure 9, and the cluster 3 (in blue) in Figure 8, and also stated in [90,95,96,115,116]. An additional hot topic is the optimization of hydrogen energy storage technologies for grid-connected applications as can be summarized from the following concepts "hydrogen", "fuel cell", "electrolyser", "modeling", "simulation", and "control" in Figure 9, and the cluster 5 (in purple) in Figure 8, as also mentioned in [104–107,117].

4. Conclusions

This review article with bibliometric analysis is beneficial for a comprehensive and quantitative understanding of the development trends in the integration of photovoltaic systems into power networks. It aims to summarize the evolution of the research in the field as well as point out potential research directions for future studies. We evaluated the current research progress and trends of integration of photovoltaic systems into power networks research, summarizing some publication characteristics such as countries, academic collaboration, journals, and authors. It was developed using data from the WoS database from 2000 to July 2021. With the help of advanced data analysis and visualization tools such as the Bibliometrix R-package and VOSviewer, a total of 7146 publications were analyzed.

The analysis that was performed shows a steadily increasing number of publications on the integration of photovoltaic systems into power networks. A total of 95.3% of the records are published since 2010, with an average annual growth rate of 20.4%, and the numbers continue to grow.

The results revealed that India is the leading country concerning total publications (992); however, it is ranked 9th with regard to the number of citations per document, indicating that the impact varies considerably. Regarding the number of publications, China (754) and the United States (592) come in second and third, respectively. Furthermore, the Aalborg University in Denmark has the maximum contribution in terms of the total volume of studies with nearly 2% of the world's publications in this field, followed by North China Electric Power University in China (109 publications), and then Iran's Islamic Azad University (93 publications). Among the top 10 most productive authors, the author Bhim Singh from the Indian Institute of Tech Delhi (India) has the highest number of publications (44) and a local h-index equal to 8. Frede Blaabjerg has 37 publications, a local h-index equal to 15, and the highest average number of citations per document (TC/TP) of 101.7. Additionally, Josep Guerrero, with 34 records, has the highest local h-index (16) among the top 15 authors. Concerning the number of publications, they are ranked second and third, respectively. The study also revealed that the three journals with more publications are Energies with 328 publications (4.58%), Renewable & Sustainable Energy Reviews with 237 records (3.31%), and Renewable Energy with 234 publications (3.27%).

Based on the co-occurrence analysis, the results revealed that interesting emerging keywords that are likely to gain attraction in the coming period are divided into five clusters: (i) power quality issues that are caused by the solar photovoltaic penetration in power networks; (ii) algorithms for energy storage, demand response, and energy management in the smart grid; (iii) optimization, techno-economic analysis, sensitivity analysis, and energy cost analysis for an optimal hybrid power system; (iv) renewable energy integration, self-consumption, energy efficiency, and sustainable development; and (v) modeling, simulation, and control of battery energy storage systems. In addition, the analysis showed that the optimal design and energy management, the power quality, voltage, and frequency fluctuation problems, as well as the technical-economic analysis, are the current research hotspots that might be considered as potential future research topics. Further research on these areas may improve the knowledge of integrating PV systems into the power network, providing new insights into promoting both energy security and addressing the environmental concerns of the sector.

The quality of the data that were used in a bibliometric study significantly impacts the study's findings. It was attempted to include a large number of the most relevant papers in the solar PV integration research. It is also recommended to expand the database that was analyzed to obtain a more global perspective of the topic, and then analyze the topic of interest using a mixed-method study (bibliometric + traditional review and survey analysis) to gain a more in-depth understanding of the topic that was analyzed. However, the authors believe that the result of this study should offer valuable indications for solar PV industries, academics, and policymakers.

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Nomenclature

EU	European Union
IF	Impact Factor
Local g-index	g-index calculated from our dataset
Local h-index	h-index calculated from our dataset
Local m-quotient	m-quotient calculated from our dataset
MCP	Multiple Country Publications
PV	Photovoltaic
PY_start	Publication Year starting
RESs	Renewable Energy Sources
SCP	Single Country Publications
TC	Total number of Citations
TC/TP	Average Citations per document
TP	Total number of Publications
WoS	Web of Science

Appendix A

Search query used in WoS database:

$$\text{TS} = (TS_1\ AND\ TS_2\ AND\ TS_3)\ AND\ (TS_4\ OR\ TS_5) \quad \text{(A1)}$$

TS = (

((“Renewable energ*” OR “Green energ*” OR “Clean energ*” OR “RES-based” OR “Renewable Power” OR “Non-conventional energ*” OR “Eco-friendly” OR “Earth-friendly”)

AND

(“Solar Energy” OR “Solar Power” OR “Solar Farm” OR “PV” OR “Photovoltaic*”)

AND

(“Self-consumption” OR “Stand-alone” OR “Grid” OR “ Autonomous “))

AND

((“Integrat*” OR “Interconnect*” OR “Multi-interconnect*” OR “Connect*” OR “Microgrid*” OR “Power energ* system*” OR “Distribution Network*” OR “Distributed generation source*” OR “Multi-source system*” OR “Hybrid multi-source” OR “multi-energy system*”)

OR

(“energy storage” OR “short term* storage” OR “Medium term* storage” OR “Long term* storage” OR “Hybrid energ* storage” OR “Thermal energy storage” OR “TES” OR “P-H2-PEM” OR “Pumped hydro” OR “CAES” OR “Molten Salt” OR “PHS” OR “Lead Batter*” OR “NaS Batter*” OR “VR-FB” OR “Ni-Cd” OR “Li-ion” OR “Batter* storage system*” OR “fuel cell*” OR “power storage” OR “flywheel*”)))

Appendix B

Table A1. Top 15 authors in the integration of solar PV systems into power networks during 2000–2021.

Affiliations	Number of Publications	Country
Aalborg University	126	Denmark
North China Electric Power University	109	China
Islamic Azad University	93	Iran
Indian Institute of Technology Delhi	54	India
Polytechnic University of Catalonia	54	Spain
Polytechnic University of Milan	52	Italy
National Renewable Energy Laboratory	49	USA
University of Malaya	49	Malaysia
Tsinghua University	48	China
Nanyang Technological University	41	Singapore
University of Tehran	41	Iran
China Electric Power Research Institute	40	China
University of Lisbon	40	Portugal
Jaen University	38	Spain
University of Technology Malaysia	38	Malaysia

Appendix C

Table A2. Top 15 authors in the integration of solar PV systems into power networks during 2000–2021.

Author	Affiliation	Country	TP	TC	TC/TP	Local h-Index	Local g-Index	Local m-Quotient	PY_Start
Singh B	Indian Institute of Technology Delhi	India	44	226	5.1	8	14	1.333	2016
Blaabjerg F	Aalborg University	Denmark	37	3762	101.7	15	35	0.75	2002
Guerrero JM	Aalborg University	Denmark	31	1702	54.9	16	28	0.6	2008
Senjyu T	University of the Ryukyus	Japan	31	308	9.9	9	17	0.818	2011
Zhang Y	North China Electric Power University	China	27	150	5.6	6	11	0.667	2013
Jurado F	University of Jaén	Spain	23	798	34.7	13	18	1.300	2012
Li Y	China Electric Power Research Institute	China	23	334	14.5	6	15	0.5	2010
Kumar A	University of Alberta	Canada	22	181	8.2	6	13	0.43	2005
Bansal RC	University of Sharjah	United Arab Emirates	20	323	16.2	10	17	1	2012
Yang YH	Aalborg University	Denmark	19	408	21.5	9	16	0.900	2012
Mekhilef S	University of Malaya	Malaysia	18	1061	58.9	10	14	1.429	2015
Catalao JPS	University of Lisbon	Portugal	17	509	29.9	8	12	1.143	2015
Shafiullah GM	Murdoch University	Australia	16	88	5.5	6	9	0.500	2012
Zhang L	China Electric Power Research Institute	China	16	673	42.1	5	8	0.417	2010
Khalid M	King Fahd University of Petroleum and Minerals	Saudi Arabia	15	282	18.8	6	12	1.000	2016

TP = Total number of publications, TC = Total number of citations, TC/TP = Average citations per document, Local h-index = h-index calculated from our dataset, Local g-index = g-index calculated from our dataset, Local m-quotient = m-quotient calculated from our dataset, PY_start = Publication year starting.

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