AIMS Energy

AIMS Energy, 11(6):1131–1152.
DOI: 10.3934/energy.2023052
Received: 06 September 2023
Revised: 12 October 2023
Accepted: 01 November 2023
Published: 14 November 2023

http://www.aimspress.com/journal/energy

Review

Building-integrated photovoltaic (BIPV) systems: A science mapping approach

Eliseo Zarate-Perez[1,2,*], Juan Grados[3], Santiago Rubiños[3], Herbert Grados-Espinoza[3] and Jacob Astocondor-Villar[3]

[1] Department of Engineering, Universidad Privada del Norte (UPN), Av. Alfredo Mendiola 6062, Los Olivos 15314, Peru
[2] International Doctoral School (EIDUNED), Universidad Nacional de Educación a Distancia (UNED), C/Bravo Murillo, 38, Madrid, 28015, Spain
[3] Faculty of Electrical and Electronic Engineering, Universidad Nacional del Callao, Av. Juan Pablo II 306, Bellavista 07011, Peru

* **Correspondence:** Email: juanzarateperez@gmail.com; ezarate9@alumno.uned.es.

Abstract: Solar energy is one of the most important renewable energy sources due to its wide availability and applicability. One way to use this resource is by building-integrated photovoltaics (BIPV). Therefore, it is essential to develop a scientific map of BIPV systems and a comprehensive review of the scientific literature that identifies future research directions. For that reason, the bibliometric research methodology enables the quantification and evaluation of the performance, quality and influence of the generated maps and their elements. In this regard, an analysis of the scientific production related to BIPV, indexed from 2001 to 2022, was carried out using the Scopus database. This was done using a scientific mapping approach via the SciMAT tool to analyze the co-occurrence of terms through clustering techniques. The BIPV was integrated with the themes of buildings, investments, numerical models, office buildings, photovoltaic modules, roofs, solar cells and zero-energy buildings. As photovoltaic technology progresses, the production of flexible PV elements is increasing in lieu of silicon substrate-based PV elements, and this is of current scientific interest. The evaluations of BIPVs in various climatic contexts are encouraging in warm and sunny climates. BIPVs demonstrated high-energy generation, while in temperate climates, BIPV windows exhibited a reduction in heating and cooling loads, indicating notable efficiency. Despite significant benefits, BIPVs face challenges such as upfront costs, integration complexities and durability concerns. Therefore, silicon solar cells are considered a cross-cutting theme within the BIPV research field. It is highlighted that this study

provides a comprehensive scientific mapping and critical review of the literature in the field of BIPV systems. This bibliometric analysis not only quantifies the performance and quality of the generated maps but also identifies key thematic areas that have evolved.

Keywords: building integrated photovoltaics; renewable energy; silicon solar cells; shading effect; SciMAT; bibliometric analysis

1. Introduction

Although electricity is essential in today's society, there are approximately 1.2 billion people living without access to it [1]. Global energy consumption doubled in the four decades between 1975 and 2015, according to the International Energy Agency [2]. These facts highlight the importance of generating electricity from distributed sources in the presence of renewable sources to meet local demand [3]. Solar energy is considered the most preferred renewable energy source owing to its wide availability [2]. Therefore, photovoltaic (PV) technology is growing rapidly compared with other renewable energy sources, and the use of solar energy can be divided into two relevant fields. First, the term refers to solar thermal energy and deals with the use of solar radiation to generate heating. The second point is related to physical process phenomenon solar energy and focuses on the generation of solar energy into electricity using silicon solar cells [4].

However, the efficiency of solar photovoltaic energy is influenced by local climatic conditions and the availability of solar radiation, and the efficiency of photovoltaic cells varies within a range of 7% to 40% [5]. Furthermore, only about 80% of the incident solar radiation found in the solar spectrum can be captured by photovoltaic cells, and the amount of electrical power generated depends significantly on the conversion efficiency inherent in the technology employed [6]. This photovoltaic technology is used in two different modalities to produce energy in buildings: Building-applied/attached photovoltaics (BAPV) and building-integrated photovoltaics (BIPV). BAPV systems do not replace or interfere with conventional building construction materials, they are typically mounted on freestanding structures or installed separately. Its main function is to generate energy, which in turn contributes to mitigating heat accumulation by providing shade on ceilings or walls [7]. By contrast, BIPV systems are characterized by their ability to shape, incorporate, replace or substitute traditional building materials and envelopes, such as roofs, windows, skylights and shading elements, through the incorporation of photovoltaic components. These elements have the capacity to generate electricity to directly feed the energy needs of the building [7].

Due to the growing interest in BIPV systems, several researchers have carried out comprehensive reviews in this field. In the study [8], the research progress regarding heat transfer in photovoltaic panels integrated into double-skin facades was evaluated, considering various integration approaches. Similarly, in [9], the tools currently used for numerical simulation of energy in double-skin façades were examined, highlighting the possibilities for future development of BIPV systems. The analysis in [10] addressed the practical application of BIPV and explored the challenges it presents, as well as the directions it might take in the future. The review of [11] focused on the applications of BIPV systems to improve the energy performance of facades [11]. On the other hand, [12] synthesized various engineering design models applicable to BIPV systems, including the exploration of the use of photovoltaic cells with different colors to improve architectural aesthetics [12]. Finally, Rounis et al.

in 2021 provided a detailed review of the observed performance of BIPV systems and focused on the relevant modeling of the system, with a special focus on convective phenomena [13].

A systematic analysis of the literature on the approaches, methods, tools and characteristics was conducted with the objective of identifying the bases for an integrated evaluation of the BIPV urban rehabilitation, evaluating the potential for facades [11]. Other works focus on reviews of BIPV technology, including major developments, numerical and experimental studies and the impact of BIPV systems on building performance [14]. Similarly, bibliometric reviews are presented on the panorama of applications of photovoltaic energy on rooftops [15]. A framework integrating bibliometric and scientific mapping approaches for solar cell technological advancement was developed to strategize and plan future development of the new technology-based industry [16]. Previous studies have mainly included a review of BIPV performance in building components, while other studies have analyzed the impact on building energy consumption.

However, there are no bibliometric reviews that perform scientific and performance mapping of BIPV systems, where their structure, evolution and trends in this field can be highlighted. BIPVs have enormous power generation potential for urban applications. However, these systems are in their emerging stage, with few commercial installations [17]. In addition, it is necessary to establish standards and standardized evaluation criteria that address the energy performance of BIPV modules, considering aspects such as thermal management, solar energy capture, optical and electrical efficiency. On the other hand, the special operating conditions of BIPV systems, particularly those related to the variability of solar radiation, pose additional challenges in terms of electrical design and the ability to predict the performance of these systems. Therefore, finding an adequate balance between energy efficiency, aesthetics and visual comfort becomes a relevant factor for the successful implementation of BIPV systems [18]. Bibliometric techniques, on the other hand, provide an overview of the growth, expansion and distribution of scientific literature related to a specific research area [19].

Therefore, the main contribution of this study was the elaboration of a scientific map of the BIPV systems and a detailed identification of the scientific production that predicts future research directions. The bibliometric approach allows quantifying the performance, quality and impact of the scientific maps generated [20]. The document is organized as follows: Section 2 describes the scientific mapping approach based on the co-occurrence of terms through clustering techniques, scientific mapping and performance analysis that are applied in BIPV systems. In Section 3, the findings are analyzed. Finally, the conclusions are presented.

2. Materials and methods

2.1. Sources and data

In this study, we use scientific map analysis, which focuses on monitoring a scientific field and defining its research areas, to determine cognitive and evolutionary structure [20]. To carry out the bibliometric analysis, two computer tools were used: a) Scopus as an analysis tool to perform the synthesis of performance, and b) SciMAT used in the bibliometric analysis of content from scientific maps. Rigorous analysis is performed using the procedures of the scientific mapping approach proposed in [21,22]. This model has been used in different research topics, including the photovoltaic thermal system in [23], the future of material applications for CO_2 capture in [24], and sustainability and challenges in biodiesel production in [25]. Consequently, scientific mapping analysis comprises the following stages: Data collection and pre-processing, generation and normalization of networks, scientific mapping, analysis and visualization of the thematic network.

The Scopus database was used for article searches. It is a multidisciplinary database, and relevant information for the treated field was found [19]. Additionally, Scopus contains a higher number of unique documents compared to other databases, which is very appropriate for the identification of original research documents [26]. The search was carried out by selecting only the keyword field and using the following search equation: KEY ("Build Integrate Photovoltaics" OR "BIPV"). Similarly, only original articles were considered for the period 200–2022 (April), considering the subareas related to the field under study. From this, 938 documents were obtained. According to the combined trends of scientific production, the period was divided into three sub-periods for evolutionary analysis of the research field under study [27]. This is how the periods 2001–2010, 2011–2016 and 2017–2022 were selected, considering the documentary volume of each period to allow the detection of lines of investigation.

2.2. Bibliometric analysis tools

The initial analysis was carried out using the Scopus database tool. For this, the major authors, universities, journals and other information that identifies the scientific production of the BIPV were identified, considering the h-index [19]. In the same way, SciMAT was used to evaluate the evolution of BIPV. This tool builds maps of scientific production, monitors the scientific field, delimits research areas to determine their intellectual, social and cognitive structure, and analyzes their structural evolution in the field [28].

To determine the scientific mapping related to BIPV, the protocols described in [20] were used. SciMAT builds scientific maps by performing co-occurrence analysis on each research article selected for analysis. In addition, SciMAT analyzes the structural evolution in the elaboration of scientific maps and visualizes the evolution of a scientific area [27]. It is a bibliometric tool to produce a high-level analysis of research trends, productivity related to different fields, and patterns of scientific connections [29]. SciMAT has several advantages over other bibliometric tools, for example, CoPalRed, IN-SPIRE, VantajaPoint and VOsViewer [19].

In addition, SciMAT identifies thematic research networks through keywords. Moreover, the software builds strategic diagrams using indicators such as centrality and density. Furthermore, SciMAT identifies thematic research networks through keywords and builds strategic diagrams using indicators such as centrality and density [30], as shown in Figure 1. The concept of centrality shows the degree of strength of the external links between two terms or keywords, allowing interpretation of the importance of a topic in the global development of a field of research and is defined by the Equation:

$$c = 10 \sum e_{uv} \tag{1}$$

where u is a keyword that belongs to the topic and v is a keyword that is related to other topics. On the other hand, the density shows the internal cohesion of the related links between the keywords that the topic contains and provides an idea of the level of development of that topic and is defined by:

$$d = 100(\sum e_{eij}/n) \tag{2}$$

where i and j are the elements (keywords) belonging to the theme, and n is the number of elements (keywords) in the theme. Through centrality and density, a research field can be represented using a strategy diagram, as shown in Figure 1. SciMat shows a strategy diagram with a set of issues classified two-dimensionally into four categories [31].

Quadrant 1 illustrates the topics that have been extensively researched and that play a fundamental role in the construction of the scientific field. These themes, known as motor themes, have a high centrality and density, which makes them crucial elements for the development of research in this field.

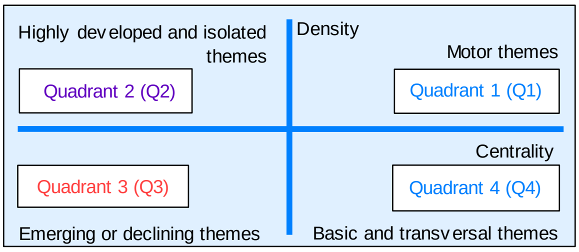


Figure 1. Structure of the strategic diagram.

Quadrant 2, on the other hand, represents topics that have been deeply explored internally but are disconnected from other areas of the scientific field. These topics, classified as isolated and highly developed, despite their high degree of development, have limited importance in the context of the general field and tend to be specialized and peripheral.

On the other hand, Quadrant 3 reflects topics that are in an initial phase of development and that have low density and centrality in the field. These topics, called emerging or declining topics, lack development and relevance in the field of research.

Finally, Quadrant 4 highlights topics that are essential to the field of research but have not yet reached a high level of development. These themes, known as basic and transversal themes, are in the process of growth and consolidation in the field.

3. Results and discussion

3.1. Performance analysis

Table 1 shows the bibliometric performance of the research field based on the number of articles published by the authors with the highest volume of research. The documents are shown by affiliation, and country/territory. Figure 2 shows the growing trend of research publications in BIPV from 2001 to April 2022 (Figure 2a). The 36% of the documents analyzed comprise conference papers, while the rest are original journal articles. Figure 2b shows the trend of publications according to the most representative journals in the field of research according to the data extracted from Scopus.

3.2. Strategic diagram

Figure 3 shows six clusters from the bibliometric analysis for the period 2001–2010, of which three are classified as motor themes, and the other three are a basic and transversal theme, an emerging or declining theme and a highly developed and isolated theme. The size of each cluster is proportional to the number of core documents associated with the topic. The performance analysis of the research topics is shown, through centrality and density, in addition to the sum of citations and h-index. It is observed that 55 articles report on studies directly related to BIPV systems, establishing this as a driving theme for the field of research. While two articles deal with maximum output, which is related to the extraction of the maximum power from the integrated photovoltaic module [32], it is also considered a driving theme. In the same way, the solar system is within the same quadrant and is related to the concentrating photovoltaic/thermal system [33]. In contrast, renewable resource are classified as a specialized and isolated topic, while thin films appear to be declining and are related to the efficiency of thin film solar cells [34].

Table 1. Documents by author, affiliation and country/territory.

Documents by author		Documents by affiliation		Documents by country/territory	
Author	Units	Affiliation	Units	Country/territory	Units
Rüther, R.	20	National University of Singapore	27	China	129
Mallick, T.K.	14	Hong Kong Polytechnic University	25	Italy	77
Yang, H.	14	Concordia University	22	United States	71
Athienitis, A.K.	12	Universidade Federal de Santa Catarina	21	United Kingdom	68
Driesen, J.	12	Scuola Universitaria Professionale della Svizzera Italiana	20	India	66
Frontini, F.	11	KU Leuven	18	Spain	59
Ravyts, S.	11	Politecnico di Milano	17	Switzerland	56
Ghosh, A.	10	University of Exeter	17	South Korea	55
Jelle, B.P.	10	Norges Teknisk-Naturvitenskapelige Universitet	15	Hong Kong	40
Lau, S.K.	10	Indian Institute of Technology Indian School of Mines, Dhanbad	14	Netherlands	38
Martín-Chivelet, N.	10	Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas	13	Canada	37

In the 2011–2016 period (Figure 4), the seven most relevant clusters were presented for the BIPV research field. Among them, the BIPV system cluster reappears as a driving theme, with a h-index of 41 and 4519 citations. Also in this quadrant is the grid-connected photovoltaics cluster, with a h-index of 2 and 79 citations. These on-grid solar power systems are directly connected to the grid, feeding power into the grid during the day or only when sunshine is available. Unlike off-grid solar power systems, which are equipped with an energy storage system, they can provide backup power to the load even when sunlight is not available [35]. However, the environmental impact and shading effect clusters are presented as specialized and isolated issues because they are in the second quadrant. The second case is related to the shadow effect to which the BIPV is subjected due to the integration of photovoltaic panels in the building envelope, such as in the replacement of roof tiles or wall cladding [5]. More specifically, other studies have focused on crystalline photovoltaic technologies that are prone to irreversible damage due to shading effects [36].

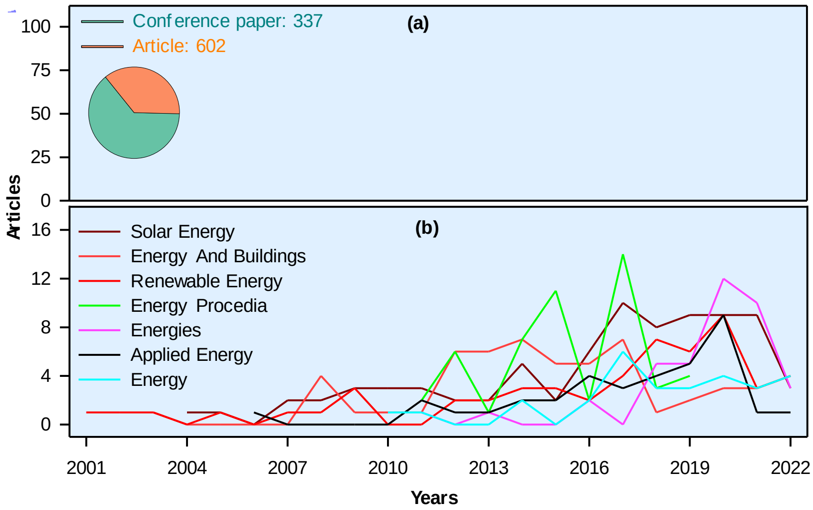


Figure 2. (a) Research publications in BIPV; (b) Leading research journals.

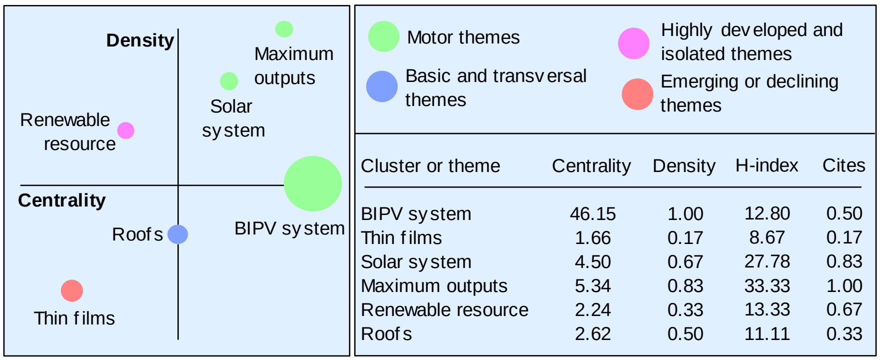


Figure 3. Strategic map and bibliometric performance for the period 2001–2010.

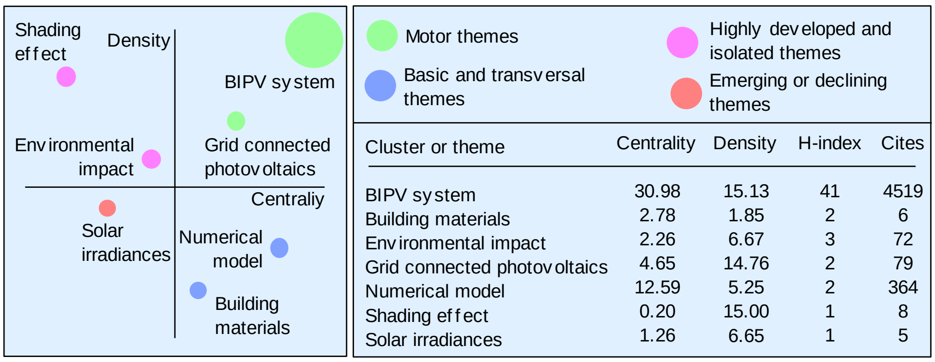
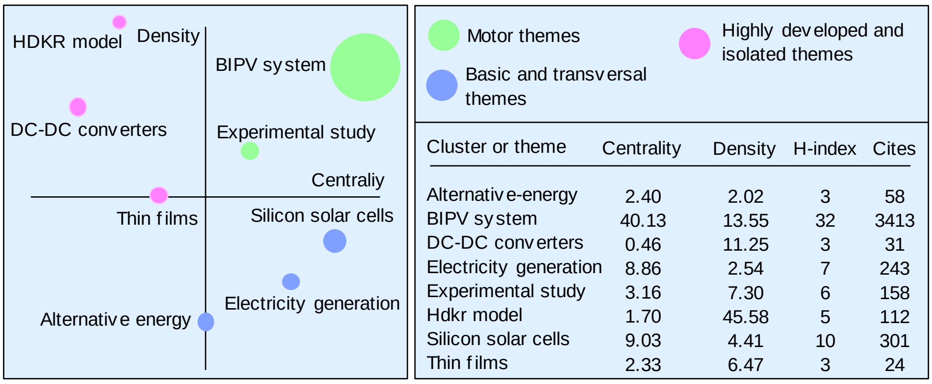


Figure 4. Strategic map and bibliometric performance for the period 2011–2016.

Within the seven relevant clusters for this period, solar irradiance was presented as a declining theme with a h-index of 1 and 5 citations. However, building materials and numerical models are considered transversal, and developing clusters for this period are evaluated within the BIPV. Building materials are photovoltaic products used in construction as substitutes for conventional building materials [37]. Numerical models are related to studies on thermal comfort using BIPV systems [38]. Similarly, it focuses on the heat and mass transfer of materials with various concentrations of different nanoparticles connected to the back of the BIPV [39], the thermal and electrical performance of a hybrid collector that includes a BIPV system in [40], evaluation of the thermal comfort of a double envelope facade with a BIPV system considering several climatic zones [41] and others.

For the last evaluated period 2017–2022, 8 representative clusters were presented within the BIPV systems, as shown in Figure 5. The BIPV system was maintained with h-indices of 32 and 3413 citations. The experimental study cluster was in the same quadrant, with a h-index of 6 and 158 citations. The HDKR model, DC-DC converters and thin films exist within the specialized and isolated clusters in the second quadrant of the strategic map. HDKR models are related to studies on the theoretical and experimental performance of photovoltaic cells and tracking surfaces using simulations of isotropic and anisotropic (HDKR) models in different applications, such as single- and double-axis systems [42].



Cluster or theme	Centrality	Density	H-index	Cites
Alternative-energy	2.40	2.02	3	58
BIPV system	40.13	13.55	32	3413
DC-DC converters	0.46	11.25	3	31
Electricity generation	8.86	2.54	7	243
Experimental study	3.16	7.30	6	158
Hdkr model	1.70	45.58	5	112
Silicon solar cells	9.03	4.41	10	301
Thin films	2.33	6.47	3	24

Figure 5. Strategic map and bibliometric performance for the period 2017–2022.

Finally, the fourth quadrant covers issues that are both cross-cutting and in the process of development. Within this category, we find groups related to silicon solar cells (with a h-index of 10 and 301 citations), electricity generation (h-index of 7,243 citations) and alternative energy (h-index of 3, 58 quotes). Although silicon-based solar cells are currently dominant in the photovoltaic market, they still have relatively low-power conversion efficiency [43]. However, the shift towards photovoltaic technology based on flexible solar cells is motivated by the increasing demand for devices that offer high flexibility, lightness, conformability and flexibility, which are fundamental qualities for BIPV systems [44]. As a result, solar panels incorporating flexible silicon-based materials represent an emerging technology that is being adopted in BIPV systems. This change marks the beginning of a new era in solar energy conversion systems and flexible electronic devices.

3.3. Thematic evolution

Figure 6 shows the overlay map and thematic evolution structure of BIPV. Referring to the map superimposed on Figure 6a, in the first subperiod (2001–2010) of 127-word constructions, 78% are included in the second subperiod (99 terms), in addition to 133 new constructions, generating a consistent research field. Similarly, through the transition from the second (2011–2016) to the third subperiod (2017–2022), of 232-word constructions, 170 thematic constructions were maintained, representing 73%. Finally, 62-word constructions were not transferred from the second to the third period, whereas 141 new terms entered the field of research. Therefore, research in this field is constantly growing. This is related to the thematic evolution map in Figure 6b, where the BIPV system cluster presents an increasing evolution in the number of articles found for each subperiod. This cluster is related in a conceptual way between sub-periods; it also has a direct relationship, although not conceptual, with environmental impact in the second sub-period. Similarly, between the second and third sub-periods, it was conceptually related to silicon solar cells, electricity generation and experimental studies.

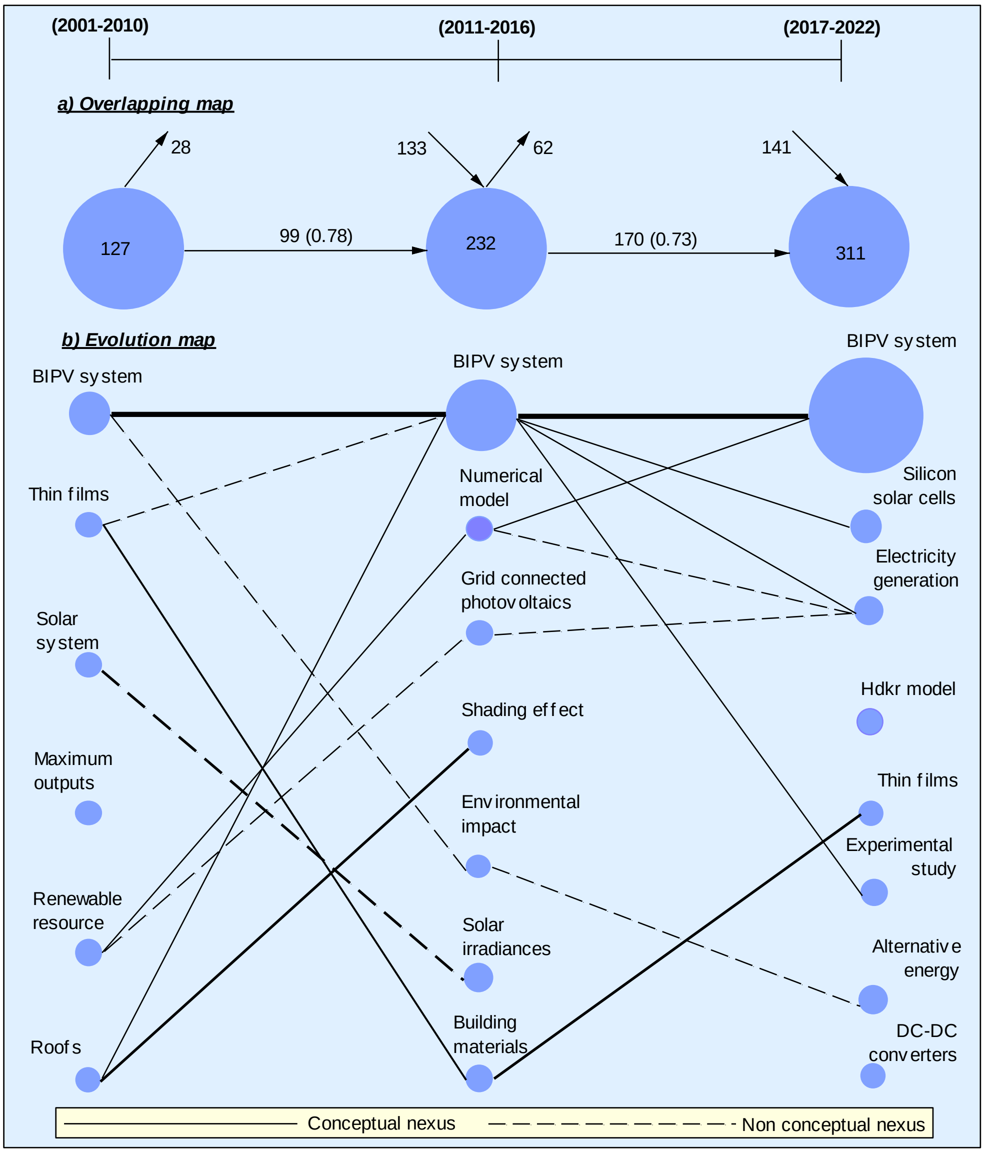


Figure 6. Thematic evolution structure of BIPV for the period 2001–2022. (a) Overlapping map; (b) Evolution map.

3.4. Thematic network

Figure 7 shows the structure of the thematic network for BIPV, considering the driving and transversal themes of the final evaluated period 2017–2022. According to Figure 7a, the BIPV system and the experimental study are the motor clusters of the BIPV research field for the evaluated period and are presented in Figure 7b and c, respectively. Silicon solar cells, electricity generation and alternative energy represent the cross-cutting and developing themes, and their thematic networks are shown in Figure 7d, e and f, respectively.

The BIPV system is integrated with the topics of buildings, investments, numerical models, office buildings, photovoltaic modules, roofs, solar cells and zero-energy buildings. This thematic network is oriented with the growing interest in BIPV, mainly because many countries are setting specific goals related to net-zero energy buildings [7]. In this sense, BIPV systems must respond to multifunctional roles, and several factors are considered, including the temperature of the PV module, installation angle, orientation and shading. However, the temperature and irradiance of the PV module are the most important factors because they are directly related to the energy performance of buildings based on the efficiency of the BIPV system.

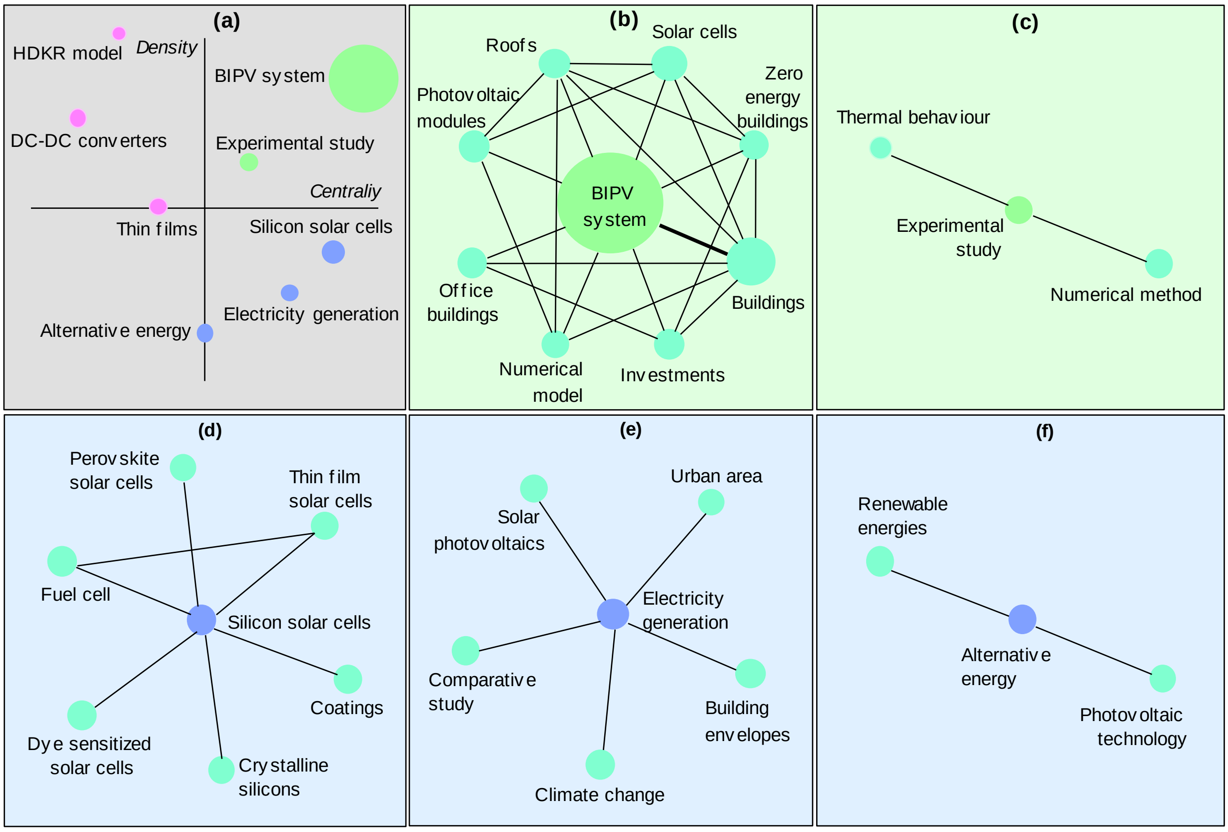


Figure 7. Thematic network structure of BIPV to motor and transversal themes (2016–2022): (a) Strategic map 2017–2022; (b) BIPV system thematic network; (c) Experimental study thematic network; (d) Silicon solar cells thematic network; (e) Electricity generation thematic network; (f) Alternative energy thematic network.

Similarly, an experimental study is linked to the numerical method and thermal behavior, given that when the temperature of the BIPV increases, the conversion efficiency deteriorates. This thematic network focuses on evaluating the thermal behavior using numerical methods related to experimental studies. For this, systems that use phase change materials for BIPV thermal control have been proposed [45]. Numerical models are suggested which include empirical correlations for the estimation of the heat transfer coefficients by convection in the airspace between the photovoltaic panel and the rear wall of the system [46].

As PV technology has advanced, the possibility of developing flexible PV elements instead of PV elements based on silicon wafer substrates is currently of scientific interest [44]. Therefore, silicon solar cells are considered a cross-cutting theme within the field of BIPV research. However, focused technologies must be developed to overcome the current limitations associated with BIPV applications [47]. Similarly, the electricity generation cluster is a cross-cutting theme, and its thematic network is related to building envelopes, climate change, comparative study, solar photovoltaics and urban areas. This thematic network focuses on the interaction of different external factors that can affect the energy efficiency of a building. Among the various elements of a building, the envelope is an important part of energy consumption studies [48]. This is the physical separation between the conditioned and unconditioned rooms of a building from air, heat, sound, light and water.

For example, in hot climates, low-cost methods, including roofs and walls with reflective exterior shades and low-radiation window treatments, can also reduce the energy used for cooling. In cold climates, the rate of passive heating can be improved by optimizing building design and using modern window and glazing systems. The efficient use of the energy used in the building envelope depends largely on the diffusion of current technologies in the market. Because it is a transversal thematic network, studies are being presented where it is reported that it is feasible to replace conventional facade materials with BIPV modules for the construction of cladding [49]. The results show that the BIPV system, as a building material encapsulating all building envelopes, can not only pay all investment costs, but also become a source of building revenue.

Finally, the thematic network of alternative energy is related to renewable energies and photovoltaic technology. This network is oriented to be studied in a smaller market. Therefore, this technology is not competitively priced on a retail scale compared to conventional PV panels because it is still under development. Similarly, there are no standards, and further experience needs to be developed. Unlike the conventional PV module, it is relatively common worldwide; therefore, experienced installers use industry-developed standards [50]. However, applications involving sloped surfaces are generally employed in BIPV. In general, the ceiling system had a lower shading effect than that of the floor supply system. Roofs often provide large unused areas for BIPV applications. A more complex approach to BIPV system integration is the use of photovoltaic cells integrated with building materials. That is, the BIPV module is installed like any other block and can perform the same resistance work as the conventional one.

In addition, the influence of wind speed on the interaction with the PV solar panel components and the increased weight that the BIPV power generation system adds to the roof are considered. However, it is crucial to highlight that translucent glass elements are widely used for aesthetic and architectural reasons [51], since they facilitate the entry of natural light into the interior of buildings. Adjustment of the amount of light passing through these structures is achieved through measurements and can be effectively balanced by varying the number and arrangement of the PV cells using crystalline silicon technology.

Transparent BIPV units find various applications in windows, facades and shading systems. In the context of windows, the incorporation of translucent BIPV modules presents significant advantages, as they concentrate the dispersion of light into a focal point and offer a clear surface for the installation of photovoltaic panels. Similarly, these BIPV modules can be integrated into window frames, allowing the creation of partially transparent facades [52]. Transparency is achieved by implementing flexible thin film BIPV technology or crystalline silicon (c-Si) BIPV technology. Translucent BIPV modules can play multiple roles, such as window shading elements or an integral part of architectural cladding.

3.5. Comparative analysis of BIPV performance strategies across diverse climate zones

Different types of climates have a significant influence on the environment and weather conditions of a region and BIPV systems [53], as shown in Table 2. For example, the arid climate is characterized by its extreme dryness and lack of precipitation, which results in dry conditions and a notable variation in temperatures between day and night due to the lack of moisture in the air. In contrast, cold weather is defined by low temperatures, especially during the winter months, and can include snowfall and temperatures that drop below freezing [54]. On the other hand, a hot and humid climate is found in areas with high levels of humidity in the air and high temperatures for most of the year. This type of climate is known for its hot and humid conditions, which can influence wind chill. Moreover, a warm climate is characterized by having high temperatures for a significant part of the year, although without the high humidity typical of hot, humid climates [55].

As for the climates most influenced by bodies of water, the maritime climate, also known as oceanic, is characterized by moderate temperatures throughout the year and a relatively uniform distribution of precipitation. Similarly, the Mediterranean climate presents hot and dry summers, contrasting with mild and humid winters, which are common in areas near the Mediterranean Sea. On the other hand, high-altitude or mountainous climates exhibit lower temperatures as one ascends in altitude, often presenting notable variations between day and night. In the case of semi-arid climates, they are located between arid and subtropical climates, showing moderate rainfall but insufficient to maintain dense vegetation [56].

Subtropical climates are distinguished by warm to hot temperatures and high humidity during the summer, although winters are relatively mild. For their part, temperate climates have well-defined seasons with warm summers and cold winters, which is a common climate in many parts of the world. In contrast, tropical climates are known for their high temperatures throughout the year and a rainy season that can be very pronounced. Similarly, hot, sunny weather combines high temperatures with a high incidence of sunlight, which can influence the design and efficiency of photovoltaic systems [53].

The energy performance of BIPV systems has been evaluated in different climatic contexts. In hot and sunny climates, such as Shenzhen, China, a BIPV system was implemented in an office, achieving a notable annual production of 133.19 kWh, indicating high performance in power generation [57,58]. Likewise, in areas with a warm and sunny climate in Brazil, it is suggested that a 1 MWp BIPV system could satisfy around 30% of the energy demand of a large commercial building [59].

Under mild climatic conditions, such as those observed in Daegu, Korea, an 18.2% reduction in heating and cooling loads has been demonstrated with amorphous silicon (a-Si) BIPV windows, demonstrating good performance in this context [60]. Regarding resistance to environmental conditions, the performance of BIPVs in different environments has been evaluated. In Shenzhen, China, a significant reduction in CO_2 emissions was observed under hot summer and mild winter climate conditions [57]. On the other hand, in Daegu, Korea, the performance of amorphous silicon (a-Si) BIPV in offices was analyzed, considering operating conditions in temperate climates (Article 16).

Thermal analysis has also been addressed in these studies. In Shenzhen, China, a BIPV was implemented in an office with a hot summer and mild winter climate, which demonstrated improved energy savings [58]. In Daegu, Korea, the thermal performance of office buildings with amorphous silicon (a-Si) BIPV windows was evaluated [60]. Additionally, shadow analysis was examined, which is crucial to the efficiency of BIPVs. In Shenzhen, China, the performance of BIPV with bifacial PV modules was evaluated to provide shade and generate electricity [57]. In Daegu, Korea, the performance of amorphous silicon (a-Si) BIPV windows in offices was analyzed, considering orientation and shading [60].

Table 2. Comparison of studies on performance of BIPVs in different climatic conditions

Article	Climate type	Energy performance	Efficiency and losses	Environmental conditions resistance	Thermal analysis	Shadow analysis
[61]	Arid	✓	✓	✓	✓	✗
[62]	Cold	✓	✓	✗	✓	✓
[63]		✓	✓	✗	✓	✓
[64]		✓	✓	✗	✓	✓
[65]	Hot and humid	✓	✓	✗	✓	✓
[66]		✓	✓	✗	✓	✗
[67]	Hot	✓	✓	✗	✓	✗
[68]	Maritime	✓	✓	✗	✓	✓
[69]	Mediterranean	✓	✓	✗	✓	✓
[70]		✓	✓	✓	✓	✓
[57]	Montane	✓	✓	✓	✓	✗
[71]	Semi-arid	✓	✓	✗	✓	✓
[72]		✓	✓	✗	✓	✓
[73]	Subtropical	✓	✓	✗	✓	✓
[74]		✓	✓	✗	✓	✓
[75]	Temperate	✓	✓	✗	✓	✓
[76]		✓	✓	✗	✓	✓
[60]		✓	✓	✗	✓	✓
[77]	Tropical	✓	✓	✗	✓	✓
[78]		✓	✓	✗	✓	✓
[79]		✓	✓	✗	✓	✗
[80]		✓	✓	✗	✓	✗
[81]		✓	✓	✗	✓	✗
[82]		✓	✓	✗	✓	✗
[83]	Warm and humid	✓	✓	✗	✓	✓
[84]		✗	✗	✗	✗	✗

Continued on next page

Article	Climate type	Energy performance	Efficiency and losses	Environmental conditions resistance	Thermal analysis	Shadow analysis
[59]	Warm and sunny	✓	✓	✗	✓	✓
[85]		✓	✓	✗	✓	✓
[86]	Warm	✓	✓	✗	✓	✓
[58]		✓	✓	✗	✓	✓

Therefore, BIPVs show excellent performance in hot, sunny climates, generating a significant amount of energy in places such as Shenzhen, China and Brazil. Additionally, they demonstrate their ability to improve energy efficiency in temperate climates, as seen in Daegu, Korea. These systems also show good resistance to diverse environmental conditions and provide benefits in terms of reducing CO_2 emissions. Thermal and shading analysis also demonstrates its positive impact on the energy efficiency of buildings. Overall, BIPVs are a promising technology for power generation and efficiency improvement in different climates.

Other important strategies address the problem of heat losses in PV/T systems by proposing the integration of silica air gel on the top surface to reduce these losses and the inclusion of composite phase change material (PCM) on the upper surface. Back to dissipate accumulated heat [87]. Likewise, other work focuses on the integration of phase change material (PCM) walls, BIPVs and HVAC systems to highly achieve energy-efficient buildings and reduce heating/cooling loads. A platform is established to study the synergistic functions between these elements, including the improvement of thermal inertia, solar shading and renewable energy generation [74].

In the context of environmental assessments, both passive and active strategies have been formulated with the aim of moving towards decarbonization, giving priority to the implementation of on-site renewable energy systems. The findings underline the crucial relevance of active strategies, evidencing significant reductions in emissions by integrating photovoltaic solar panels into built infrastructure [73]. Likewise, the notable effectiveness of data-based models is highlighted, while an approach supported by Artificial Intelligence (AI) is proposed to enhance operational robustness in environments characterized by uncertainty. AI also finds valuable applications when it comes to the security and stability of renewable energy systems. These advances represent a comprehensive overview covering the historical development, most recent progress and challenges on the horizon of AI applications in renewable energy systems [88]. This perspective contributes significantly to the configuration of intelligent and robust energy systems that drive decarbonization in the field of buildings.

3.6. *Holistic perspectives on BIPV technology: trends, challenges and future*

The evolution of hot topics in Building Integrated Photovoltaics (BIPV) research responds to changing priorities within this field. Initially, the research focused mainly on fundamental aspects, with an emphasis on understanding the essential principles of BIPV systems. Over time, however, there has been a notable shift toward more applied and multidisciplinary approaches. This is reflected in the emergence of issues related to environmental impact, shading effects and the integration of BIPV with construction materials. Researchers are exploring new ways to optimize power generation while ensuring harmonious integration with architectural designs. Furthermore, the rise of flexible solar cell technology indicates a growing interest in adaptable and aesthetically appealing BIPV solutions. These trends denote a broader recognition of the potential of BIPV in sustainable construction practices.

BIPV faces several challenges in both research and practical application. One of the main concerns is the cost associated with manufacturing and installation. Although BIPV systems offer long-term energy savings, the initial investment can be a significant barrier to wider adoption. Additionally, integrating BIPV into existing structures can be complex and may require structural modifications. Ensuring the durability and longevity of BIPV components under various environmental conditions is crucial, as these materials must withstand exposure to varying weather patterns and external factors over time. Addressing issues related to shading effects and potential damage to crystalline PV technologies is essential to optimizing the performance of BIPV systems.

The future of BIPV technology looks bright and is poised for continued growth. Ongoing research and innovations in materials and manufacturing processes are expected to reduce costs, making BIPV more accessible to a broader market. As environmental regulations and sustainability initiatives become more stringent, BIPV will play an increasingly vital role in improving energy efficiency and reducing carbon footprints in buildings. The integration of energy storage solutions with BIPV systems represents an interesting area for further development, allowing better management of the generated energy and greater independence from the grid. Furthermore, the adoption of flexible silicon-based materials in solar panels signals a new era in BIPV technology, characterized by greater flexibility, lightweight design and adaptability. This shift heralds a transformative phase in both solar energy conversion systems and flexible electronic devices.

4. Conclusions

Our main objective of this study was to create a scientific map of building integrated photovoltaics (BIPV) and provide a comprehensive understanding of the scientific production in this field. A close interconnection of the body of research is observed with related areas such as buildings, investments, numerical models, office buildings, photovoltaic modules, roofs, solar cells and zero-energy buildings.

- Flexible solar panels are expected to lead to products suitable for applications requiring lightness, mechanical flexibility and the ability to take on complex shapes.
- Likewise, the central and multidisciplinary role of silicon solar cells in the field of BIPV research is highlighted.
- Regarding the different types of climates, their significant impact on the performance of BIPVs is confirmed.
- The results of evaluations in various climatic contexts are encouraging in warm and sunny climates, BIPVs demonstrated high-energy generation, while in temperate climates, BIPV windows exhibited a reduction in heating and cooling loads, indicating notable efficiency.
- Despite significant benefits, BIPVs face challenges such as upfront costs, integration complexities and durability concerns.

Therefore, research in BIPV has undergone an evolution towards more applied and multidisciplinary approaches, focusing on optimizing energy generation, environmental impact and architectural integration. Advances in materials and manufacturing processes are expected to reduce costs and make BIPV technology more accessible. The integration of energy storage solutions and flexible silicon-based materials represents an exciting prospect for the future of BIPVs.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

We sincerely thank the Universidad Privada del Norte (UPN) and the Universidad Nacional del Callao (UNAC) for their valuable support and collaboration, which significantly contributed to the completion of this research work. In addition, we wish to express our gratitude to CONCYTEC Peru for providing us with access to various sources of knowledge that were essential to carrying out this study.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

Author contributions

Eliseo Zarate-Perez: research, formal analysis, software, writing (original draft), writing the review, editing and supervision. Juan Grados, Santiago Rubiños, Herbert Grados-Espinoza and Jacob Astocondor-Villar: conceptualization, validation, writing, review and current edition.

References

1. Biyik E, Araz M, Hepbasli A, et al. (2017) A key review of building integrated photovoltaic (BIPV) systems. *Jestech* 20: 833–858. https://doi.org/10.1016/j.jestch.2017.01.009
2. Almulhim AI (2022) Understanding public awareness and attitudes toward renewable energy resources in Saudi Arabia. *Renewable Energy* 192: 572–582. https://doi.org/10.1016/j.renene.2022.04.122
3. Zarate-Perez E, Sebastián R (2022) Autonomy evaluation model for a photovoltaic residential microgrid with a battery storage system. *Energy Rep* 8: 653–664. https://doi.org/10.1016/J.EGYR.2022.07.085
4. Anderson TN, Duke M, Morrison GL, et al. (2009) Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector. *Sol Energy* 83: 445–455. https://doi.org/10.1016/J.SOLENER.2008.08.013
5. Debbarma M, Sudhakar K, Baredar P (2017) Comparison of BIPV and BIPVT: A review. *Resour-Effic Technol* 3: 263–271. https://doi.org/10.1016/J.REFFIT.2016.11.013
6. Makki A, Omer S, Sabir H (2015) Advancements in hybrid photovoltaic systems for enhanced solar cells performance. *Renewable Sustainable Energy Rev* 41: 658–684. https://doi.org/10.1016/J.RSER.2014.08.069
7. Peng C, Huang Y, Wu Z (2011) Building-integrated photovoltaics (BIPV) in architectural design in China. *Energy Build* 43: 3592–3598. https://doi.org/10.1016/J.ENBUILD.2011.09.032

8. Agathokleous RA, Kalogirou SA (2016) Double skin facades (DSF) and building integrated photovoltaics (BIPV): A review of configurations and heat transfer characteristics. *Renewable Energy* 89: 743–756. https://doi.org/10.1016/J.RENENE.2015.12.043
9. Catto Lucchino E, Goia F, Lobaccaro G, et al. (2019) Modelling of double skin facades in whole-building energy simulation tools: A review of current practices and possibilities for future developments. *Build Simul* 12: 3–27. https://doi.org/10.1007/S12273-019-0511-Y
10. Shukla AK, Sudhakar K, Baredar P, et al. (2018) BIPV based sustainable building in South Asian countries. *Sol Energy* 170: 1162–1170. https://doi.org/10.1016/J.SOLENER.2018.06.026
11. Saretta E, Caputo P, Frontini F (2019) A review study about energy renovation of building facades with BIPV in urban environment. *Sustain Cities Soc* 44: 343–355. https://doi.org/10.1016/J.SCS.2018.10.002
12. Kuhn TE, Erban C, Heinrich M, et al. (2021) Review of technological design options for building integrated photovoltaics (BIPV). *Energy Build* 231: 110381. https://doi.org/10.1016/J.ENBUILD.2020.110381
13. Rounis ED, Athienitis A, Stathopoulos T (2021) Review of air-based PV/T and BIPV/T systems-Performance and modelling. *Renewable Energy* 163: 1729–1753. https://doi.org/10.1016/J.RENENE.2020.10.085
14. Yang T, Athienitis AK (2016) A review of research and developments of building-integrated photovoltaic/thermal (BIPV/T) systems. *Renewable Sustainable Energy Rev* 66: 886–912. https://doi.org/10.1016/J.RSER.2016.07.011
15. Shen Y, Ji L, Xie Y, et al. (2021) Research landscape and hot topics of rooftop PV: A bibliometric and network analysis. *Energy Build* 251: 111333. https://doi.org/10.1016/J.ENBUILD.2021.111333
16. Li X, Zhou Y, Xue L, et al. (2015) Integrating bibliometrics and roadmapping methods: A case of dye-sensitized solar cell technology-based industry in China. *Technol Forecast Soc Change* 97: 205–222. https://doi.org/10.1016/J.TECHFORE.2014.05.007
17. Pillai DS, Shabunko V, Krishna A (2022) A comprehensive review on building integrated photovoltaic systems: Emphasis to technological advancements, outdoor testing, and predictive maintenance. *Renewable Sustainable Energy Rev* 156: 111946. https://doi.org/10.1016/J.RSER.2021.111946
18. Martín-Chivelet N, Kapsis K, Wilson HR, et al. (2022) Building-integrated photovoltaic (BIPV) products and systems: A review of energy-related behavior. *Energy Build* 262: 111998. https://doi.org/10.1016/j.enbuild.2022.111998
19. Salazar-Concha C, Ficapal-Cusí P, Boada-Grau J, et al. (2021) Analyzing the evolution of technostress: A science mapping approach. *Heliyon* 7: e06726. https://doi.org/10.1016/J.HELIYON.2021.E06726
20. Cobo MJ, Lõpez-Herrera AG, Herrera-Viedma E, et al. (2012) SciMAT: A new science mapping analysis software tool. *J Am Soc Inf Sci Technol* 63: 1609–1630. https://doi.org/10.1002/asi.22688
21. Cobo MJ, López-Herrera AG, Herrera-Viedma E, et al. (2011) Science mapping software tools: Review, analysis, and cooperative study among tools. *J Am Soc Inf Sci Technol* 62: 1382–1402. https://doi.org/10.1002/asi.21525
22. Zarate-Perez E, Rosales-Asensio E, González-Martínez A, et al. (2022) Battery energy storage performance in microgrids: A scientific mapping perspective. *Energy Rep* 8: 259–268. https://doi.org/10.1016/J.EGYR.2022.06.116

23. Azad AK, Parvin S (2022) Bibliometric analysis of photovoltaic thermal (PV/T) system: From citation mapping to research agenda. *Energy Rep* 8: 2699–2711. https://doi.org/10.1016/J.EGYR.2022.01.182
24. Naseer MN, Zaidi AA, Dutta K, et al. (2022) Past, present and future of materials' applications for CO_2 capture: A bibliometric analysis. *Energy Rep* 8: 4252–4264. https://doi.org/10.1016/J.EGYR.2022.02.301
25. Chen C, Chitose A, Kusadokoro M, et al. (2021) Sustainability and challenges in biodiesel production from waste cooking oil: An advanced bibliometric analysis. *Energy Rep* 7: 4022–4034. https://doi.org/10.1016/J.EGYR.2021.06.084
26. Sánchez AD, de la Cruz Del Río Rama M, García JÁ (2017) Bibliometric analysis of publications on wine tourism in the databases Scopus and WoS. *ERMBE* 23: 8–15. https://doi.org/10.1016/J.IEDEEN.2016.02.001
27. Zarate-Perez E, Sebastián R, Grados J (2021) Online labs: A perspective based on bibliometric analysis. *19th LACCEI International Multi-Conference for Engineering, Education Caribbean Conference for Engineering and Technology* 175610. https://doi.org/10.18687/LACCEI2021.1.1.267
28. Moral-Muñoz JA, Cobo MJ, Peis E, et al. (2014) Analyzing the research in integrative & complementary medicine by means of science mapping. *Complement Ther Med* 22: 409–418. https://doi.org/10.1016/j.ctim.2014.02.003
29. Ellegaard O, Wallin JA (2015) The bibliometric analysis of scholarly production: How great is the impact? *Scientometrics* 105: 1809–1831. https://doi.org/10.1007/S11192-015-1645-Z/TABLES/9
30. López-Robles JR, Cobo MJ, Gamboa-Rosales NK, et al. (2021) Mapping the intellectual structure of the international journal of computers communications and control: A content analysis from 2015 to 2019. *Adv Intell Syst Comput* 1243: 296–303. https://doi.org/10.1007/978-3-030-53651-0_25
31. Gutiérrez-Salcedo M, Martínez MÁ, Moral-Munoz JA, et al. (2017) Some bibliometric procedures for analyzing and evaluating research fields. *Appl Intell* 48: 1275–1287. https://doi.org/10.1007/S10489-017-1105-Y
32. Hadj Arab A, Taghezouit B, Abdeladim K, et al. (2020) Maximum power output performance modeling of solar photovoltaic modules. *Energy Rep* 6: 680–686. https://doi.org/10.1016/J.EGYR.2019.09.049
33. Li H, Huang J, Wang H, et al. (2021) Effects of receiver parameters on the optical efficiency of a fixed linear-focus Fresnel lens solar system with sliding adjustment. *Energy Rep* 7: 3348–3361. https://doi.org/10.1016/J.EGYR.2021.05.072
34. Li B, Zhao A, Xiang D, et al. (2022) Smooth Cu electrodeposition for Cu (In, Ga) Se_2 thin-film solar cells: Dendritic clusters elimination by Ag buffer layer. *Energy Rep* 8: 1847–1852. https://doi.org/10.1016/J.EGYR.2021.12.079
35. Dey D, Subudhi B (2020) Design, simulation and economic evaluation of 90 kW grid connected Photovoltaic system. *Energy Rep* 6: 1778–1787. https://doi.org/10.1016/J.EGYR.2020.04.027
36. Zsiborács H, Zentkó L, Pintér G, et al. (2021) Assessing shading losses of photovoltaic power plants based on string data. *Energy Rep* 7: 3400–3409. https://doi.org/10.1016/J.EGYR.2021.05.038
37. Shukla AK, Sudhakar K, Baredar P, et al. (2017) BIPV in Southeast Asian countries-opportunities and challenges. *Renew Energy Focus* 21: 25–32. https://doi.org/10.1016/J.REF.2017.07.001

38. Ghosh A, Sarmah N, Sundaram S, et al. (2019) Numerical studies of thermal comfort for semi-transparent building integrated photovoltaic (BIPV)-vacuum glazing system. *Sol Energy* 190: 608–616. https://doi.org/10.1016/J.SOLENER.2019.08.049
39. Kant K, Anand A, Shukla A, et al. (2020) Heat transfer study of building integrated photovoltaic (BIPV) with nano-enhanced phase change materials. *J Energy Storage* 30: 101563 https://doi.org/10.1016/j.est.2020.101563
40. Assoa YB, Sauzedde F, Boillot B (2018) Numerical parametric study of the thermal and electrical performance of a BIPV/T hybrid collector for drying applications. *Renewable Energy* 129: 121–131. https://doi.org/10.1016/J.RENENE.2018.05.102
41. Yang S, Cannavale A, Prasad D, et al. (2019) Numerical simulation study of BIPV/T double-skin facade for various climate zones in Australia: Effects on indoor thermal comfort. *Build Simul* 12: 51–67. https://doi.org/10.1007/S12273-018-0489-X
42. Batayneh W, Bataineh A, Soliman I (2019) Investigation of solar tracking performance using isotropic and anisotropic models. *Adv Build Energy Res* 15: 390–408. https://doi.org/10.1080/17512549.2019.1625810
43. Wang Y, Gawryszewska-Wilczynsk P, Zhang X, et al. (2020) Photovoltaic efficiency enhancement of polycrystalline silicon solar cells by a highly stable luminescent film. *Sci China Mater* 63:544–551. https://doi.org/10.1007/S40843-019-1246-5
44. Kim S, Quy HV, Bark CW (2021) Photovoltaic technologies for flexible solar cells: beyond silicon. *Mater Today Energy* 19:100583. https://doi.org/10.1016/J.MTENER.2020.100583
45. Jun Huang M (2011) The effect of using two PCMs on the thermal regulation performance of BIPV systems. *Sol Energy Mater Sol Cells* 95: 957–963. https://doi.org/10.1016/J.SOLMAT.2010.11.032
46. Agathokleous RA, Kalogirou SA (2018) Part II: Thermal analysis of naturally ventilated BIPV system: Modeling and simulation. *Sol Energy* 169: 682–691. https://doi.org/10.1016/J.SOLENER.2018.02.057
47. Li X, Li P, Wu Z, et al. (2021) Review and perspective of materials for flexible solar cells. *Mater Rep: Energy*, 100001. https://doi.org/10.1016/J.MATRE.2020.09.001
48. Aslani A, Bakhtiar A, Akbarzadeh MH (2021) Energy-efficiency technologies in the building envelope: Life cycle and adaptation assessment. *J Build Eng* 21: 55–63. https://doi.org/10.1016/J.JOBE.2018.09.014
49. Gholami H, Røstvik HN (2020) Economic analysis of BIPV systems as a building envelope material for building skins in Europe. *Energy* 204: 117931. https://doi.org/10.1016/J.ENERGY.2020.117931
50. Shukla AK, Sudhakar K, Baredar P (2017) Recent advancement in BIPV product technologies: A review. *Energy Build* 140: 188–95. https://doi.org/10.1016/J.ENBUILD.2017.02.015
51. Shukla KN, Rangnekar S, Sudhakar K (2015) Mathematical modelling of solar radiation incident on tilted surface for photovoltaic application at Bhopal, M.P., India. *Int J Ambient Energy* 37: 579–588. https://doi.org/10.1080/01430750.2015.1023834
52. Shukla AK, Sudhakar K, Baredar P (2016) Exergetic analysis of building integrated semitransparent photovoltaic module in clear sky condition at Bhopal India. *Case Stud Therm Eng* 8: 142–151. https://doi.org/10.1016/J.CSITE.2016.06.009

53. Skandalos N, Wang M, Kapsalis V, et al. (2022) Building PV integration according to regional climate conditions: BIPV regional adaptability extending Köppen-Geiger climate classification against urban and climate-related temperature increases. *Renewable Sustainable Energy Rev* 169: 112950. https://doi.org/10.1016/j.rser.2022.112950
54. Bailey HP (1979) Semi-Arid climates: Their definition and distribution, In: Hall, A.E., Cannell, G.H., Lawton, H.W. *Agriculture in Semi-Arid Environments*, Eds, Springer, Berlin, Heidelberg, 73–97. https://doi.org/10.1007/978-3-642-67328-3_3
55. Tsutsumi H, Tanabe S ichi, Harigaya J, et al. (2007) Effect of humidity on human comfort and productivity after step changes from warm and humid environment. *Build Environ* 42: 4034–4042. https://doi.org/10.1016/J.BUILDENV.2006.06.037
56. Loader NJ, Santillo PM, Woodman-Ralph JP, et al. (2008) Multiple stable isotopes from oak trees in southwestern Scotland and the potential for stable isotope dendroclimatology in maritime climatic regions. *Chem Geol* 252: 62–71. https://doi.org/10.1016/J.CHEMGEO.2008.01.006
57. Barthwal M, Rakshit D (2021) Artificial neural network coupled building-integrated photovoltaic thermal system for indian montane climate. *Energy Convers Manage* 244: 114488. https://doi.org/10.1016/j.enconman.2021.114488
58. Li C, Zhang W, Tan J, et al. (2023) Energy performance of an innovative bifacial photovoltaic sunshade (BiPVS) under hot summer and warm winter climate. *Heliyon* 9: e18700. https://doi.org/10.1016/j.heliyon.2023.e18700
59. Sorgato MJ, Schneider K, Rüther R (2018) Technical and economic evaluation of thin-film CdTe building-integrated photovoltaics (BIPV) replacing façade and rooftop materials in office buildings in a warm and sunny climate. *Renewable Energy* 118: 84–98. https://doi.org/doi:10.1016/j.renene.2017.10.091
60. An HJ, Yoon JH, An YS, et al. (2018) Heating and cooling performance of office buildings with a-Si BIPV windows considering operating conditions in temperate climates: The case of Korea. *Sustainability* 10: 4856. https://doi.org/10.3390/su10124856
61. Rodriguez-Ubinas E, Alhammadi N, Alantali M, et al. (2020) Building integrated photovoltaic solutions in arid climates: Experimental analysis of copper indium gallium selenide and crystalline silicon modules integrated as ventilated façades. *WIT Trans Built Environ* 195: 115–123. https://doi.org/10.2495/ARC200091
62. Yang T, Athienitis AK (2015) Performance evaluation of air-based building integrated photovoltaic/thermal (BIPV/T) system with multiple inlets in a cold climate. *Procedia Eng* 121: 2060–2067. https://doi.org/10.1016/j.proeng.2015.09.207
63. Dash A, Agrawal S, Gairola S, et al. (2018) Optimization and performance characteristics of building integrated photovoltaic thermal (BIPVT) system in cold climatic conditions. *Asian J Water Environ Pollut* 15: 63–72. https://doi.org/10.3233/AJW-180044
64. Hailu G, Dash P, Fung AS (2015) Performance evaluation of an air source heat pump coupled with a building-integrated photovoltaic/thermal (BIPV/T) system under cold climatic conditions. *Energy Procedia* 78: 1913–1918. https://doi.org/10.1016/j.egypro.2015.11.370
65. Do SL, Shin M, Baltazar JC, et al. (2017) Energy benefits from semi-transparent BIPV window and daylight-dimming systems for IECC code-compliance residential buildings in hot and humid climates. *Sol Energy* 155: 291–303. https://doi.org/10.1016/j.solener.2017.06.039

66. Alhammadi N, Rodriguez-Ubinas E, Alzarouni S, et al. (2022) Building-integrated photovoltaics in hot climates: Experimental study of CIGS and c-Si modules in BIPV ventilated facades. *Energy Convers Manage* 274: 116408. https://doi.org/10.1016/j.enconman.2022.116408
67. Ardiani NA, Suhendri, Koerniawan MD, et al (2019) Application of building integrated photovoltaic in hot humid climate. Case study: office building in Indonesia. *IOP Conf Ser Earth Environ Sci* 291: 012026. https://doi.org/10.1088/1755-1315/291/1/012026
68. Brennan DA, White C, Barclay M, et al. (2019) Performance characterisation and optimisation of a building integrated photovoltaic (BIPV) system in a maritime climate. *Futur Cities Environ* 5: 1–9. https://doi.org/doi:10.5334/fce.62
69. Bot K, Aelenei L, Gonçalves H, et al. (2021) Performance assessment of a building-integrated photovoltaic thermal system in a mediterranean climate-an experimental analysis approach. *Energies* 14: 2191. https://doi.org/doi:10.3390/en14082191
70. Salem T, Kinab E (2015) Analysis of building-integrated photovoltaic systems: A case study of commercial buildings under mediterranean climate. *Procedia Eng* 118: 538–545. https://doi.org/doi:10.1016/j.proeng.2015.08.473
71. Abdelhakim M, Kandar MZ, Lim YW (2019) Experimental investigation of overall energy performance in Algerian office building integrated photovoltaic window under semi-arid climate. *J Daylighting* 6: 23–41. https://doi.org/10.15627/jd.2019.3
72. Mesloub A, Albaqawy GA, Kandar MZ (2020) The optimum performance of building integrated photovoltaic (BIPV) windows under a semi-arid climate in Algerian office buildings. *Sustainability* 12: 1654. https://doi.org/10.3390/su12041654
73. Pan D, Yu X, Zhou Y (2023) Cradle-to-grave lifecycle carbon footprint analysis and frontier decarbonization pathways of district buildings in subtropical Guangzhou, China. *J Cleaner Prod* 416: 137921. https://doi.org/10.1016/j.jclepro.2023.137921
74. Zhou Y (2022) Demand response flexibility with synergies on passive PCM walls, BIPVs, and active air-conditioning system in a subtropical climate. *Renewable Energy* 199: 204–225. https://doi.org/10.1016/j.renene.2022.08.128
75. Evola G, Margani G (2016) Renovation of apartment blocks with BIPV: Energy and economic evaluation in temperate climate. *Energy Build* 130: 794–810. https://doi.org/10.1016/j.enbuild.2016.08.085
76. Alrashidi H, Ghosh A, Issa W, et al. (2020) Thermal performance of semitransparent CdTe BIPV window at temperate climate. *Sol Energy* 195: 536–543. https://doi.org/10.1016/j.solener.2019.11.084
77. Mangkuto RA, Tresna DNAT, Hermawan IM, et al. (2023) Experiment and simulation to determine the optimum orientation of building-integrated photovoltaic on tropical building façades considering annual daylight performance and energy yield. *EBE* 3: 414–425. https://doi.org/10.1016/j.enbenv.2023.01.002
78. Humada AM, Hojabri M, Hamada HM, et al. (2016) Performance evaluation of two PV technologies (c-Si and CIS) for building integrated photovoltaic based on tropical climate condition: A case study in Malaysia. *Energy Build* 119: 233–241. https://doi.org/10.1016/j.enbuild.2016.03.052
79. Jhumka H, Yang S, Gorse C, et al. (2023) Assessing heat transfer characteristics of building envelope deployed BIPV and resultant building energy consumption in a tropical climate. *Energy Build* 298: 113540. https://doi.org/10.1016/j.enbuild.2023.113540

80. Ekoe A Akata AM, Njomo D, Agrawal B (2017) Assessment of building integrated photovoltaic (BIPV) for sustainable energy performance in tropical regions of Cameroon. *Renewable Sustainable Energy Rev* 80: 1138–1152. https://doi.org/10.1016/j.rser.2017.05.155
81. Hamzah AH, Go YI (2023) Design and assessment of building integrated PV (BIPV) system towards net zero energy building for tropical climate. *e-Prim* 3: 100105. https://doi.org/10.1016/j.prime.2022.100105
82. Mendis T, Huang Z, Xu S (2020) Determination of economically optimised building integrated photovoltaic systems for utilisation on facades in the tropical climate: A case study of Colombo, Sri Lanka. *Build Simul* 13: 171–83. https://doi.org/10.1007/s12273-019-0579-4
83. Shetty S, Bajpai V, Bysani S, et al. (2022) Impact of BIPV panels across various window-to-wall ratios in commercial buildings, to reduce its energy performance index in warm and humid climate zone of India. *Commun Comput Inf Sci* 1612: 151–172. https://doi.org/10.1007/978-3-031-17098-0_8
84. Nibandhe A, Bonyadi N, Rounis E, et al. (2019) Design of a coupled BIPV/T-solid desiccant cooling system for a warm and humid climate. *SWC/SHC 2019 Proceedings*, 2670–2680. https://doi.org/10.18086/swc.2019.55.10
85. Braun P, Rüther R (2010) The role of grid-connected, building-integrated photovoltaic generation in commercial building energy and power loads in a warm and sunny climate. *Energy Convers Manage* 51: 2457–2466. https://doi.org/10.1016/j.enconman.2010.04.013
86. Rüther R, Braun P (2009) Energetic contribution potential of building-integrated photovoltaics on airports in warm climates. *Sol Energy* 83: 1923–1931. https://doi.org/10.1016/j.solener.2009.07.014
87. Zheng X, Zhou Y (2023) A three-dimensional unsteady numerical model on a novel aerogel-based PV/T-PCM system with dynamic heat-transfer mechanism and solar energy harvesting analysis. *Appl Energy* 338: 120899. https://doi.org/10.1016/j.apenergy.2023.120899
88. Zhou Y (2022) Artificial intelligence in renewable systems for transformation towards intelligent buildings. *EAI* 10: 100182. https://doi.org/10.1016/j.egyai.2022.100182