

# A bibliometric and scientific mapping of the research landscape and trending topics in building integrated photovoltaic systems

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## ABSTRACT

The present article aims to identify emerging trends in the building integrated photovoltaic (BIPV) field through an analysis of the most prominent articles, authors, keywords, sources, and countries through bibliometric analysis of the same. To fulfil the study's aims, 1552 articles published in Scopus databases between 1985 and 2022 are reviewed and analysed using the Bibliometrix - R software, VOSviewer, and SciMAT. Since 2016, the results indicated that the number of publications per year in this domain has consistently increased. The China, UK, and USA were the most prominent contributors to this research area in terms of overall publications and citations. In addition, the results highlight the most significant sections of the article from the perspective of the highest citations, publications, keywords, and authors. Through co-citation analysis and keyword co-occurrence network, the major knowledge base and the most prominent hot themes of BIPV study field were identified. The minimum number of co-occurrences of keywords is set to the value of five which results in 166 threshold keywords out of these 146 keywords are selected and divided into 9 clusters. Cluster-1 (Red) contains a total of 32 keywords. BIPV has the highest connection of 63 links and 67 documents followed by phase change material (52 links and 45 documents). The results pointed to a potential gap in the literature regarding the use of artificial neural networks in BIPV systems.

## 1. Introduction

Today, around 80 % of the world's energy production is based on fossil fuels, and this dependency on fossil fuel is declining in recent years [1]. Most of the energy consumed is within the buildings for lighting and air conditioning. Thus, to reduce dependency on fossil fuels for energy requirement and develop a zero-emission building, photovoltaic panels can be installed or mounted on the buildings to obtain both electrical and thermal energy. Such integrated systems are known as building integrated photovoltaic (BIPV) system which can play an important role in energy saving [2,3]. In this technology, energy-consuming buildings are transformed into energy-producing sources by using BIPV products which are used as construction components such as tiles, foils, and windows [4]. The BIPV can be installed in two ways first a rooftop and second as a facade. Rooftops are the most preferable location for integrating solar PV modules due to less shading than a facade [5]. Usually, rooftops allow a significant open surface for the BIPV system and more solar irradiation in comparison to the facade system. However, a few reports suggested the convenient use of a facade system instead of

rooftops as suitable for prestigious buildings with attractive facades and skylights [6]. There were some major concerns involved with the facade system such as town barriers and covering from neighbouring buildings or trees which can significantly affect its potential [7].

According to Azadian and Radzi [8], there are four major concerns about the use of the BIPV system: policy issues, environmental acceptance, financial issues, and technical issues. Likely, we can simply challenge popular acceptance by evaluating financial barriers. A financial analysis of a BIPV system to generate electricity has been undertaken, revealing that the net present value of BIPV systems is dependent on factors such as the higher cost of PV systems, the PV electricity tariff, and financial subsidies from the government. The stochastic nature of weather-based renewable energy systems was studied by Shayan et al. [9]. In order to attain zero greenhouse gas emissions, they recommended that HRES management incorporate 100 % renewable energy systems. Shayan et al. [10] designed, built, and evaluated elastic solar panels aided by flexible photovoltaic systems for a 1 m<sup>2</sup> scale. Their economic findings showed that the capital return time was 8.58 years with the internal rate of return is 34.81 %. The fabrication and structural

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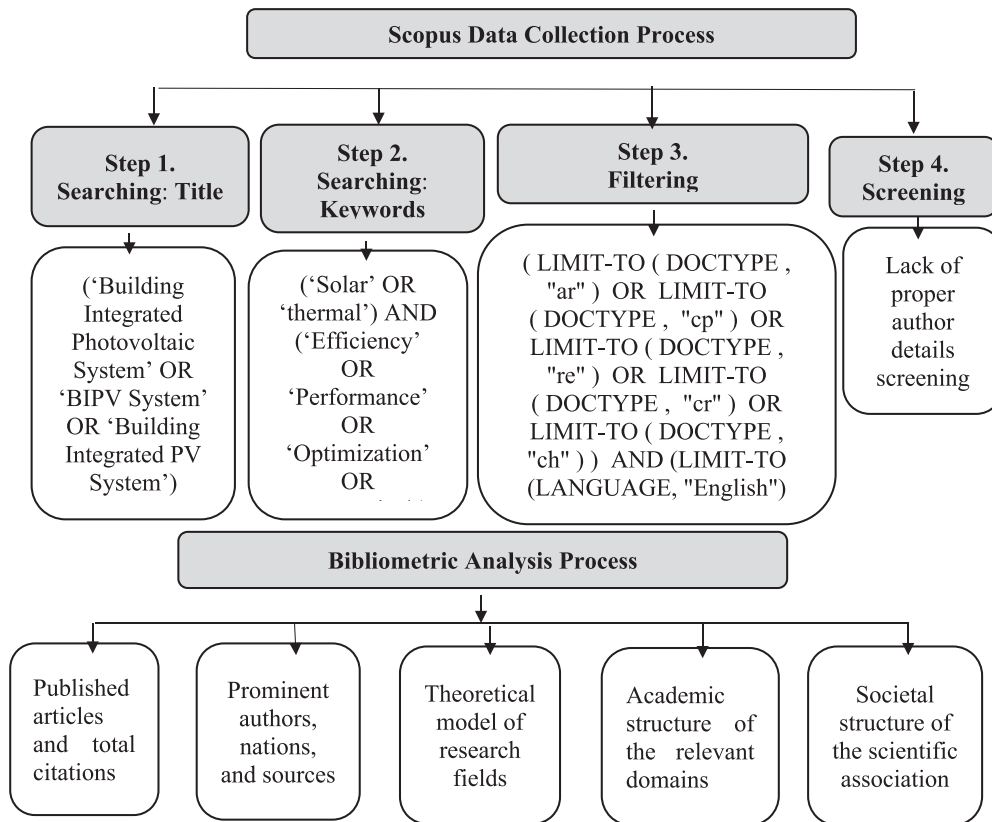


Fig. 1. Methodology for article selection and evaluation [30].

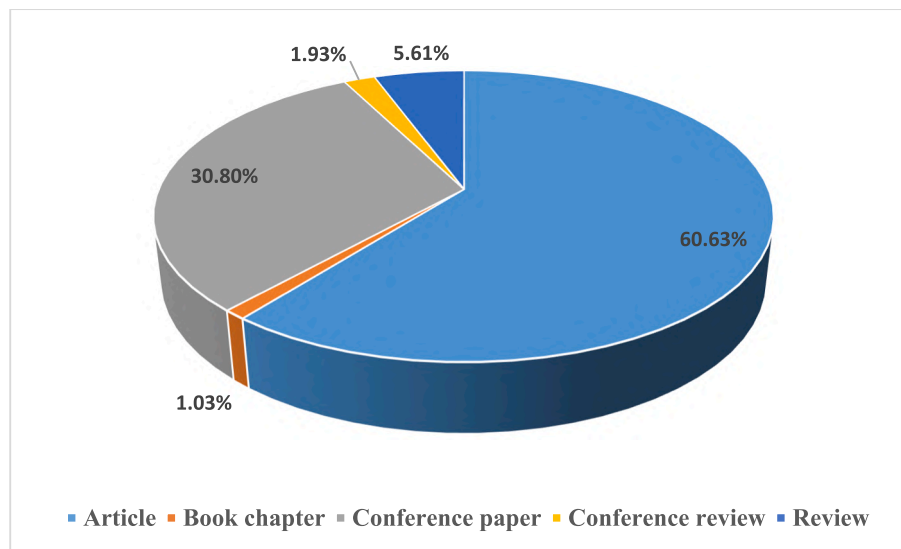


Fig. 2. Most frequent type document of BIPV system literature.

phases like ground and rooftop PV systems required primary energy and electricity [11]. Kannan et al. [12] estimated that monocrystalline silicon-based PV modules require 61.07 MJ/W of primary energy for ground systems and 51.84 MJ/W for rooftop systems. Seng et al. [13] evaluated the PV system from an economic and environmental aspect. The owners that installed the PV system achieved a profit if the PV electricity pricing was greater than RM 0.82 per kWh with a government subsidy of 50–60 % costing between RM 14,000–16,000. According to environmental considerations, 2 MWp PV systems with a lifespan of 30 years could save RM 10.26 million in natural gas (fossil fuel) and

minimize greenhouse gas emissions by 35,140 tonnes.

To enable high-performance photovoltaic (PV) modules, more materials have been developed, including amorphous silicon (a-Si), indium copper selenide, silicon, and cadmium telluride [14]. Simultaneously, the BIPV system works like a building covering materials and power generators [15]. In addition, the BIPV system does not require constructional parts i.e. brackets, bars, etc. According to surveys, flexible BIPV is the fastest-growing trend in thin-film PV modules, which are used to envelop materials such as tiles, metal roofing, and film roofing. Amorphous silicon (a-Si) could be prominent in flexible BIPV systems

**Table 1**  
Summary of bibliometric entities.

Description	Results
<b>Main information about data</b>	
Timespan	1985:2022
Sources (Journals, Books, etc)	431
Documents	1552
Average years from publication	6.09
Average citations per document	25.05
Average citations per year per doc	3.646
References	48,925
<b>Document types</b>	
Article	941
book chapter	16
conference paper	478
conference review	30
Review	87
<b>Document contents</b>	
Keywords plus (ID)	7224
Author's keywords (DE)	3482
<b>Authors</b>	
Authors	3790
Author appearances	6015
Authors of single-authored documents	64
Authors of multi-authored documents	3726
<b>Authors collaboration</b>	
Single-authored documents	105
Documents per author	0.409
Authors per document	2.44
Co-authors per documents	3.88
Collaboration index	2.57

because it is suitable for all weather conditions in comparison to thin-film PV materials such as copper indium gallium selenide (CIGS) and dye-sensitive cell (DSC) [16]. Shukla et al. [17] demonstrated that dye-sensitized PV cells of thin-film PV modules have the potential for low costs and high electricity generation. Song et al. [18] converted a thin-film solar cell into a double-glazed module using a thick layer of transparent glass to investigate the output power according to the inclination position and azimuth angle on a full-scale model and compare it to the simulation results for PV modules. The PV module installed at an angle of 30° south facing and an azimuth angle of 0° produced a greater yearly power production of 844.4 kWh/kWp than the horizontal and vertical PV modules with a relative inaccuracy of 8.5%. Shayan et al. [19] investigated the actual capability of flexible solar panel energy conversion. Annual energy production was observed to be 810 kWh, 960 kWh and 1000 kWh for the horizontal, cylinder and hemisphere surfaces respectively. They concluded that it was preferable to implement electrical systems on the side of the building with the greatest average amount of shade using these flexible surfaces. Apart from BIPV, some of the researchers also worked on other energy systems.

For instance, Shayan et al. [20] carried out experimental and numerical evaluation of heat transfer and pressure drop on roughness of absorber plate within the solar air heater. For both inline and staggered designs, the maximum Nusselt number was found at a dimensionless pitch-to-height ratio of 3.33 and the values of heat transfer and pressure drop were 4.87 and 4.2 times greater than that of the smooth duct, respectively.

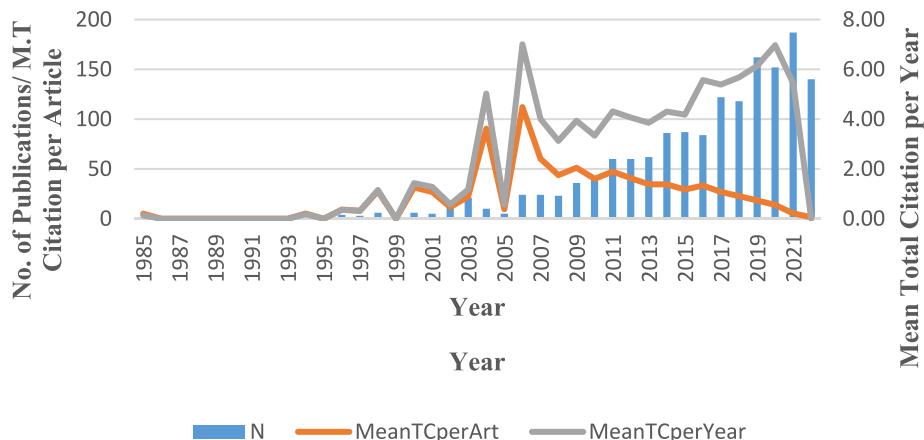
Shayan et al. [21] used a multi-criteria approach to assess various alternative fuels for a heavy-duty diesel engine, including the Taguchi method and the response surface method. The authors reported that environmental approach was highly influenced by emissions of CO and NOx, as well as gas heat. They concluded that major impact on environmental approach was through engines output.

BIPV systems are solar PV material which replaces conventional building materials in parts of the building envelopes, such as the rooftops or walls. Furthermore, BIPV are considered as functional part of building structure which can be integrated within the designs of building. To establish a thorough understanding of the various dimensions of research in the BIPV systems a bibliometric analysis is necessary in-depth. Bibliometric research which refers to the study of published statistical analyses on a particular topic allows for the rapid processing and evaluation of hundreds of papers, as well as the discovery of correlations between papers, keywords, citations, and co-citations [22]. Recent studies have used the bibliometric approach to present an overview of a variety of energy-related research topics, such as energy management techniques for hybrid electric vehicles [23], rooftop PV systems[24,25], and the use of data envelopment analysis to energy efficiency [26], but not for BIPV systems.

The main objective of this research is to use bibliometric analysis to differentiate and identify the several approaches for assessing research trends and knowledge gaps to discover the most promising areas for BIPV evolution. There are several other types of analysis, such as author analysis, country analysis, and publications analysis. As a result, bibliometric analysis is an effective tool for evaluating present and future advances in a variety of domains. [27].

The following are the key research questions for this observation:

- What was the development trend of BIPV systems between 1985 and 2022?
- What countries, authors, and sources have made the highest contributions to BIPV research?
- What research gaps in photovoltaics exist now and would exist in the future?
- What significant challenges and trends are currently arising or could emerge in the next years?
- How have the major themes of BIPV evolved?



**Fig. 3.** History of publications and citations on the BIPV system.

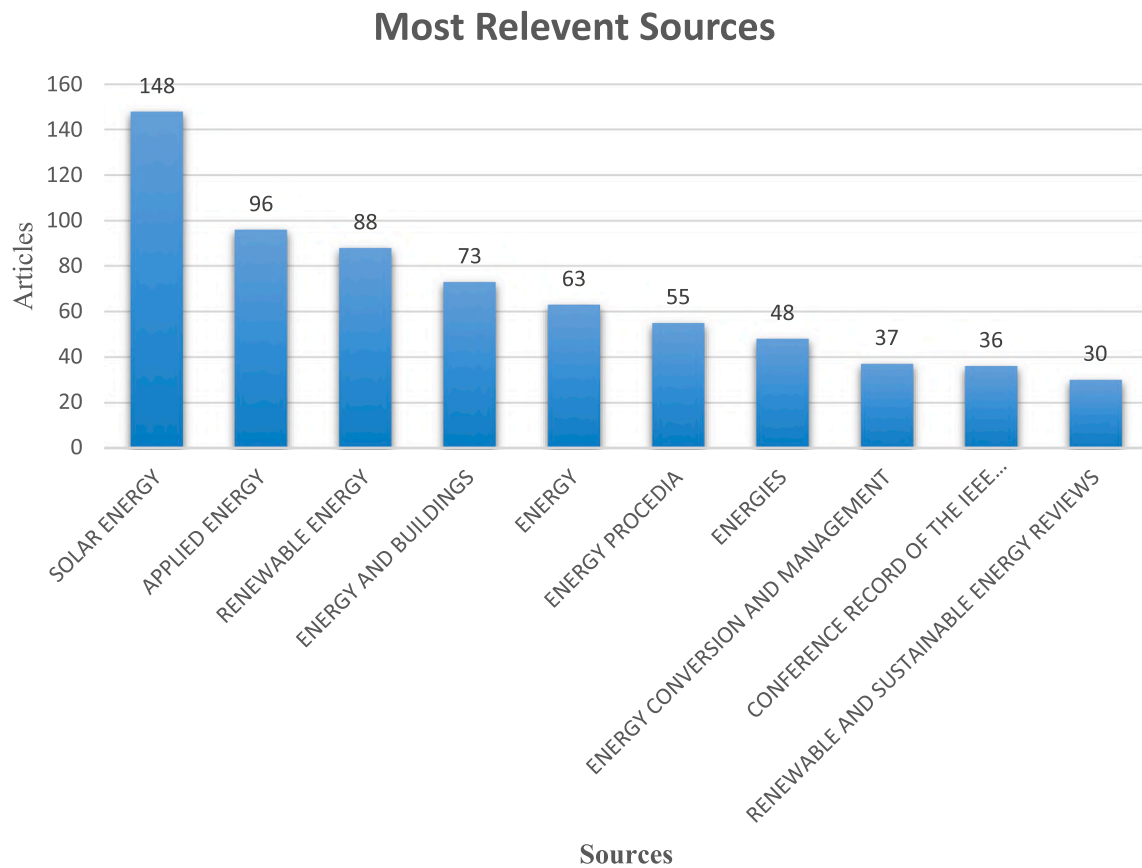


Fig. 4. Top ten impactful sources for the BIPV system.

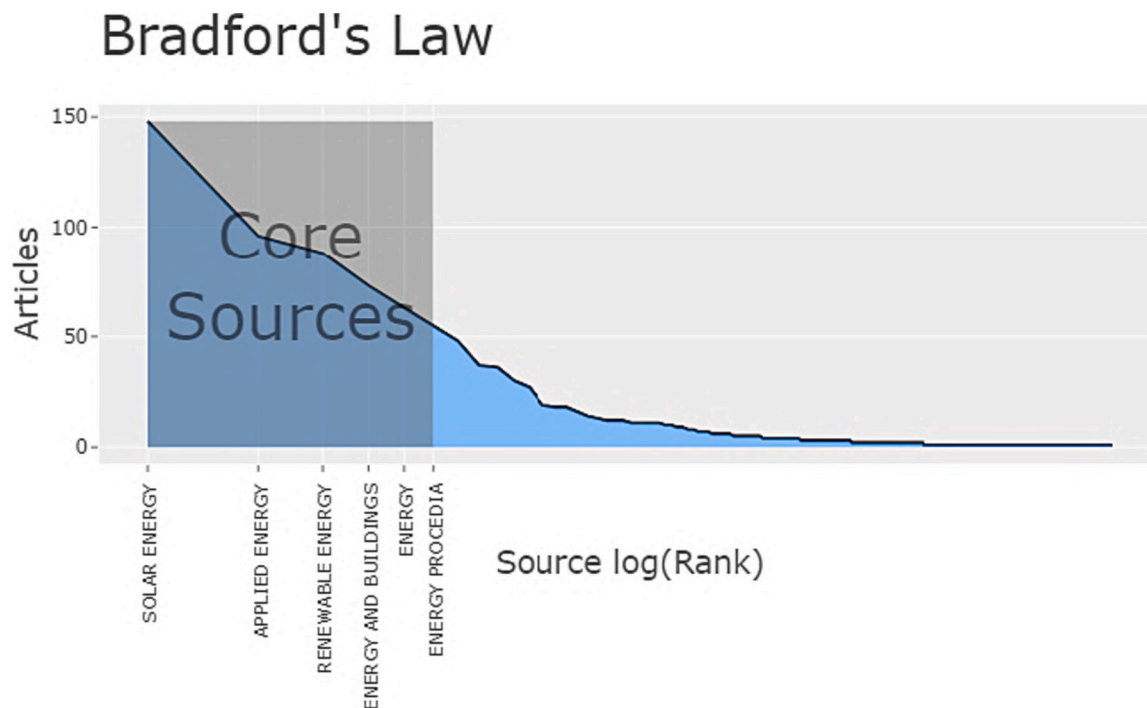


Fig. 5. Distribution analysis with Bradford's law core sources.

The current article discussed the detailed bibliometric and thematic analysis of said objectives. This kind of analysis is useful to identify the research progress, trends and gaps in the field of BIPV. The article is

presented in systematic manner discussing methodology adopted for analysis, bibliometric results analysis, thematic analysis, discussion on identified results and conclusion in different sections.

**Table 2**  
List of the leading journals contributing to the selected topic.

Source	h_index	g_index	m_index	TC	NP	PY_start
Solar Energy	46	85	1.84	8037	148	1998
Applied Energy	43	67	2.53	4658	96	2006
Renewable Energy	27	53	1.00	3145	88	1996
Energy and Buildings	38	58	1.90	3512	73	2003
Energy	26	41	1.86	1820	63	2009
Energy Procedia	18	37	1.50	1504	55	2011
Energies	14	24	2.00	616	48	2016
Energy Conversion and Management (ECM)	23	37	0.61	1594	37	1985
Conference Record of The IEEE Photovoltaic Specialists Conference	10	13	0.34	247	36	1994
Renewable and Sustainable Energy Reviews (RSER)	23	30	1.35	2835	30	2006
Sustainability	9	12	1.13	184	27	2015
Solar Energy Materials and Solar Cells	13	19	0.59	1612	19	2001
Building and Environment	12	18	0.57	720	18	2002
Journal of Cleaner Production	10	16	1.25	350	16	2015
Sustainable Energy Technologies and Assessments	5	10	1.67	102	14	2020
Progress In Photovoltaics: Research and Applications	9	13	0.33	945	13	1996
International Journal of Photoenergy	7	12	0.50	190	12	2009
Journal of Solar Energy Engineering, Transactions of The ASME	6	12	0.30	151	12	2003
Applied Thermal Engineering	7	11	0.54	297	11	2010
ASHRAE Transactions	5	9	0.29	94	11	2006
Sustainable Cities and Society	7	11	1.00	261	11	2016
Journal of Building Engineering	5	8	1.25	80	10	2019
International Journal of Energy Research	6	9	0.60	115	9	2013
Buildings	5	7	0.83	61	8	2017
Procedia Engineering	6	8	0.75	102	8	2015
Building Simulation	5	6	0.63	64	6	2015
Energy And Environmental Science	5	5	0.45	524	5	2012

(Notes: TC = Total citations, NP = Number of Publications, PY\_start: Publication year start).

## 2. Methodology

The traditional method for assessing and reviewing scientific literature is to select a structured literature review to carry out an in-depth assessment of the relevant literature [28]. But in practical implementation, this method has limitations due to more time-consuming. Bibliometric is a highly effective tool for statistically analysing the written publications of a specific research area from the perspective of the rapid increases in the number of publications [29]. The bibliometric analysis gives a broad overview of specific research areas including the major contributing nations, prominent institutions, authors, and most impactful journals and publications.

The Scopus database is used to find the related documents for the current research. Scopus is the superior database since it contains more engineering-related research documents than web of science (WoS). Present review shows the state of global studies conducted in the last 37 years (1985–2022) on BIPV systems. As a result, the following inquiry was made: (Title-abs-key, building and integrated and photovoltaic and system) OR Title-abs-key (BIPV and system) OR Title-abs-key (building and integrated and PV and system) and Title-abs-key (Solar or thermal) and title-abs-key (efficiency OR performance OR optimization OR economical) and (Limit-to (doctype, “ar”) OR limit-to (doctype, “cp”) OR limit-to (doctype, “re”) OR limit-to (doctype, “cr”) OR limit-to (doctype, “ch”) and (limit-to (language, “english”). All non-english languages were eliminated during analysis. In the end, a total of 1552 documents were retrieved. Fig. 1 demonstrate the methodology of article selection and evaluation. The ‘Biblioshiny’ function of the R package ‘Bibliometrix’ is configured to perform bibliometric analysis and visualization of equivalent VOS viewer software.

This study is carried out with respect to five different aspects to evaluate the knowledge-based literature gap regarding the performance analysis of BIPV: (i) published articles and total citations; (ii) prominent authors, nations, and sources, (iii) theoretical model of research fields; (iv) academic structure of the relevant domains, and (v) societal structure of the scientific association for relevant areas of research. For each aspect, the number of publications, citations, co-citations, keywords, and the most prominent authors, sources, countries, and institutions are determined.

## 3. Results and discussion

### 3.1. Generalized data

In this study, there are 1552 selected documents, and a total of 3,790 writers are identified, with just 105 single-authored documents. There is an average of 2.44 authors per document and the average number of citations per document is 25.05. The average number of annual publications is 6.09. Furthermore, 7224 keywords and 3482 author words have been found. The collaboration index is 2.57, which is close to the average of 2.44 authors per document. Due to the interdisciplinary nature of the topic, these numbers indicate that association between experts from other fields is required. In addition, after eliminating the results that were inappropriate for the topic under consideration and have information gaps, the bibliometric analysis of 941 (60.6 %) articles, 478 (30.8 %) conference articles, 87 (5.6 %) review articles, 30 (1.9 %) conference reviews, and 16 (1 %) books/book chapters is obtained and represented in Fig. 2. Table 1 presents this information.

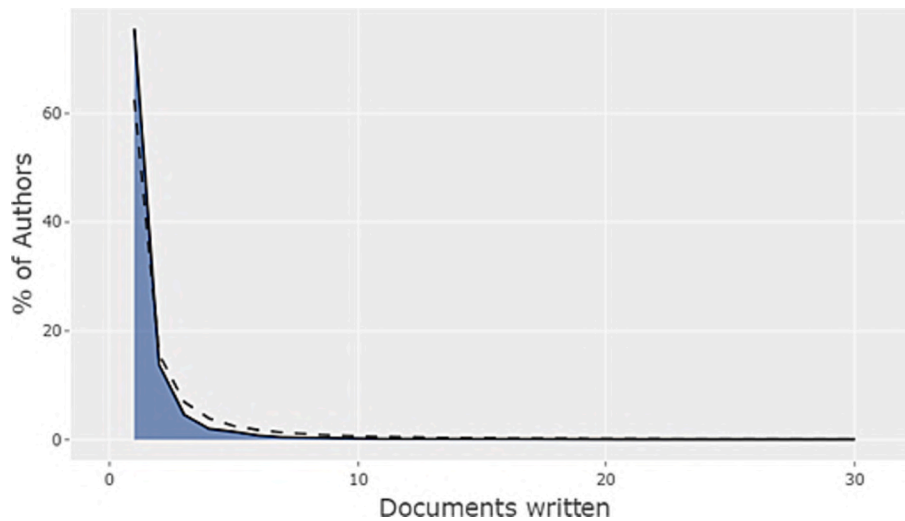
### 3.2. Analysis of bibliographic performance

#### 3.2.1. Publication and citation trends

The number of publications has increased during the past four decades (1985–2022) as per the Scopus database, [31]. The first article was published to investigate the performance of a solar air-conditioned Arabian Gulf villa. Even though this is not exactly our area of interest. However, in this study, authors proposed the utilization of solar-

**Table 3**  
Distribution of publications in journals [32].

Zone	Journal	Journal %	Articles	Articles %	Ratio	Theoretical ratio (1: n: n <sup>2</sup> )	Theoretical no. of Journals
1	6	1.39	523	33.70	0.6	1	10
2	43	9.98	520	33.50	4.3	4.3	43
3	382	88.63	509	32.80	38.2	18.49	185
Total	431	100	1552	100			238



**Fig. 6.** Frequency distribution of scientific productivity.

**Table 4**  
Top authors with a minimum of 20 papers.

Authors	Articles
Na Na	30
Athienitis A K	27
Ji J	27
Yang H	25
Mallick T K	24
Athienitis A	21
Tiwari G N	21

powered air conditioning, which was a major factor that contributes to initial research in this area.

Fig. 3 shows the published paper as well as the average number of citations per publication and year during the period of the study. The overall tendency may most likely be separated into four different stages. (i) Initial exploration (1985–1994): research on BIPV systems was in the early stage. Seven relevant articles were published during this time, six of which published in 1994. (ii) Initial development period (1995–2004): Approximately 71 papers were published during this period, with an annual average of seven; the number of articles produced exhibits a slight upward trend with fluctuations, resulting in a growth phase. (iii) Stable development stage (2005–2014): As a result of the increasing demand for renewable energy in 2008, approximately 421 papers were published during this period. The average annual number of papers published during this period is 78, and in contrast to the preceding period, this period demonstrates a consistent rising trend. (iv) Phase of rapid expansion (2015–2022): During this period, the number of papers published increased rapidly to 1052. On average, 113 related papers were published each year, and the field reached its peak point in 2021 with highest publications of 187.

After reaching a peak in 2006, the average number of citations per article began to decline. This could be due to similar articles having expanded massively over the years or a small number of studies have largely contributed to this amount of information. This shows that the

growth in this research field was once quick but has subsequently declined due to a missing good research findings. However, the average amount of citations each year fluctuated between the years 2006 and 2021.

### 3.2.2. Source influence

This part covers the very prominent and significant sources on BIPV systems. The Scopus database shows that 1552 documents were collected from 431 sources. Fig. 4 depicts the top ten relevant sources. Based on published articles, Solar Energy (SE) is rated first with 148 articles, followed by Applied Energy (AE) (96), Renewable Energy (RE) (88), Energy and Buildings (EAB) (73), Energy (63), Energy Procedia (EP) (55), and Energies (48). Bradford’s law states that the number of journals in the second and third zones will be  $n$  and  $n^2$  times larger than the number of journals in the first zone, respectively. Thus, it should be possible to estimate the total number of journals carrying articles on a subject if the number of journals in the core and the middle zone is known. Bradford’s Law structured the sources in decreasing order of article productivity on a given fields and divide in to multiple zones based on the cumulative publishing frequency. Bradford’s Law highlights the leading six journals (Solar Energy to Energy Procedia in Fig. 5) as the primary sources (zone 1) of BIPV literature, and 523 is the cumulative publishing frequency for zone 1. As shown in Table 2, Solar Energy is the best source when all bibliometric parameters such as the publications quantity, total citations, h-index<sup>2</sup>, and g-index<sup>3</sup> are considered. Table 3 shows the distribution of publications in journals.

### 3.2.3. The most impactful authors

As illustrated in Fig. 6, Lotka’s law map was used in this study to analyse the prominent authors of the under consideration research [33]. This figure indicates that 2864 researchers have published a single article, which accounts for 75.6 % of all articles. Moreover, 521 researchers published two articles and 405 authors published more than two papers, accounting for 13.7 % and 10.6 % of the total number of publications respectively. The dotted and solid lines represent the

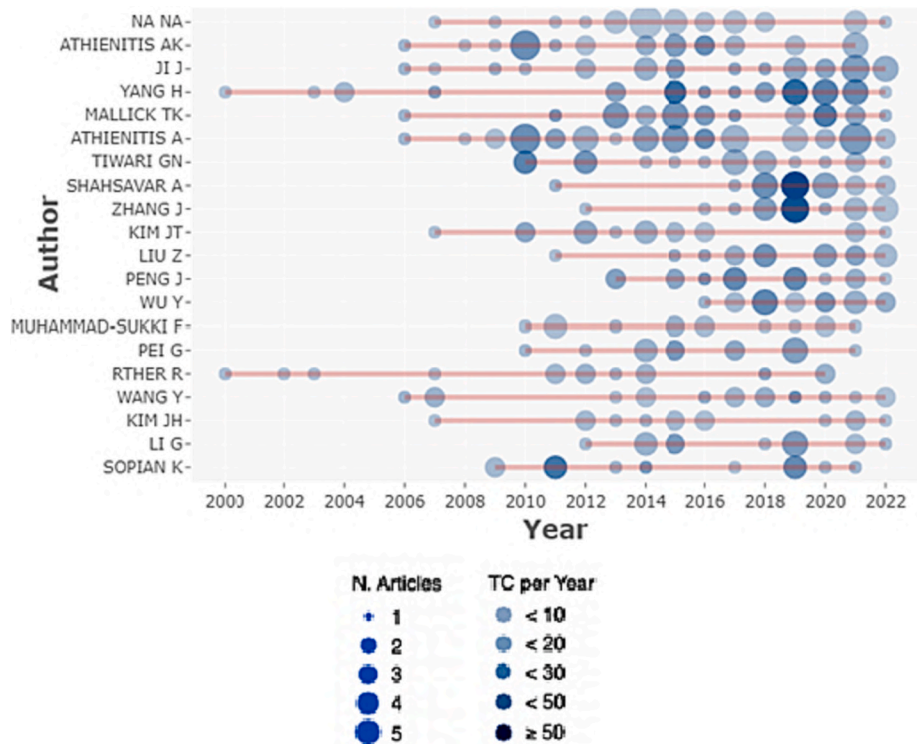


Fig. 7. Year-wise publications by authors.

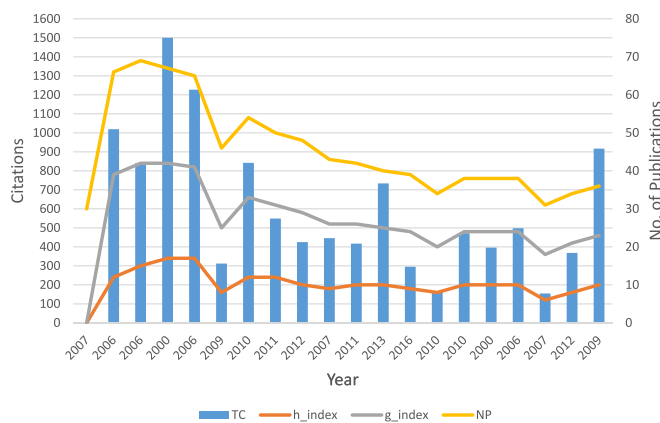


Fig. 8. Total yearly citations of the published articles.

authors' publishing rate in the field of BIPV systems and the actual publishing rate of authors in this field respectively. The top authors with a minimum of 20 publications are listed in Table 4.

Bibliometric analysis is an excellent method for evaluating the productivity of authors' publications. Fig. 7 depicts the top authors' contributions to the analysis of BIPV systems over time. The colour intensity in Fig. 7 corresponds to the annual frequency of citations, while the size of the bubbles represents the proportional annual production of each author. Shahsavari A. and Zhang J. received the most citations in 2019 as shown in Fig. 8. The five authors that have given the longest contributions to this field are Yang H, Rther R, Ji J, Athienitis A K, and Wang Y. In 2006, Athienitis A K received approximately 1019 citations per year, whereas Yang H received approximately 1500 citations per year in 2000 as shown in Fig. 8. In 2010, Athienitis A K received approximately 1019 citations per year, whereas Yang H received approximately 1500 citations per year in 2019 as shown in Fig. 8. The five authors that have given the longest contributions to this field are Yang H, Rther R, Ji J,

Athienitis A k, and Wang Y. In addition, Yang H is the most productive author in this research area, with an h-index of 17, a g-index of 25, no. of publications of 25, and a total of 1500 citations. Further Mallick TK is also good author with h-index 17, g-index 24, no. of publications 24, total citations 1227 and Ji J has also h-index 15, g-index 27, no. of publications 27, total citations 840 as shown in Figs. 7 and 8.

### 3.2.4. The most impactful articles

Article analysis determines the academic structure of topic knowledge by determining the credibility and number of cited literature. As per the Scopus citation data, Table 5 shows the 20 most cited articles, ranging from 224 to 1309 global citations. Specifically, Soto et al. [34], Shah et al. [35], and Dubey et al. [36] received 1,309, 651, and 612 global citations respectively, and were recognized as the three most cited publications. Soto et al. [34] evaluated the performance of the photovoltaic array for energy production under all operating conditions and developed a model of five parameters like manufacture data, absorbed solar radiation, and temperature of cell with empirical formulations to predict the characteristics of V-I curve. Shah et al. [35] found the electrical and optical properties of thin film silicon solar cells and reported the energy yields in thin film solar modules in comparison to the normal PV module. They suggested that a thin film solar module could be used in building an integrated photovoltaic system.

### 3.2.5. Main research country

Articles from various countries may be used as a general indicator of the influence and significance of BIPV systems. Overall, if a country publishes more publications in a given scientific area then it would improve the citation index and publication volume which shows the effectiveness and quality of its articles. The top countries in terms of total citations are summarised in Table 6. The number of single and multiple publications is depicted in Fig. 9. The countries have been differentiated based on the author's nationality. The China, the United Kingdom, and the United States have all achieved international publishing collaboration. As depicted in Fig. 9, the majority of peer-reviewed journal publications originate from the same country,

**Table 5**  
The top 20 cited documents.

Reference	D.O.I	Year	Total Citations	TC per Year
Soto et al. (2006)	<a href="https://doi.org/10.1016/j.solener.2006.05.010">https://doi.org/10.1016/j.solener.2006.05.010</a>	2006	1309	77.00
Shah et al. (2004)	<a href="https://doi.org/10.1002/pip.533">https://doi.org/10.1002/pip.533</a>	2004	651	34.26
Dubey et al. (2013)	<a href="https://doi.org/10.1016/j.egypro.2013.05.072">https://doi.org/10.1016/j.egypro.2013.05.072</a>	2013	612	61.20
Romn et al. (2006)	<a href="https://doi.org/10.1109/TIE.2006.878327">https://doi.org/10.1109/TIE.2006.878327</a>	2006	513	30.18
Skoplaki and Palyvos (2009)	<a href="https://doi.org/10.1016/j.renene.2008.04.009">https://doi.org/10.1016/j.renene.2008.04.009</a>	2009	462	33.00
Peter et al. (2012)	<a href="https://doi.org/10.1016/j.solmat.2011.12.016">https://doi.org/10.1016/j.solmat.2011.12.016</a>	2012	375	34.09
Skoplaki et al.2008	<a href="https://doi.org/10.1016/j.solmat.2008.05.016">https://doi.org/10.1016/j.solmat.2008.05.016</a>	2008	360	24.00
Fakharuddin et al. (2014)	<a href="https://doi.org/10.1039/c4ee01724b">https://doi.org/10.1039/c4ee01724b</a>	2014	330	36.67
Ibrahim et al. (2011)	<a href="https://doi.org/10.1016/j.rser.2010.09.024">https://doi.org/10.1016/j.rser.2010.09.024</a>	2011	305	25.42
Hasan et al. (2010)	<a href="https://doi.org/10.1016/j.solener.2010.06.010">https://doi.org/10.1016/j.solener.2010.06.010</a>	2010	299	23.00
Tonui and Tripanagnostopoulos (2007)	<a href="https://doi.org/10.1016/j.renene.2006.03.006">https://doi.org/10.1016/j.renene.2006.03.006</a>	2007	290	18.13
Tonui and Tripanagnostopoulos (2007)	<a href="https://doi.org/10.1016/j.solener.2006.08.002">https://doi.org/10.1016/j.solener.2006.08.002</a>	2007	288	18.00
Huang et al. (2006)	<a href="https://doi.org/10.1016/j.solener.2005.10.006">https://doi.org/10.1016/j.solener.2005.10.006</a>	2006	260	15.29
Zhou et al. (2007)	<a href="https://doi.org/10.1016/j.apenergy.2007.04.006">https://doi.org/10.1016/j.apenergy.2007.04.006</a>	2007	258	16.13
Norton et al. (2011)	<a href="https://doi.org/10.1016/j.solener.2009.10.004">https://doi.org/10.1016/j.solener.2009.10.004</a>	2011	250	20.83
Chemisana (2011)	<a href="https://doi.org/10.1016/j.rser.2010.07.017">https://doi.org/10.1016/j.rser.2010.07.017</a>	2011	249	20.75
Mekhilef et al. (2012)	<a href="https://doi.org/10.1016/j.rser.2011.08.003">https://doi.org/10.1016/j.rser.2011.08.003</a>	2012	240	21.82
Ma T et al. (2015)	<a href="https://doi.org/10.1016/j.rser.2014.12.003">https://doi.org/10.1016/j.rser.2014.12.003</a>	2015	231	28.88
Biyik et al. (2017)	<a href="https://doi.org/10.1016/j.jjestch.2017.01.009">https://doi.org/10.1016/j.jjestch.2017.01.009</a>	2017	224	37.33
Agrawal and Tiwari (2010)	<a href="https://doi.org/10.1016/j.apenergy.2009.06.011">https://doi.org/10.1016/j.apenergy.2009.06.011</a>	2010	224	17.23

indicating that authors contact mostly with national peers. Independent research is prioritized by the majority of the countries, and local collaborative publications exceed international ones.

### 3.2.6. Relationship

The projection of Sankey diagrams is yet another important function offered by the bibliometric program. In this study, the three fields plot illustrated the correlations between the keywords, writers, country, and sources of the primary authors. In this instance, different-coloured rectangles represented the diagram's significant elements. The

**Table 6**  
Top countries publishing articles in the selected theme of research.

Country	Total Citations	Average Article Citations
China	3590	19.30
United Kingdom	3513	33.14
USA	3251	31.87
Greece	2356	112.19
Hong Kong	2285	45.70
India	2250	27.78
Spain	1816	42.23
Canada	1763	26.31
Italy	1480	23.13
Malaysia	1439	46.42

rectangle's height was established by combining the relationships between the rectangle element (one of the author's keywords, authors, and source diagrams) and the diagrams of the other elements. The element has more connections hence the rectangle's size grows.

Figs. 10 and 11 depicts the diagram for BIPV system research, highlighting the relationships between the primary authors, their countries, keywords, and sources. The analysis determined which sources of BIPV systems were most referenced during publications. According to the analysis of the top authors are Mallick T K, Athienitis A K, Yang H and Tiwari G N, countries; top nations are China, UK, Malaysia, Canada and India; top keywords are Energy efficiency, BIPV/T, Thermal performance and optimization and top sources are Solar Energy, Renewable Energy, Applied Energy and Energy and Buildings.

### 3.3. Keywords analysis

#### 3.3.1. High-Frequency keyword analysis

In order to better comprehend the themes mentioned in the reviewed research papers, a biblioshiny tool is used to retrieve and count the authors most frequently used keywords. Keywords with word frequencies greater than 10 are filtered, and a word tree map is generated, as shown in Fig. 12. BIPV, Solar energy, photovoltaic, renewable energy, energy efficiency, exergy and phase change material (PCM) are the research topic's most frequently used terms, accounting for 16 %, 10 %, 8 %, 4 %, 3 %, 2 %, and 2 %, respectively, of the high-frequency keywords. There are some other keywords related to the BIPV system such as optimise the performance of the system by using PCM. This conclusion demonstrates that research on BIPV systems has concentrated on photovoltaics, energy efficiency, and exergy to a great extent. BIPV systems promote the sustainable development of the society and decrease the consumption of the building energy.

#### 3.3.2. Cluster and multivariate statistical analysis

This article analyses BIPV system keywords using the hierarchical clustering technique. The keywords in each cluster are first treated as a set, and then each cluster is combined with the one that shares the most similarities with it. After that, each new cluster is merged with the one that is most similar. Repeat the above steps until all clusters are grouped. The complete classification system is then represented as a tree diagram to illustrate the connection among the keywords in the field BIPV systems and represented in Fig. 13.

From the facts as shown in Fig. 13, the research area of BIPV systems could be concise into the following categories as.

- The first category mostly comprises the connection between solar radiation and PV system. PV systems generate electricity using solar irradiation and with a proper cooling technology its efficiency is also increases. Furthermore, BIPV systems decrease the energy demand in buildings result in promote sustainability development for the society.
- The second category reflects the relationship between energy efficiency and energy storage. For the better performance of the BIPV

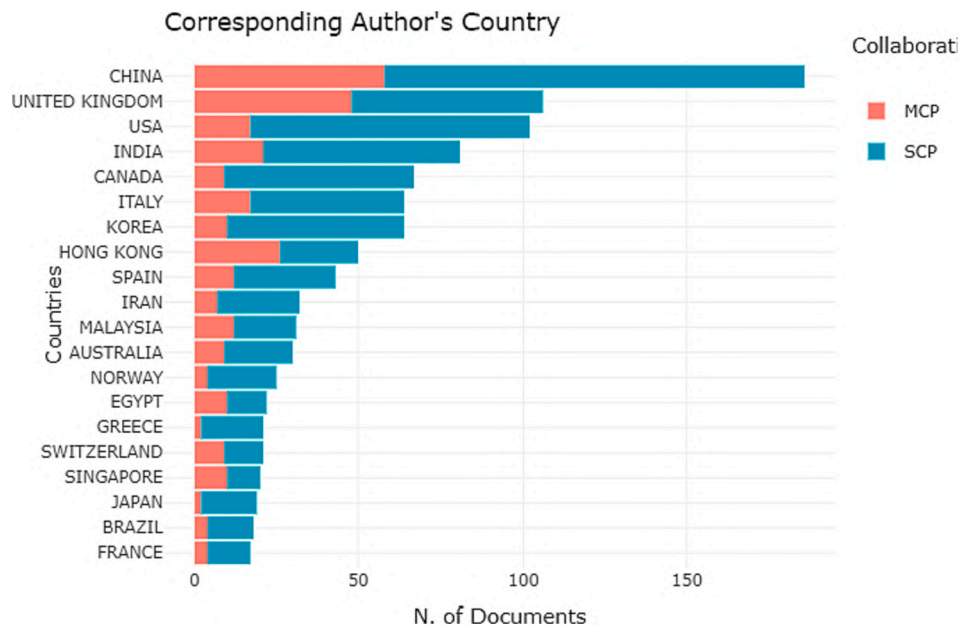


Fig. 9. Multiple country publication (MCP) and single country publication for corresponding author's countries.

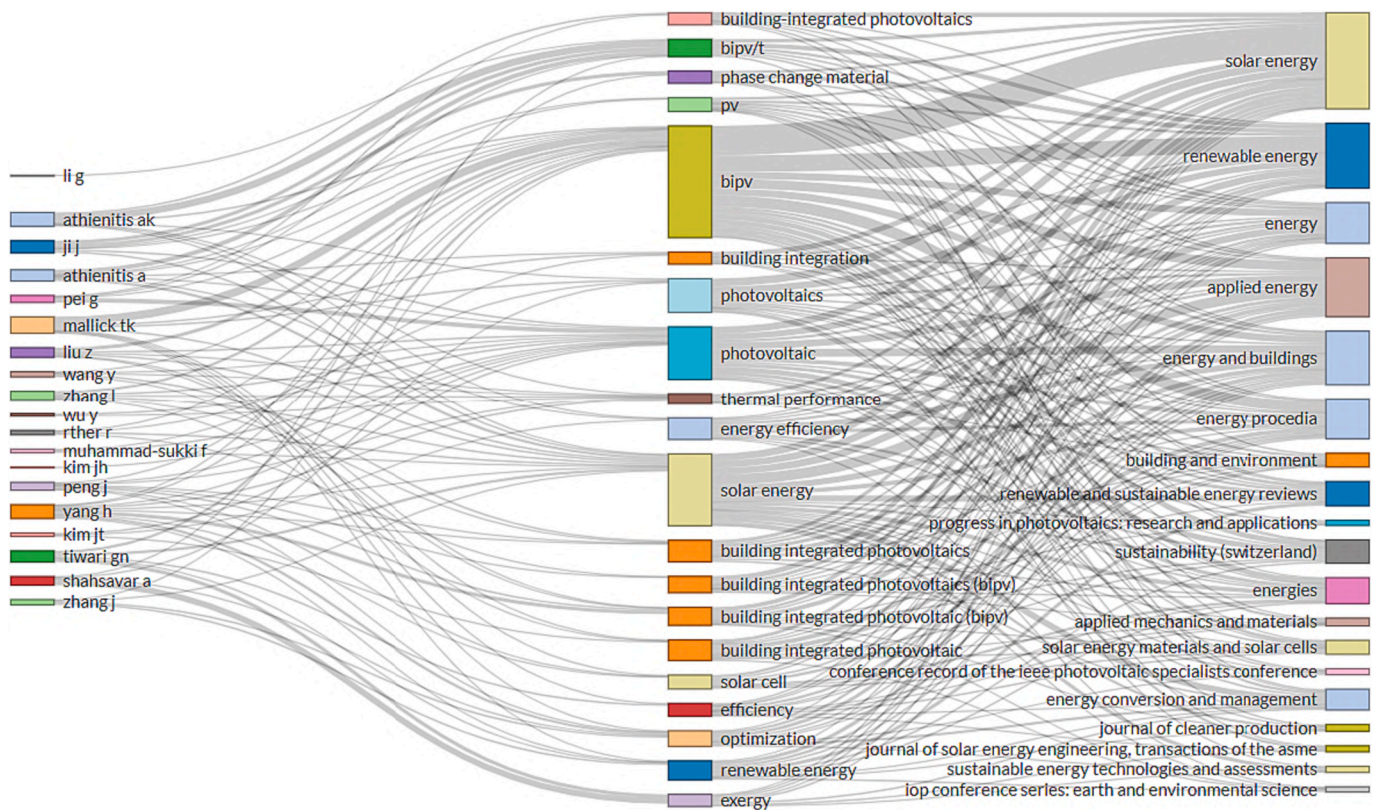


Fig. 10. Three field plots for the relationship among authors, keywords, and sources.

system, its electrical and thermal efficiency should be enhanced by using proper cooling methods. There are various cooling techniques for the temperature control in BIPV system but the most useful techniques is use of energy storage material such as PCM. It extracts the excess heat from the back surface of BIPV panel and later used for heating of buildings.

- The third category mainly focused on the relationship between energy and exergy optimization and efficiency. It can be optimized by

providing natural ventilation of excess heat and unshaded areas for the BIPV system.

### 3.4. Mapping results with VOSviewer software

The VOSviewer tool was used to examine the bibliometric indicators in this area. This program allows us to report on the bibliographical diversity of countries, the citations of authors and articles, and the co-

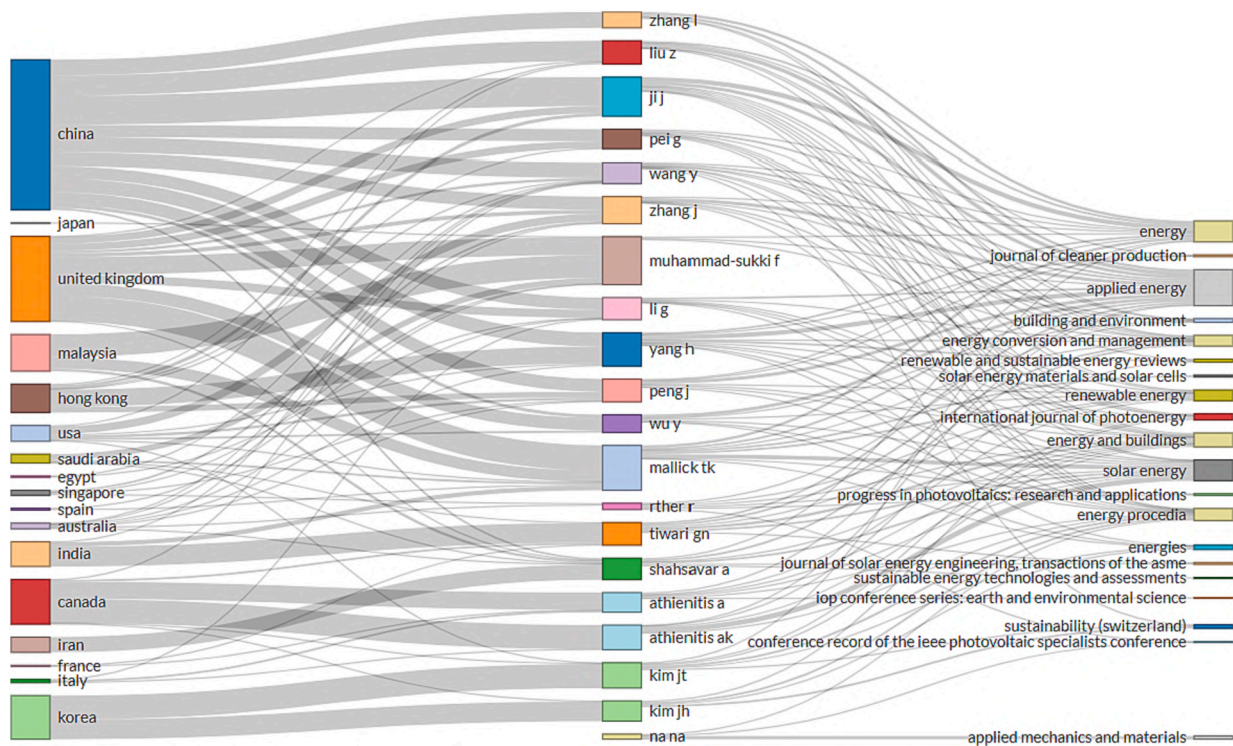


Fig. 11. Three field plots for relationships among countries, authors, and sources.

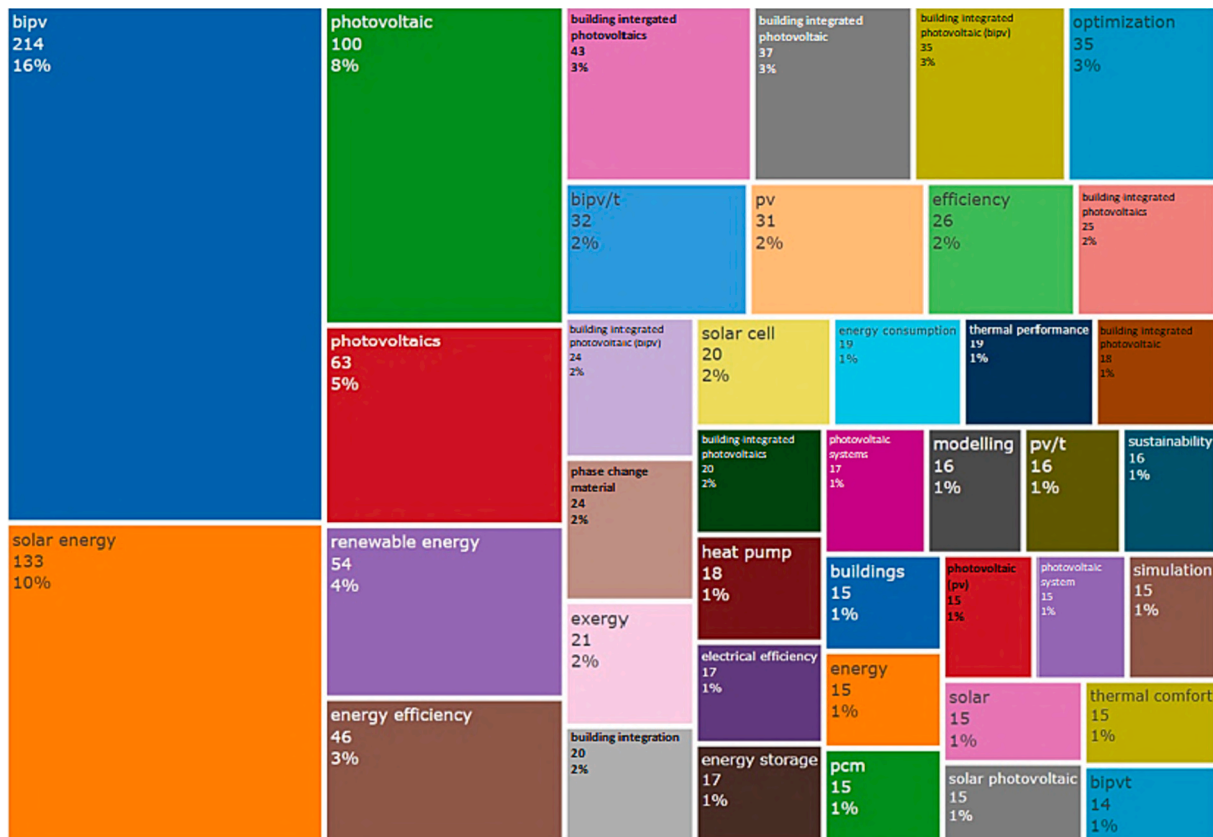


Fig. 12. Word tree map of high-frequency keywords in the field of BIPV.

occurrence of the author’s keywords.

Fig. 14 depicts the co-authorship of publications by country. Each link between two nodes in different countries indicates that the

organizations in these nations collaborate. Total seven clusters and 279 links are found. In the cluster 1 (Red colour), the highest link of collaboration is for the Italy (23 links and 113 documents), followed by

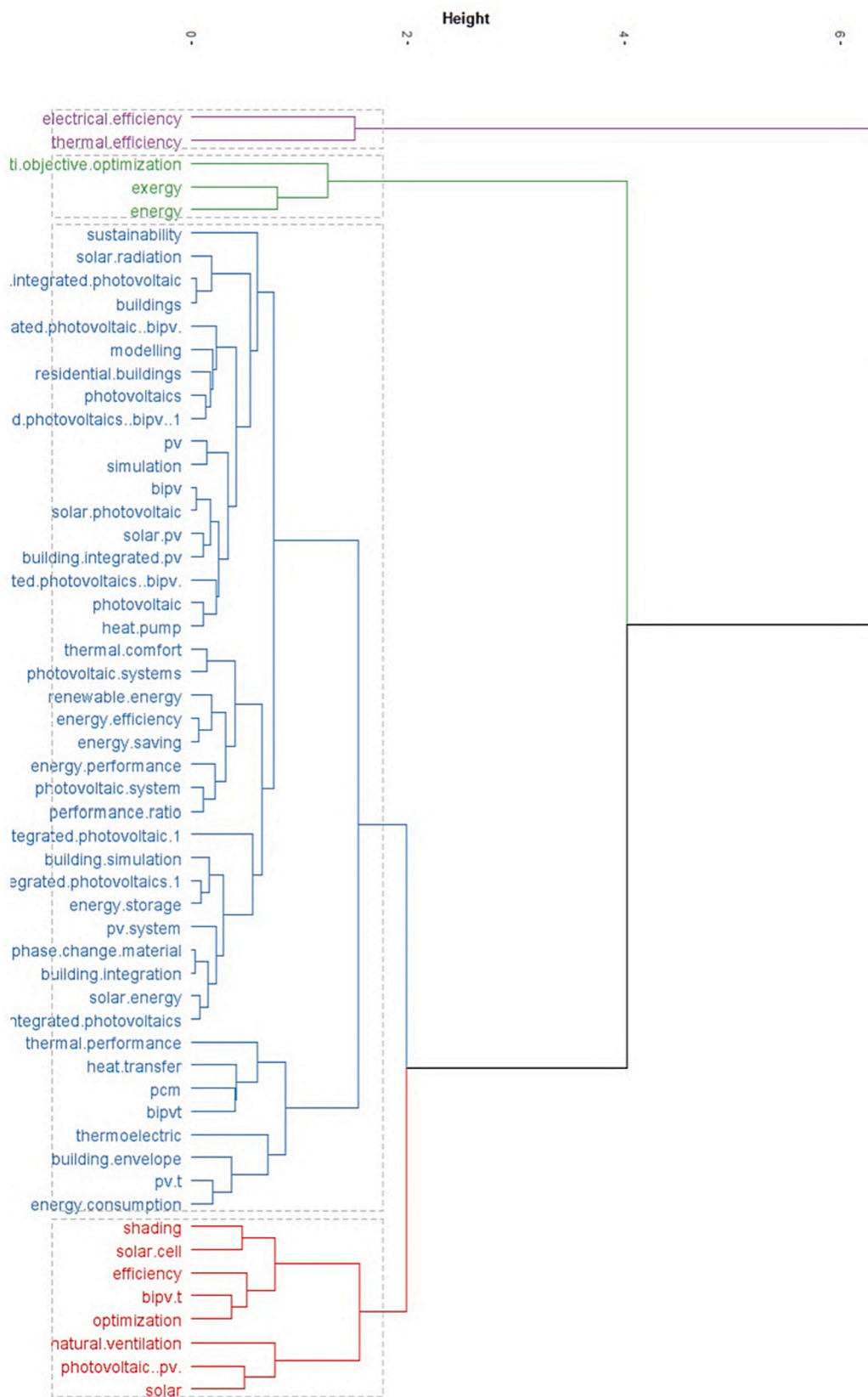


Fig. 13. Tree dendrogram of the hierarchical clustering of keywords in the BIPV system.

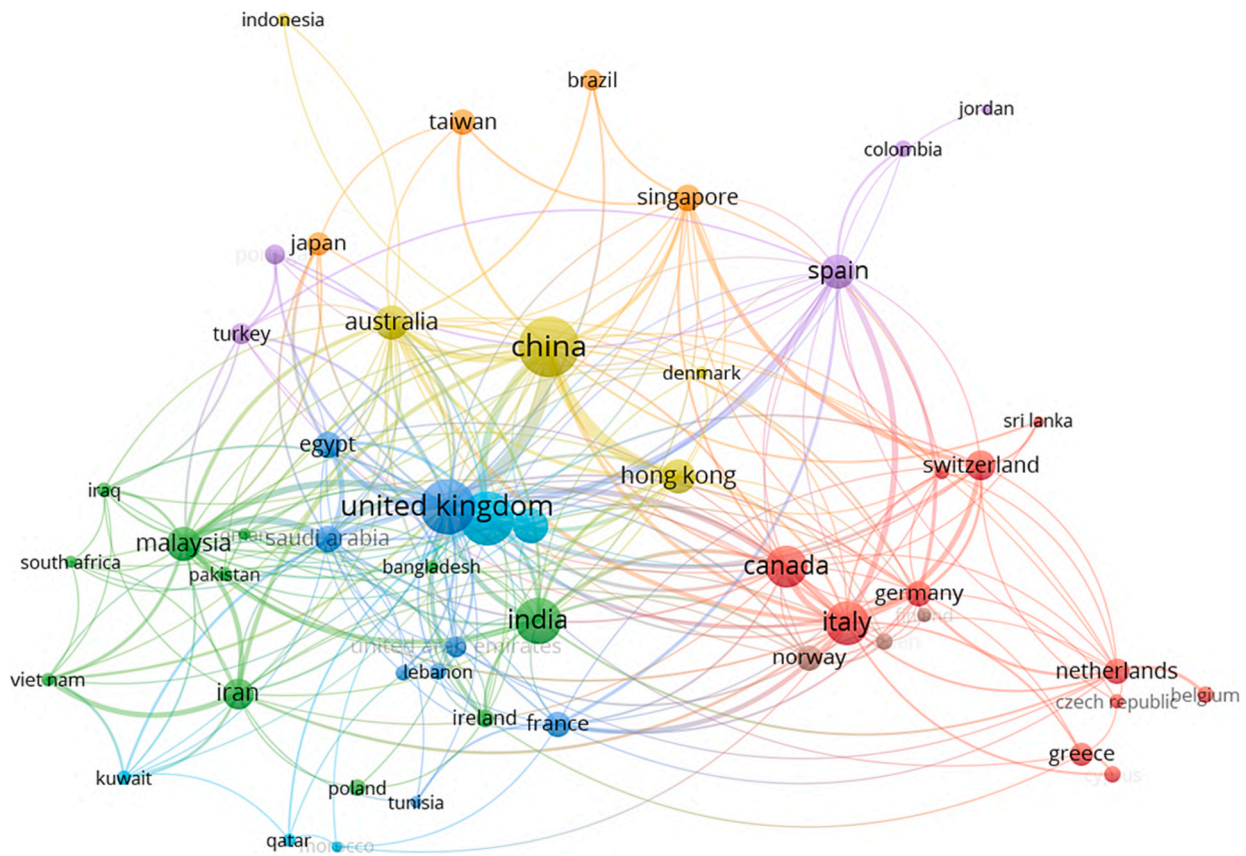


Fig. 14. Bibliometric network map of co-authorship for countries.

the Canada (18 links and 102 documents), the Germany (17 links and 33 documents), the Netherlands (14 links and 34 documents) and the Switzerland (12 links and 46 documents). In the cluster 2 (Green colour), the highest link of collaboration is for the Malaysia (20 links and 62 documents), followed by the Iran (17 links and 51 documents), and the Iraq (10 links and 10 documents). Further in the cluster 3 (Blue colour), the highest link of collaboration is for the UK (34 links and 179 documents), followed by the Saudi Arabia (21 links and 35 documents), the France (15 links and 33 documents), and the Egypt (11 links and 38 documents). In the cluster 4 (Yellow colour), the highest link of collaboration is for the China (26 links and 220 documents), followed by the Australia (29 links and 62 documents), and the Singapore (15 links and 36 documents). In the cluster 5 (Violet colour), the highest link of collaboration is for the India (19 links and 125 documents), followed by the Hong Kong (16 links and 63 documents), and the Norway (11 links and 33 documents). In the Cluster 6 (light blue colour), the highest link of collaboration is for the US (24 links and 175 documents), followed by the South Korea (07 links and 70 documents). Further in the cluster 7 (Orange colour), the highest link of collaboration is for the Spain (22 links and 65 documents), followed by the Turkey (09 links and 21 documents). It supports our finding from Fig. 9, where the China, the UK, the USA, the India, and the Canada have all performed admirably in international cooperative publishing relations.

The co-occurrence of keywords is analysed using the VOSviewer's network analysis and represented in Fig. 15. The minimum number of co-occurrences of keywords is set to the value of five which results in 166 threshold keywords out of which 146 keywords are selected and divided into 9 clusters. Cluster-1 (Red) contains a total of 32 keywords. BIPV has the highest connection of 63 links and 67 documents followed by phase change material (52 links and 45 documents). It was found from figure 16 that the cluster-2 (Green) contains a total of 26 keywords, where solar energy (77 links and 132 documents) is the most frequently

used keyword followed by renewable energy (53 links and 54 documents). Cluster-3 (Blue) contains a total of 16 keywords, where building integrated photovoltaic and building enveloping material is the most frequently used keyword (75 links and 82 documents). Further, the cluster-4 (Yellow) contains a total of 16 keywords, where photovoltaic simulation is the most frequently used keyword (69 links and 100 documents) followed by energy savings (17 links and 11 documents). Cluster-5 (Violet) contains a total of 15 keywords, where sustainability is the most frequently used keyword (25 links and 16 documents) followed by heat transfer (24 links and 14 documents). Cluster-6 (light blue) contains a total of 14 keywords, where electrical efficiency is the most frequently used keyword (21 links and 17 documents) followed by the performance (19 links and 10 documents). Further, cluster-7 (brown) contains a total of 13 keywords, where energy performance is the most frequently used keyword (33 links and 21 documents) followed by shading (15 links and 09 documents). Cluster-8 (orange) contains a total of 12 keywords, where exergy is the most frequently used keyword (32 links and 15 documents). The last cluster-9 (pink) contains a total of 10 keywords, where solar photovoltaic optimum tilt angle is the most frequently used keyword (26 links and 19 documents). Fig. 13 illustrates the relationship between the keywords.

### 3.5. Thematic analysis of bibliometric

SciMAT software is being utilized by scientists due to its capability to combine the advantages of conventional scientific mapping approaches with co-citation and co-word analysis[37]. SciMAT uses both strategic diagrams and thematic networks to visualize themes. A strategic diagram is a two-dimensional graph containing density and centrality as shown in Fig. 16(a). In this figure centrality measures shows the internal relationship between the themes. A high degree of centrality shows that a theme has strong internal connections with other themes which are



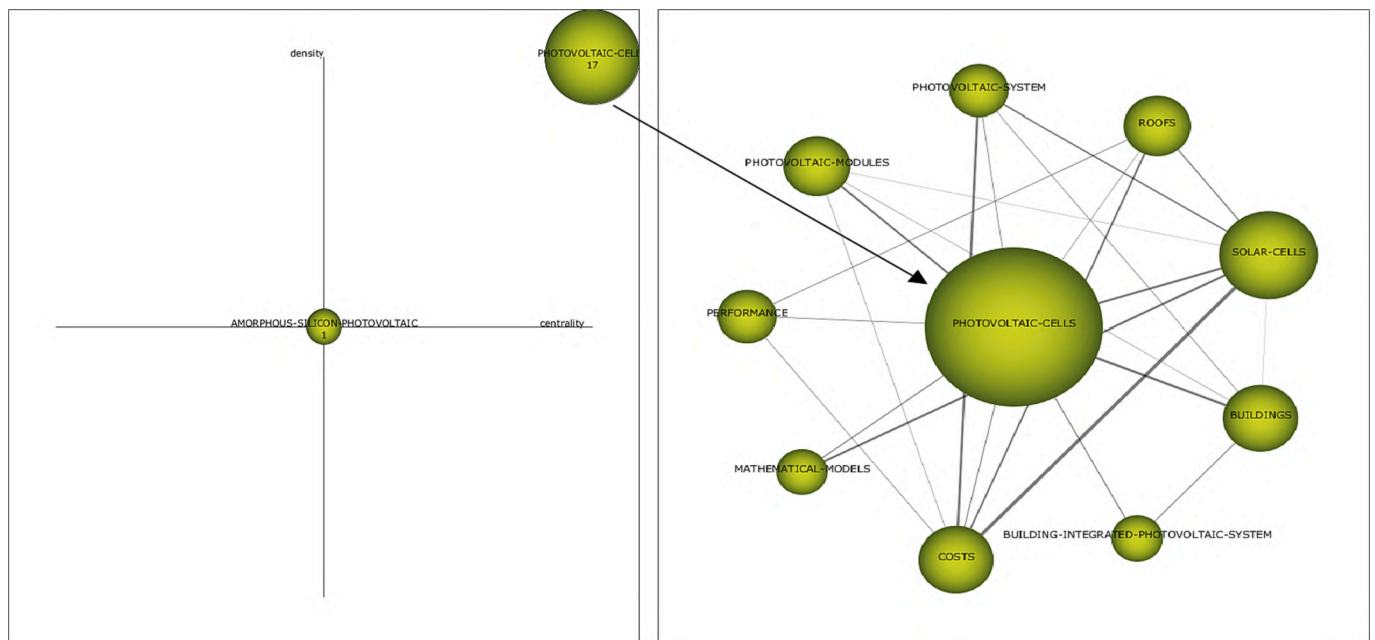


Fig. 17. key themes of the first period (1985–2000).

illustrates the inheritance link, whereas the dashed line indicates thematic divergence. The thickness of the line is proportional to the degree of linkage between the topics, as described by the specified index, and the absence of a line denotes a gap.

To explore the scientific evolution of the BIPV system with more precision, eliminate data repetition, and ensure cross-period comparability, the entire period (1985–2022) was split into three phases: 1985–2000, 2001–2010, and 2011–2022. The rationale for the unequal periodization is that the modern research topic has been intensively studied since 2008, as shown by the number of publications demonstrating an exceptionally high level of activity during this time frame as above stated in Fig. 3.

During the first period (1985–2000), two important research issues concerning the BIPV systems are presented i.e. photovoltaic cell and amorphous silicon photovoltaic as presented in Fig. 17. The period's motor theme was a photovoltaic cell with 17 core documents, 8 h-index, and 222 sum citations. Other themes are not available during this period. As a result, the first sub-period was devoted to photovoltaic cells and amorphous silicon photovoltaic. Further six BIPV system related themes are presented during the second period (2001–2010) which are categorized as photovoltaic systems, BIPV, roofs, heat pumps, semi-transparent photovoltaic, and residential buildings as depicts in Fig. 18. With 92 core documents, 44 h-indexes, and 7,530 total citations, the photovoltaic system was emerged as a research hotspot during this period. A new research area semi-transparent photovoltaic was also invented during this period with two supporting documents. The relationship between heat pumps and residential structures was well-developed and isolated, indicating that it has developed but remains of minor importance over this period. BIPV and roofs are the transverse themes, signifying major yet unexplored themes. In the second phase, the motor themes remained the same as in the first. Without a doubt, this research area is extremely dynamic and will have a significant impact on forthcoming research.

Fig. 19 presented a summary of seventeen significant research themes related to creating BIPV systems during the third period (2010–2022). The three main themes are photovoltaic systems, pumps, and silicon PV cell systems. The themes of energy management, energy demands, life cycle assessment, surface temperature, neural networks, and HDKR models that account for the effects of the sun's diffuse and horizon-brightening radiation on an inclined surface are highly

developed and unique. Facades and energy performance are two topics that are newly emerging or declining during third period. The BIPV systems, photovoltaic thermal, simulation, solar concentrators, investments, and dye-sensitized solar cells are important and transversal themes of the third period. The silicon PV cells are turning their focus to a motor theme at present. The evolution map (Fig. 20) depicts the thematic evolution of the field during the period of the investigation.

During the first period (1985–2000), two research themes were identified as shown in Fig. 18 and photovoltaic cells dominated scholarly papers. As a new field, photovoltaic systems, BIPV systems, roofs, residential buildings, and semi-transparent photovoltaics emerged in the second period. The theme of photovoltaics from the first period was carried over to the second era. There is a clear distinction between themes with a strong connection to the first period's concerns (continuous lines), such as BIPV and roofs. In the final phase (2010–2022), the number of research themes increased once more, while the theme from the preceding era continued.

Fig. 21 presented the overlay graph, which illustrates the level of stability between two successive eras. The total number of shared terms is represented by the horizontal arrow. The number enclosed by parenthesis represents the index of era similarity. The arrow in the upper-left corner indicates which terminology from the first era was eliminated. The incoming arrow, on the other hand, illustrates the number of newly introduced keywords that do not immediately apply.

### 3.6. Discussions

In the present research a systematic literature review and bibliometric analysis was carried out to create the first comprehensive, descriptive study of BIPV research from 1985 to 2022. There was a comprehensive analysis of how the study's findings responded to each of the five queries that prompted it.

- The overall trend is most likely divided into four distinct phases. (i) During the period of initial exploration (1985–1994), research on BIPV systems was in its very early stages. (ii) During the period of initial development (1995–2004), the number of articles produced shows a modest upward trend with fluctuations, resulting in a growth phase. (iii) Stable development stage (2005–2014): this period exhibits a steady upward trajectory. (iv) Phase of rapid

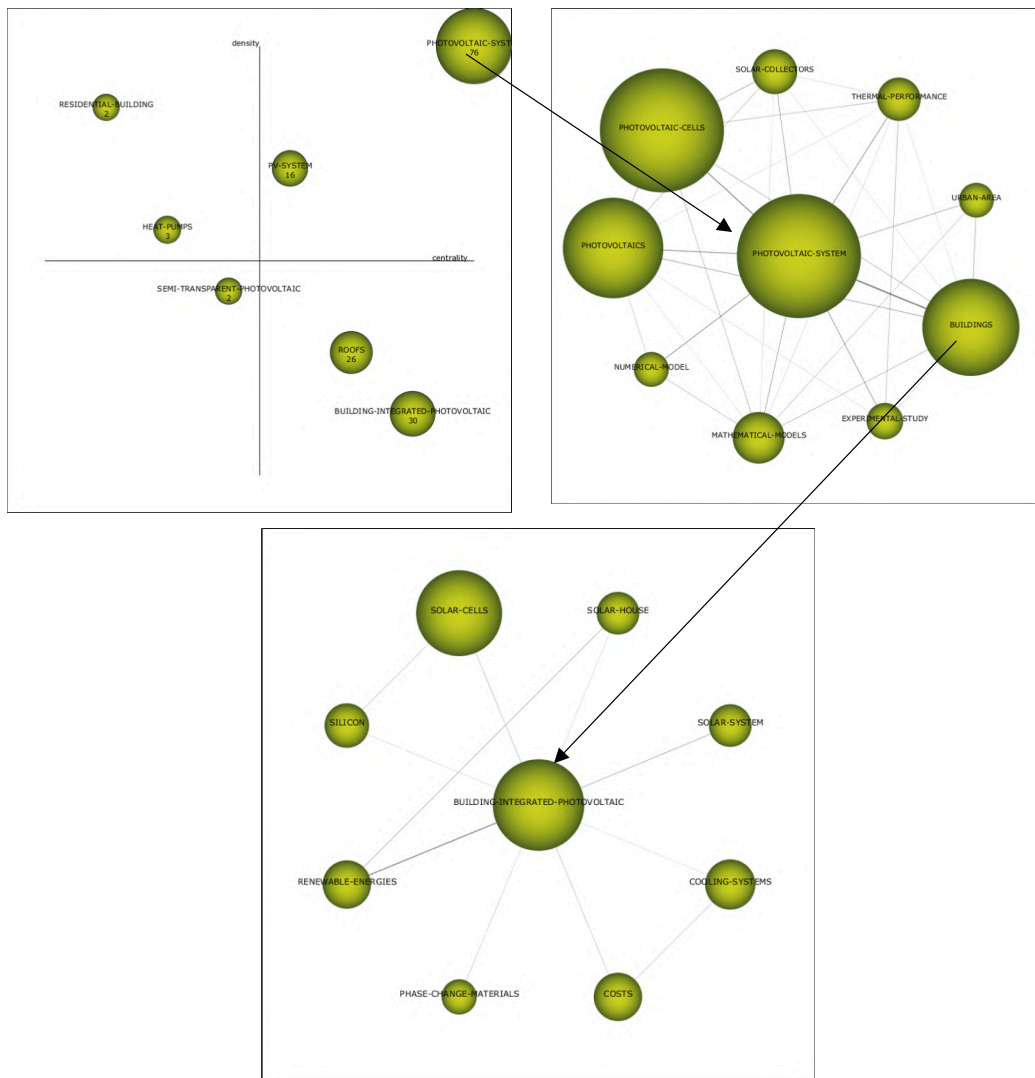


Fig. 18. Key themes of the second period (2001–2010).

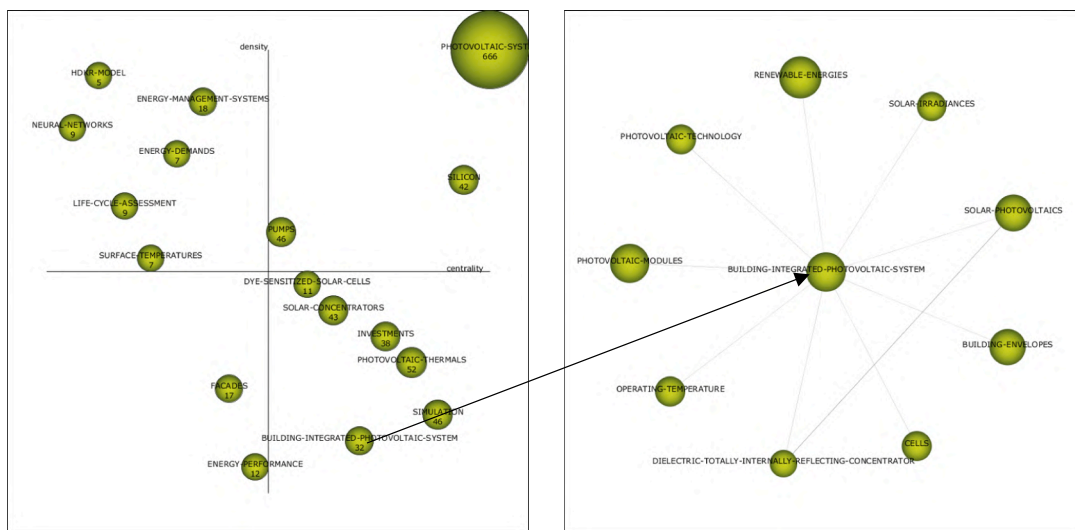


Fig. 19. Key themes of the third period (2010–2022).

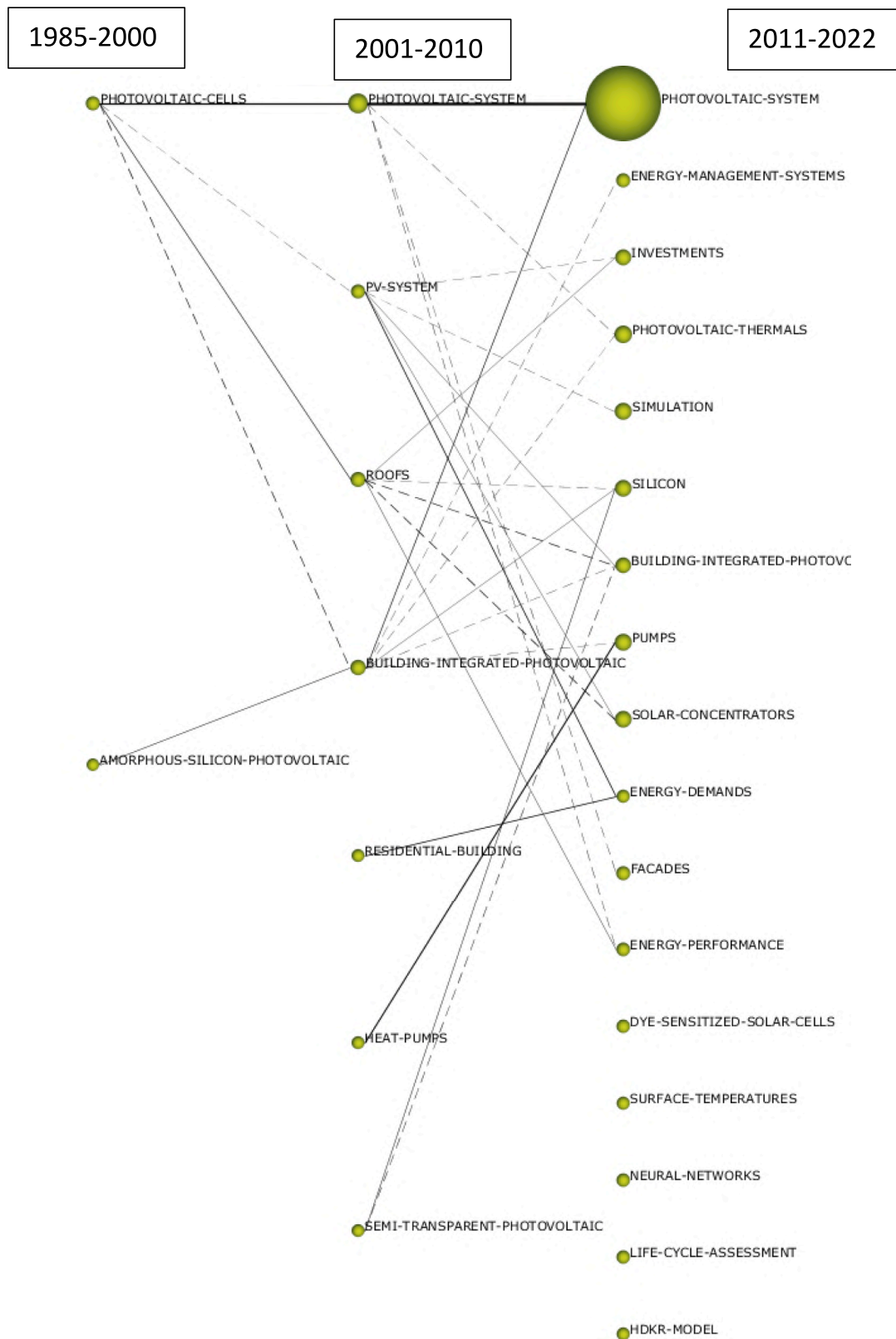


Fig. 20. The thematic evolution of the field during the period of the investigation.

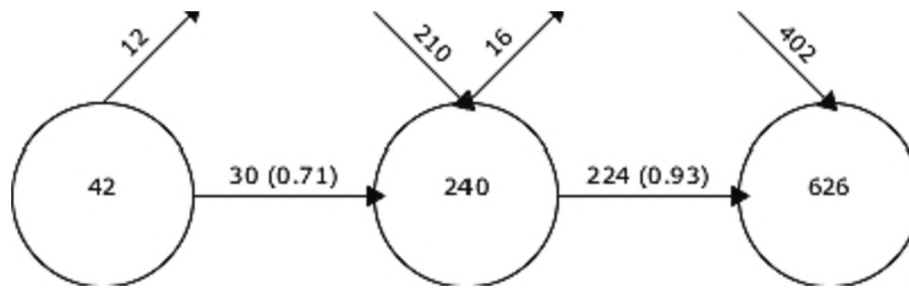


Fig. 21. Overlay graph.

expansion (2015–2022): During this period, the number of papers published increased swiftly to 1052. According to the citations in the reviewed literature, the years 2004, 2006, and 2020 were the most significant for the advancement of BIPV system research.

- The majority of BIPV-related publications and citations come from China, UK, and USA. In this area of study, Yang H is the most productive author having h-index of 17, g-index of 25, no. of publications as 25, and a total of 1500 citations. The other productive authors are Mallick TK (h-index 17, g-index 24, no. of publications 24, total citations 1227), and Ji J (h-index 15, g-index 27, no. of publications 27, total citations 840) and are shown in Figs. 7 and 8. Solar Energy, Applied Energy, Renewable Energy, Energy, Energy and Buildings, and Energy Procedia were the journals with the most published papers of this field. Bradford's Law highlights the leading six journals (Solar Energy to Energy Procedia in Fig. 5) as the primary sources (zone 1) of BIPV literature.
- It has been observed that data science neural networks can be used on the results of this study to pick up research areas that have been identified as research gaps. There is an additional research gap in this field and more extensive research might be conducted on BIPV systems with an emphasis on sustainable development and cost-effective analysis for emerging nations or rural residents.
- This study has significant limitations, including its dependence on Scopus as the only source of information for relevant publications. Several articles were excluded because they lacked important information and other key resources, such as the Web of Science and Google Scholar which may be employed in future research endeavours to provide a comprehensive quantitative and qualitative overview of the research area in this field, utilizing a variety of review techniques.
- According to the thematic analysis of the BIPV system, the PV cell and amorphous silicon PV were two of the most significant themes in the early stages of BIPV research. In the second phase, these two major themes were separated into subcategories such as building integrated photovoltaic, roofing, heat pumps, semi-transparent photovoltaic, and residential buildings. BIPV topics such as energy management, energy needs, life cycle assessment, surface temperature, and neural networks will be refined in the final stage of development.

#### 4. Conclusions

This article provides a bibliometric analysis to determine the present and future developments in BIPV systems that are based on the largest number of published articles (1552) retrieved from the Scopus database having period of research from 1985 to 2022. It introduced a range of bibliometric approaches to identify the most prolific and prominent authors, keywords, countries, sources, and publication trends in the research field throughout time. The findings of this paper are as follows:

- The descriptive study initially validates the present publishing patterns in this research field. Based on the existing literature and

output analysis, it is observed that research related to BIPV systems has increased dramatically over the past eight years. There has been a surge in the BIPV system particularly after 2016. Over time, both the significance of BIPV research and the number of researchers participating in such domain has increased.

- Developed nations, such as China, United Kingdom, and United States of America are top contributor to BIPV research in terms of overall publications and citations. India also a single-country publication has certain research capabilities. With 34 links and 179 documents, United Kingdom is the most collaborative country, followed by China with 26 links and 220 documents, and the United States with 24 links and 175 documents.
- Approximately 55 % of all publications are also accounted for by the top six core journals. Solar Energy was the most prolific journal with 148 articles, followed by Applied Energy, Renewable Energy, Energy and Buildings, Energy, and Energy Procedia. In this area of study, Yang H is the most productive author having h-index of 17, g-index of 25, no. of publications as 25, and a total of 1500 citations.
- In addition, keyword analysis enables us to identify the primary research trends in a journal, as keywords usually indicate the authors' primary areas of interest. Nine clusters including 146 keywords have been finalized. In clusters 1 and 3, the most commonly used keywords are building integrated photovoltaic systems and building enclosing materials. Solar energy, photovoltaic simulation, sustainability, phase change material, electrical efficiency, energy performance, and exergy are the most commonly used keywords in the various clusters. The most often cited article is "Improvement and validation of a model for photovoltaic array performance" authored by Soto et al. (2006).
- Combining the bibliometric analysis with the thematic trend analysis to comprehend the evolution of sub-topics in the domain of BIPV system and investigation found a variety of interesting and important keywords that are predicted to gain prominence in the future. Therefore, future research can concentrate more on BIPV sub-areas such as 'Dye-sensitized solar cells, 'life cycle assessment,' and 'photovoltaic thermal' as they relate to the usage of BIPV systems.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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