Technology Frontiers of Building-integrated Photovoltaics (BIPV): A Patent Co-citation Analysis

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Abstract

Recently, greater research attention has focused on the application of solar power generation technology in building construction to reduce building energy consumption and encourage increased sustainable development. An emerging solar power generation technology is in the use of Building-integrated Photovoltaics (BIPVs), where photovoltaic materials are used to replace conventional building materials. In order to map the development of BIPV technology over time and explore technology paths, this study retrieved a total of 4914 patents dated from 1972 to 2016 from the Derwent Innovations Index patent database. This study applies patent co-citation analysis to map the patent co-citation network in three periods based on *Ucinet* tool. Evolutional path and three key technology frontiers were identified using Social Network Analysis (SNA) and text clustering. The results of this study provide an informed reference for future researchers in understanding the historical development of BIPV, as an emerging and important solar power generation technology in the built environment. At the same time, big data of patents are analyzed using SNA and text clustering, which overcomes the limitation of previous methods of frontiers study that have depended on expert opinion or peer review.

Keywords: research frontiers; photovoltaic buildings; BIPV; patent co-citation analysis; Social Network Analysis

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1 INTRODUCTION

In the context of energy efficiency and conservation, the building sector has attracted increasing attention worldwide. In developing countries, buildings are responsible for consuming up to 40% of the total energy, with a related emission of 40% of total Greenhouse Gas (GHG) emissions [1]. As such, there is a great potential for building energy saving through the more efficient construction. At present, solar energy technology is becoming more widely adopted in the construction of buildings, particularly in urban areas, which can reduce the reliance on traditional energy sources. The combination of photovoltaic (PV) technology and its integration with conventional building materials and systems offer promising returns in efficiently capturing and utilizing solar energy resources. Building-integrated photovoltaics (BIPVs) also benefit from its architectural form with many researchers across the world researching and popularizing this technology [2–4].

Despite its potential benefits, the integration of such technology in the construction of buildings remains complex. Historically, the main problems faced in the use of BIPV are technically related: low efficiency of PV cell generation, the high cost of installation and maintenance and their impact on architectural style. However, to address future problems, researchers should reflect on technological progress, which is based on the technology diffusion process, and can promote industrial development [5].

Technologies with inherent uncertainty and ambiguity have been emerging rapidly. To reveal accurate and reliable

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technological information, patent data has been attracting increasing attention. Generally, patents are considered as concrete indicators of technological innovation and they convey the history of technological development [6]. A collection of patents may represent part of the accumulated knowledge in science and technology in a certain field. [7] Based on various patent analysis method, intelligence information of patent documents can be extracted to identify core technologies, determine novelty in patents, reveal evolutional path and forecast development trend [8–10]. Therefore, patent analysis is suitable for understanding a technological flow and development directions in various industries, exploring research roadmaps and technological frontiers [11].

In this study, since many previous studies have focused on the study of the technical challenges of BIPV instead of exploring the evolution of the BIPV technology, patent analysis is an appropriate method to acquire the comprehensive knowledge of technological development. To achieve that, this study applies patent co-citation analysis to explore main technology paths for patents in the field of BIPV and to track the current development of this technology. Based on the Social Network Analysis (SNA) mapping and text clustering, this research also identifies technology frontiers, to inform future research direction.

The results of this study can be used to further understand the developmental status of BIPV and indirectly provide credible technical information for government and enterprise decision-makers in concentrating their resources and directing research and development efforts toward the future frontiers of BIPV.

2 RELATED RESEARCH

Significant research has been conducted in the evaluation of BIPVs. For example, in design and construction domain, Yoo et al. [12] proposed a building design to have PV modules shade the building in summer, so as to reduce cooling loads. Bakos et al. [13] described the installation, technical characteristics, operation and economic evaluation of a grid-connected BIPV system. Ordenes et al. [14] performed simulations using the software tool *EnergyPlus* to more effectively integrate PV power supply with building energy demand. Chow et al. [15] measured the effectiveness of cooling by means of a natural ventilating air stream. Cheng et al. [16] developed an empirical approach for evaluating the annual solar tilted plane irradiation with inclinations from 0 to 90° and azimuths from 0 to 90° on building envelopes for BIPV applications in Taiwan. Ruther [17] and Jardim [18] studied the behavior of grid-connected, BIPV solar energy conversion in a metropolitan area, aimed at maximizing the benefits of the distributed nature of PV energy generation. Although many studies have focused on the study of the technical challenges of BIPV, no researchers have explored the evolution of BIPV technology using patent analysis based on SNA.

Patents include detailed information about a patented technology [19]. Patents are indicators of technological development at both enterprise and industry level and can be used to explore the research status of a particular technology.

Traditionally, experts in particular fields conduct manual patent analysis, which contributes to an in-depth analysis. However, this method is often subjective, labor intensive and time-consuming.

Automatic and visible patent analysis method is helpful in analyzing large amount of patens. According to Abbas et al. [20], patent analysis approaches can be summarized into two main categories: text mining techniques and visualization techniques. Text mining techniques is a popular tool for automatic and efficient patent analysis, which contains, but is not limited to, natural language processing (NLP)-based approaches [21], semantic analysis-based approaches [22] and topic-based clustering [23]. Text mining can give researchers access to technical information in patent documents, but also offer a more complete picture of the technological emergence and development process [24]. Visualization is also an important part of patent analysis, which includes patent map and patent network [20]. Visualization techniques have been proven to be useful for the patent analysis [25]. However, it still needs to perform text mining approaches to extract information from the documents.

In addition, the bibliometric analysis also plays an important role in patent analysis, which mainly employs statistical analysis and citation analysis. Statistical analysis reveals the development and distribution of patented technology, while citation analysis indicates the linkage between relevant patents [26]. On the basis of bibliometrics, scientometric analysis has been utilized widely based on to quantitatively analyze and assess the content of published documents.

To sum up, we listed the available methods of patent analysis and their corresponding advantages in Table 1 [20, 26].

Several studies had applied patent data to explore various patenting activities in different fields. For example, Albino and Ardito [27] reported the development trends of low-carbon energy technologies, as well as identified major related environmental programs, historical events and private sector initiatives explaining such trends by using patent analysis. Wu and Leu [28] proposed a patent co-word map analysis to find the trends of technological development in the area of hydrogen energy. Critical technologies were also indeitifed via patent analysis. Geum et al. [29] defined the technological convergence of biotechnology and information technology based on patent analysis. Moreover, many promising new technologies in different fields were identified from the retrospective analysis of the existing technologies based on the patent data [30–32]. As supported from these previous studies, patents analysis enables the improved understanding of technology development direction and trends in an effective way, and the importance of the patent in the development of a technology cannot be ignored.

Previous studies have applied patent co-citation information to explore technological development trends, core technology and research frontiers in different fields. Small [33] proposed the concept of co-citation, which is defined as the frequency with which two documents are cited together, based on the theory proposed by Price [38]. The co-citation between patents reflects that the technology represented by patents has some similarities [34]. Through co-citation analysis, patents can be

Table 1. *The available methods of patent analysis and their corresponding advantages.*

Patent analysis methodology	Tools	Advantages
Text mining	NLP, semantic analysis, topic-based clustering	1) Automatic and efficient; 2) extract intelligence information from unstructured text
Visualization techniques	patent map, patent network	1) Able to visualize the relationships among the patents by constructing the maps; 2) able to reveal the linkage among various patents
Bibliometric analysis	statistical analysis, citation analysis	1) Able to analyze the development and distribution of patented technology; 2) objective, reliable and easy to apply

clearly classified, thus identifying the relationships between different clusters [35]. Other examples include Wang [8], who identified the core technology structure of the electric vehicle industry through patent co-citation information. Shiau et al. [36] verified seven main factors regarding social networks based on co-citation analysis and cluster analysis. Yu and Xu [10] adopted the co-citation analysis method to assess the development trends of carbon emission trading domain. Lai and Wu [37] proposed a new approach based on co-citation analysis to assist patent manager in understanding the basic patents for a specific industry, the relationships among categories of technologies and the evolution of a technology category. Co-citation analysis can classify and cluster patents with similarities, providing input in the analysis of the research frontiers in different fields.

Price [38] firstly proposed the Research Frontier Theory based on citation networks. Small [39] believed that closely related clusters obtained by co-citation analysis reflected the research frontiers. In recent years, exploring research frontiers based on co-citation analysis had grown in popularity. Hou et al. [40] found the research frontiers of the science of metrology by co-citation analysis. Cui [41] applied co-citation analysis and thematic cluster analysis to explore the research frontiers of the bronchoalveolar lavage technique. As highlighted, the past two decades had witnessed a dramatic increase in the use of patent citation data in social science research [42]. But there still remain few researchers who have applied such a method in the engineering context. Further, to examine the patent co-cited relationships from a comprehensive perspective, more studies have addressed patent citation relations in terms of network theory [43,44]. Thus, this study applies a patent co-citation analysis based on SNA and text clustering to discover the current research frontiers, core technologies, main patent developing path and potential developing orientation in BIPV field, using Derwent Innovations Index (DII) data from 1972 to 2016.

3 METHODOLOGY

The patent data for this study was obtained from the DII database. This database enhanced the accuracy of the patent search results by means of the Derwent classification, manual rewriting of patent titles and abstracts.

The patent data search proceeded as follows: (1) a patent retrieval query was proposed as TS = (((BIPV or BAPV) AND building) or (building and photovoltaic∗)); (2) filtering out irrelevant and duplicate patents by manual review; and (3) generating a patent set related to BIPV. The study retrieved a total of 4914 patents dated 1972–2016 from the DII granted patent database. Then, co-citation analysis and SNA were adopted to provide an in-depth analysis of patent activities in the field of BIPV. The framework of this study is shown in Figure 1.

3.1 Social Network Analysis

Sternizke et al. [45] firstly proposed the use of SNA to conduct patent analysis and was important in the development of patent analysis methods. SNA is the process of investigating social structures through the use of networks and graph theory [46]. This method characterizes networked structures in terms of nodes (individual actors, people or technology within the network) and the ties, edges or links (relationships or interactions) that connect them. Xiang and Cai [47] supported the suitability of SNA-based patent citation in knowledge management research. Park and Kwahk [48] mapped the knowledge flows between firms by analyzing patent citation using SNA. Wang et al. [49] examined the structures of semiconductor companies' R&D cooperation networks and channels of knowledge spillovers using SNA. Moussa and Varsakelis [50] used SNA to examine patent data to identify the behavior of patenting abroad. Perng and Huang [51] used USPTO patents data of shading devices to investigate technological trends in sustainable development based on SNA. They identified the current technological developments of shading devices, contributing to future research development in this area. The co-citation network in this paper is undirected. A relation is established when two patents are co-cited, which means the two patents are similar. Freeman [52] proposed SNA indicators such as density, degree centrality, betweenness centrality and closeness centrality measure to important or prominent nodes in a network, which can be effective in discovering the central nodes of the network. Through SNA, the core technology is situated in the center of a network and plays a crucial role in promoting technology diffusion across the network.

3.2 Text clustering

Text clustering is an important method in text mining, and also a part of data mining [53]. Text clustering is an unsupervised learning method where similar documents are grouped into clusters. The goal is to create clusters that are coherent internally,

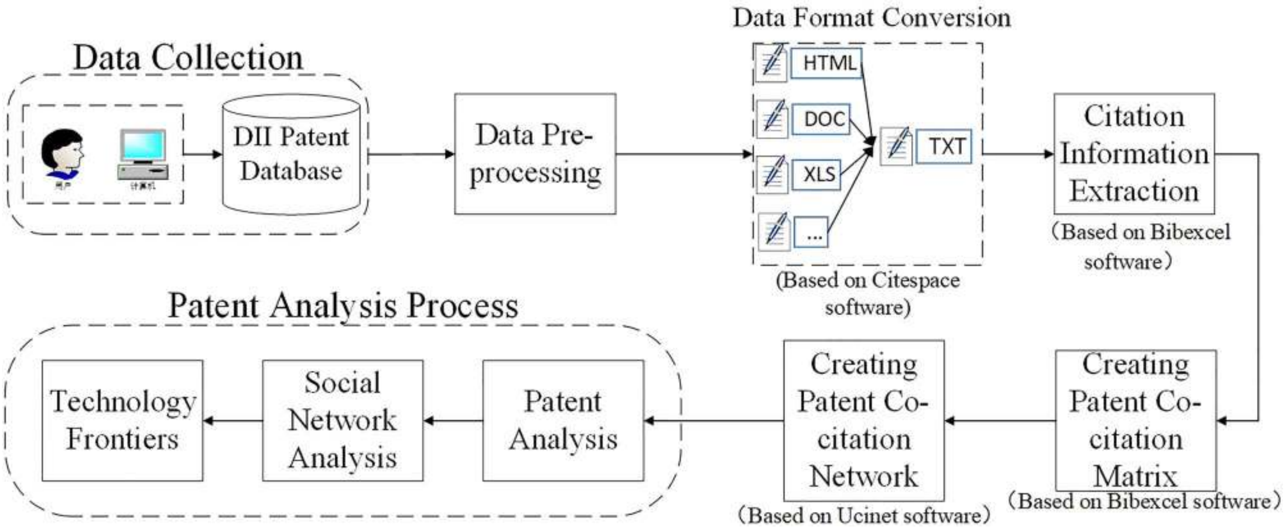

Figure 1. *Research framework.*

but different from each other [54]. Text clustering has been used extensively in the evaluation of new technology opportunities. Trappey and Wu [55] clustered different patent documents into homogenous groups and then conducted technology forecasting to evaluate possible market opportunities for future inventors and investors. Wang et al. [56] also applied text mining techniques to explore potential technological opportunities of micro-algal biofuels. They concluded that a text-based clustering approach is appropriate for identifying scientific and technological applications. Qiu and Shen [57] classified users by clustering their comments in a social network context. Further, Singh et al. [58] classified text and identified nine major research themes in the area of human resource management via text clustering. The research presented in this paper used a text clustering method to identify the research themes of several patents, which were classified into the same group.

4 PATENT ANALYSIS RESULTS

4.1 Identification of BIPV development stages

This study analyzed the technology networks in different periods to determine the changes in the frontiers of BIPV research and development over time. The development period of BIPV was divided into three stages (as shown in Figure 2) according to the theory of Technology Life-cycle proposed by Zhao [59]. The three stages are as follows:

(1) Budding Period of Technology

In this period, the number of patents and applicants increase slowly, the directed resources are insufficient at this stage and there is a great deal of uncertainty in the technical direction. The existing patents in this period may be relatively simplistic.

(2) Growth Period of Technology

In this period, the number of patents and applicants increase substantially, basic research and development goals are achieved and the technical field gradually expands.

(3) Maturity Period of Technology

In this period, the number of patents continues to increase and the number of applicants are kept relatively stable. The proportion of improved patents, based on the existing patents, significantly increases.

According to the data, related patents rapidly increased from 2008 to 2011, which implied that BIPV gained increasing greater attention from 2008. Since then, the number of patent applications has gradually increased each year, and the rate of growth has remained relatively stable. This situation suggests that the technological development of BIPV is presented a general rising trend. Patent statistics are shown in Table 2 according to their related stages.

4.2 Core patent identification

Patents with higher citation frequency are agued as having a higher level of innovation, and it is the basis of similar patent technology [60–62]. Generally, researchers regard patents that have been cited more than 15 times as the core patents. The cited frequency was low in 2012–2016 due to the time factors. This paper selected the patents cited more than 10 times as core patents to form the network and reflect BIPV development within the period of 2012–2016. The selection thresholds and the number of core patents of each period are shown in Table 3, and the top 10 most cited patents of each period are shown in Table 4.

The top 10 most cited patents of each periods were shown in Table 4.

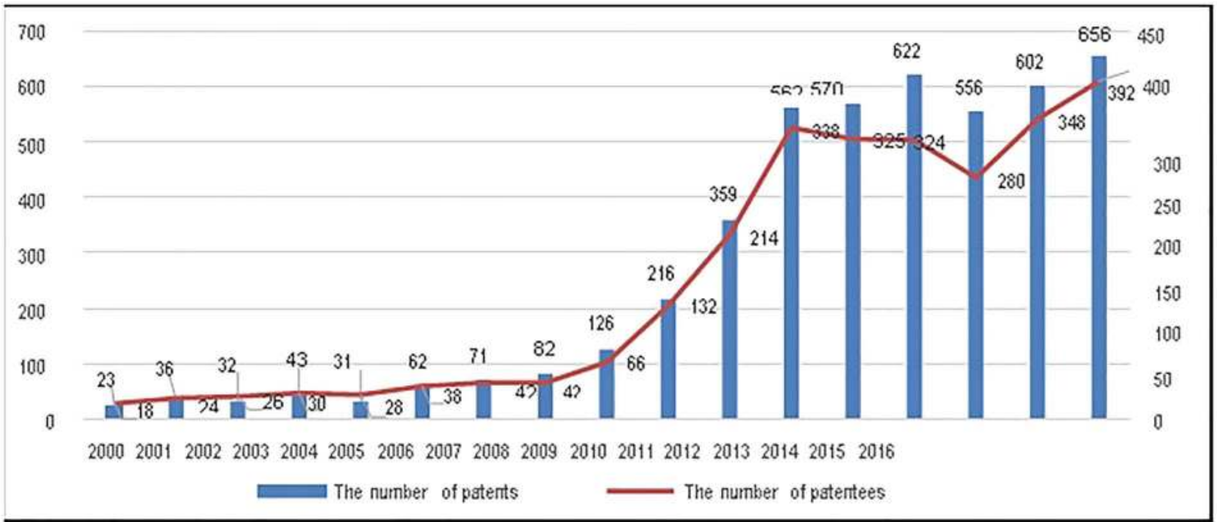

Figure 2. *Technology Life-cycle of BIPV. (1) Budding Period: before 2008 (2) Growth Period: 2008–2011 (3) Maturity Period: 2011–2016.*

Table 2. *Time span and patent number of different periods.*

	Patent granted year	Patent number
Budding period	1972–2007	499
Growth period	2008–2011	1242
Maturity period	2012–2016	2995

Table 3. *Core patent threshold and number of different periods.*

Time period	Core patent threshold	Core patent number
1972–2007	15	19
2008–2011	15	93
2012–2016	10	24

4.3 Evolutional path of BIPV based on text clustering

The co-citation matrix that consisted of the identified core patents was inputted into *Netdraw* [63] software to convert the matrix into visual co-citation networks. This study used the unique algorithm, Spring Embedding, to map the layout. The Spring Embedding algorithm achieves a layout of the network with densely connected nodes clustered together and nodes with few connections placed around the edge [64]. Thus, groups of well-connected patents tend to be grouped in the resulting visualization.

Patent clustering involving three or more patents can be regarded as a research frontier [65]. The research themes of each cluster were gained by text clustering. Each node in the network represented a patent and the bigger the node, the more times it had been cited by other patents. The connection between the nodes illustrated a co-cited relationship between the two patents. The three identified co-citation networks are discussed in chronological order as follows:

4.3.1 *Research themes from 1972 to 2007*

The co-citation network of BIPV from 1972 to 2007 consisted of 19 patents as shown in Figure 3. The average density of the network was 0.619; implying the patents were closely related, and there was frequent information exchange and knowledge sharing between patents.

There were four clusters identified for the period from 1972 to 2007. The first cluster only included one patent. Patent EP625802 was related to a frameless solar cell module using an amorphous silicon thin membrane, and it improved the weight and cost problems of conventional solar modules when installing the aluminum edge frame to ensure overall strength.

The second cluster also only included one patent. Patent US5589006 was related to a solar cell module that utilized passive solar technology. The solar module could be used to not only generate electricity, but also to exhume the warm air via the fan powered by the solar system. This technology solved the efficiency reduction of solar cells caused by heating during the system operation process and made full use of solar energy. The patent also enhanced the durability and reliability of the solar cell module by solving the problem of stacking member degradation at the perforation position of the assembly.

The third cluster was mainly for the PV roof panels and PV components, which included additional solar power generation roof structure, integrated PV roof with flexible material for the backplane, design of PV panels for board stitched roofs and the design and installation of roof shingles for PV cell integration.

The fourth cluster's theme comprised the construction of PV modules on roof, which included the solid technology and a frame system of PV cells. This technology ensured the integration of the membrane and minimized the impact of wind load on the PV modules to reduce uplift.

With the decrease in cost for solar cell components and improvement in efficiency, the integration of PV cells and building components had gained greater attention by researchers. The

Table 4. *The top 10 most cited patents of each periods.*

Rank	1972–2007 Patent number	Cited times	2008–2011 Patent number	Cited times	2012–2016 Patent number	Cited times
1	US5746839	29	US6111189	41	2009137348	20
2	US5505788	27	US6148570	40	US5746839/ 2009137353	17
3	US4677248	25	US5571338/US6617507	39	102005018173/ US6672018	16
4	US5092939/US6061978	23	US5232518	38	US7012188/ US5968287	13
5	US5316592	22	US6465724	37	US7138578	12
6	US4860509	21	US5968287/US6672018/US5505788	36	102006060815/ 202006007613/ US5409549/ US6809251/ US5232518/ US5505788/ 2010078303/	11
7	US5338369	20	US6883290/US6093884	35	US5316592/ US6105317/ US6046399/ US7328534/ 10047400/ US7600349/ US6111189/ US7260918/ 2009137352	10
8	US4040867/US5589006	18	US5409549/US5409549/US6360491	34		
9	US6148570/625802/US4189881	17	US4677248	33		
10	US6111189/US4321416/US4674244/US4886554	16	US4137098/ US6201180/ US6959517/ US5787653	32		

analytical results indicated that the research themes of this period were focused on how to integrate solar cells with building roofs, which included integrated PV modules to roofing panels, roofing shingles and roof membranes.

4.3.2 *Research themes from 2008 to 2011*

The co-citation network of BIPV from 2008 to 2011 consisted of 90 patents as shown in Figure 4. The average density of this network was 0.678; implying that patents were more closely related than in the previous period, and the information exchange and knowledge sharing between patents were also more frequent. The results also indicated that in the selection of solar cells, only one patent was related to the membrane battery components, and the remainder were related to advanced crystalline silicon battery components.

There were five clusters in the period from 2008 to 2011. The research theme of each cluster is identifed using text clustering. The first cluster was related to a fixed and installed system that linked glass plates with building support structures, ensuring that the installed glass plate had certain stability and bending flexibility, to avoid the risk of glass edge rupture. The research content of this group also included an optimized configuration of the circuit connection system between the battery elements in the PV glass components.

The second cluster was related to electrical devices and optimization methods between PV components, which was aggregated into four defined research themes as follows:

(1) Optimization of existing support structures and fixing devices of PV modules on roofs. This related technology can reduce the cost and improve the suitability of the PV support structure to the roof.
(2) Circuit connection methods of PV cells or panels. When PV components were installed in large areas, many PV components needed to be connected in series and parallel, resulting in complex wiring connections. The improved circuit connection methods can simplify installation and enhance the stability of PV system.
(3) PV system controller with a microprocessor. The integration of a microprocessor in the PV system controller was used to monitor various parameters of the system, and manage system load, with alarm control functions to ensure stable and efficient operation of the system.
(4) Solar module with non-volatile memory. The integration of non-volatile memory with the solar cell module allowed information to be stored such as the serial number and the manufacturing date for identifying the storage unit, which can assist maintenance personnel to check the operational history.

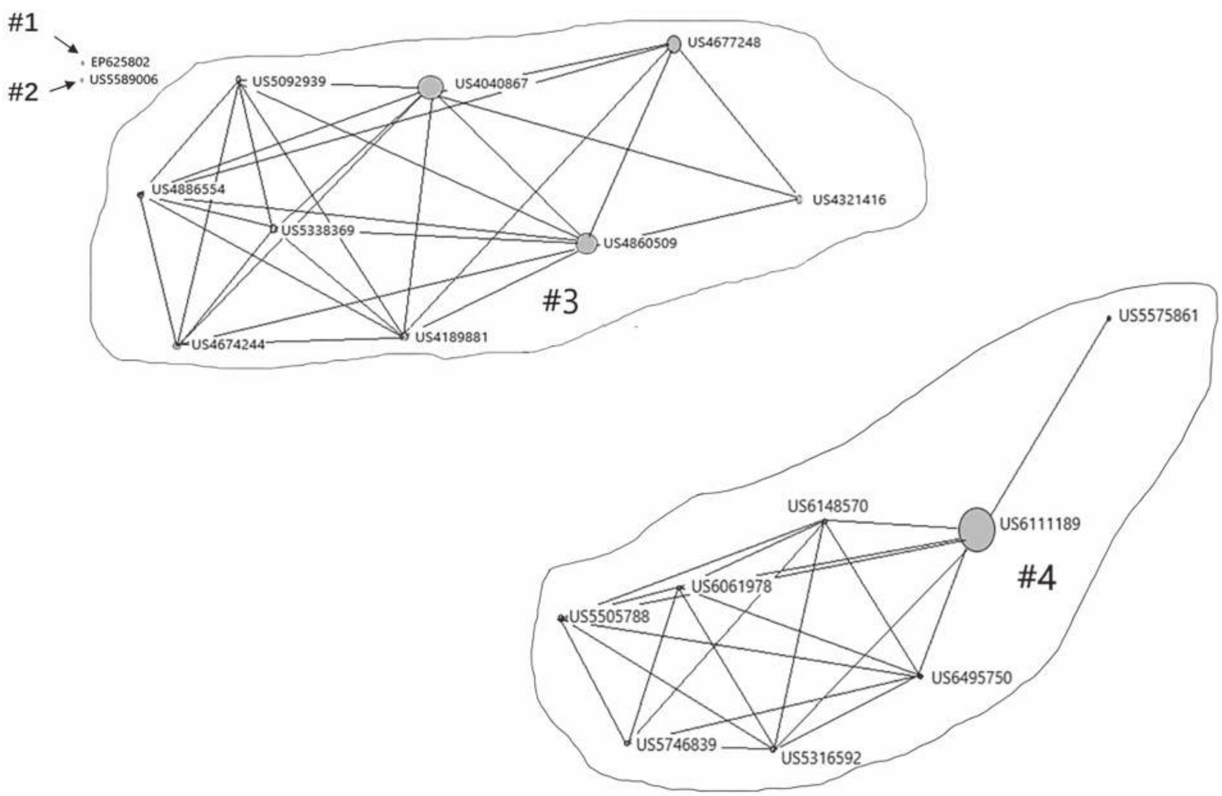

Figure 3. *Co-citation network of BIPV from 1972 to 2007.*

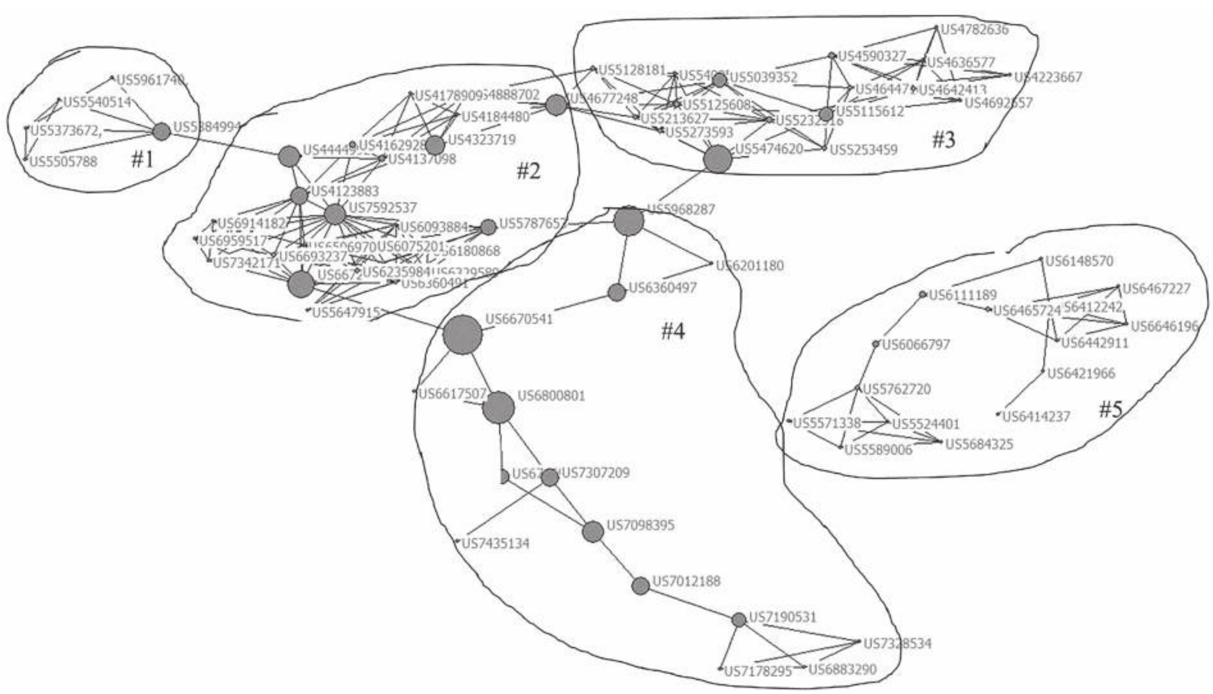

Figure 4. *Co-citation network of BIPV from 2008 to 2011.*

The third cluster was related to building facade PV component and its support systems, which was aggregated into three defined research themes as follows:

(1) Improved frame structure and supporting system of PV curtain wall components. This technology can improve the weathertightness of the horizontal and vertical joints of the PV curtain wall components and enhance the stability of the curtain wall structure.
(2) Building exterior facade PV panel integrated components and its supporting structure. This PV panel structure can improve heat preservation and sound insulation at a lower installation cost.
(3) A device or method to improve the conversion efficiency of large-scale of PV membrane modules.

The fourth cluster was mainly for PV roof components and optimization methods for PV modules, which was aggregated into four defined research themes as follows:

(1) Installation and support system for roof PV components.
(2) The electrical connection mode of PV modules
(3) The coupling structure of Finel lens and solar cell, which utilized the focusing effect of Finel lens to improve the electricity generation efficiency of the PV module.
(4) Design and installation of PV shingles. The PV shingle not only can generate electricity, but also had the drainage function of common shingles. The connection structure between the shingles can reduce the impact of wind load and reduce uplift on the shingles, thus enhancing the stability and durability of PV shingles.

The fifth cluster was mainly for PV roof and facade structure with a ventilated cavity. In summary, the results of the research frontier analysis from the period 2008 to 2011 identified a focus on large-scale PV curtain walls and building facade PV component support systems. The research themes also included advanced PV windows, PV shingles, circuit connection methods between PV modules, devices to enhance the efficiency of PV components and intelligent monitoring systems of PV components.

4.3.3 *Research themes from 2012 to 2016*

The co-citation network of BIPV from 2012 to 2016 consisted of 20 patents as shown in Figure 5. The average density of the network was 0.234. This suggested a downward trend in the information exchange and knowledge sharing between patents.

The first cluster's research themes focused on PV modules on roofs and its supporting structures. The themes primarily comprised an integral support system of tilted solar panels, a detachable PV module support system and a solar panel support system that can effectively prevent wind and rain from penetrating into the roof.

The second cluster consisted three mutually co-cited patents. The research theme focused on a new PV element vacuum laminating and adhering technique in the PV panel and its installation system on roofs. This technology also proposed an integrated PV construction and installation method on roofs, which improved the stability and weather resistance of solar panels.

The third cluster was related to safety protection device for PV systems. This device included a thermal fuse between PV units and the electrical transfer points and a safety interruption switch device to the PV component, which can switch the generator to low energy working conditions or cut the power under the dangerous circumstances, to protect building occupants.

The fourth cluster was related to improved electrical connection methods between PV modules and its installation.

The number of clusters of the period from 2012 to 2016 was less than the other two periods. The research frontiers of this period focused on installation and support systems for PV modules on roofs, electrical connection technology for PV modules and safety protection devices.

The research themes of three periods are summarized in Figure 6.

4.4 Evolutional path of BIPV based on SNA

In this section, SNA indicators such as degree, betweenness centrality and closeness centrality were applied to explore the core technologies using SNA software *Ucinet*. As shown in Figures 3–5, a patent with a higher degree had more direct co-citation relations with other patents in the co-citation network, which indicates that it had greater influence and importance than others. The patent with higher betweenness centrality played an important role in connecting the other patents, which meant it was necessary in the evolution and development of technology. The patents with higher closeness centrality had shorter distances to other patents, which can result in more rapid diffusion of knowledge with other patents in its field.

The patent with highest degree, betweenness centrality and closeness centrality of each period are presented in Table 5.

From the above text clustering analysis and co-citation network analysis, the research frontiers of three periods are summarized in Table 6.

Further, three key research frontiers were identified. The first research frontier related to PV module support systems. The research relating to the support systems of PV modules can be divided into two categories: the PV support systems of roofs and support systems of PV curtain walls and building facades. With the development of PV cell technology, the cost of PV cell components gradually decreased, with a gradual increase in the efficiency of power generation. Traditionally, the cost of the PV support systems accounted for more than 50% of the cost of the entire PV module. Due to the heavy weight and complex PV support system installation, the risk was high in damaging the building support structure. The results indicated that the development of light, convenient, low-cost, easy to install and esthetically pleasing support systems were a future trend of the installed PV modules.

The second research frontier was related to BIPV components. Development in BIPV components included advanced PV shingles, PV curtain walls and PV roofs. BIPV components did not need an additional support system because the product or component itself generates electricity and is able to architectural design requirements. As such, BIPV components became the

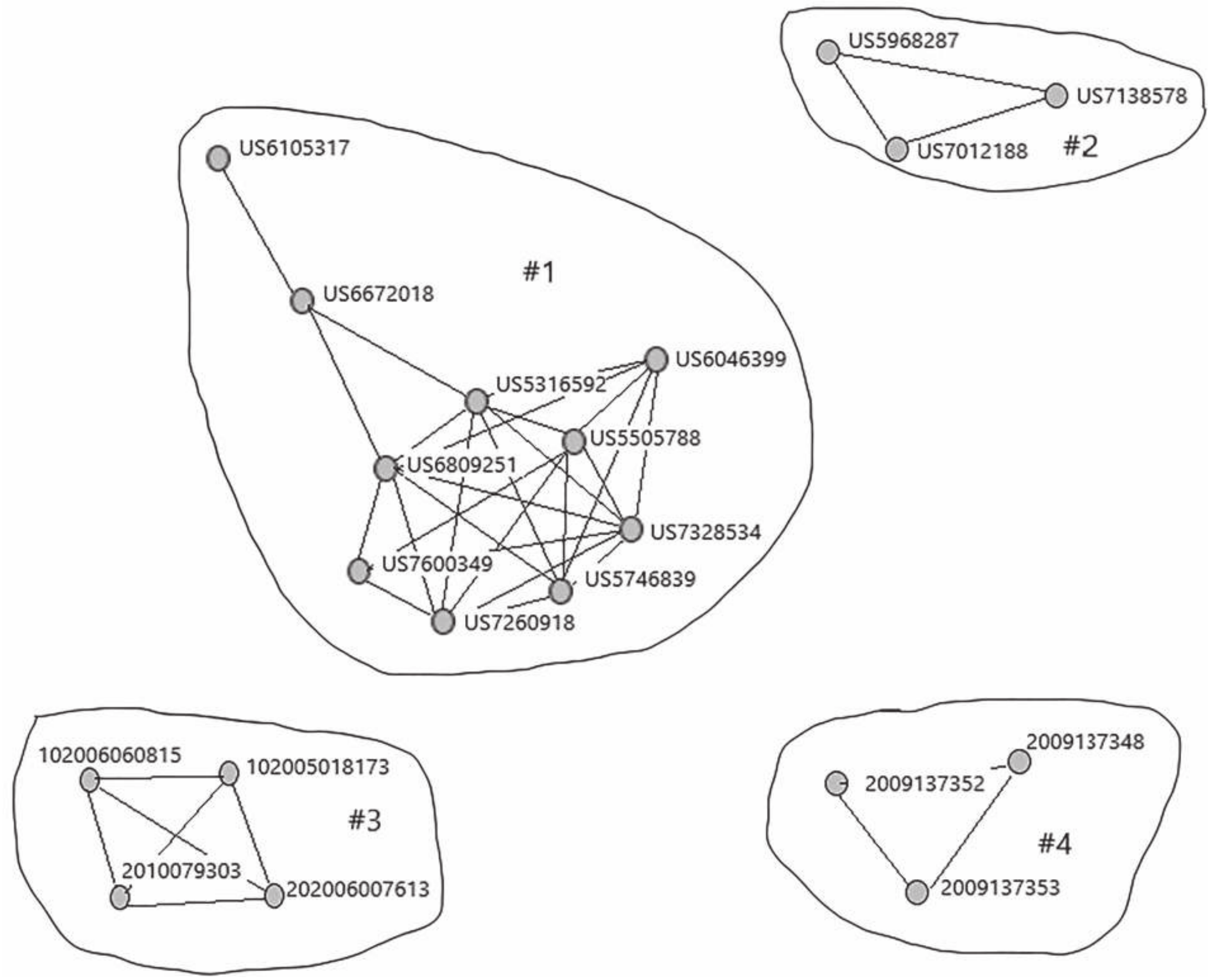

Figure 5. *Co-citation network of BIPV from 2012 to 2016.*

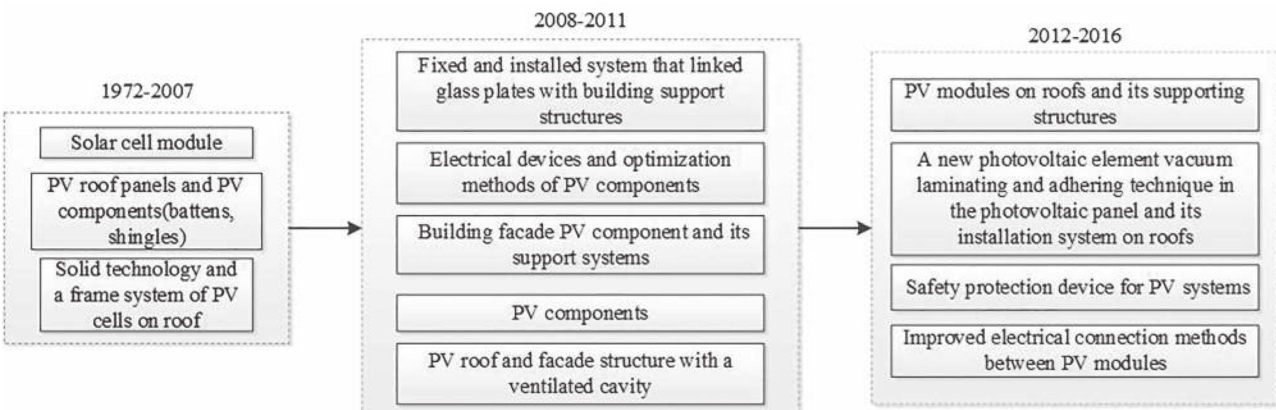

Figure 6. *Research themes of BIPV from 1972–2016.*

focus on research in the PV building technology field due to their low cost, improved water resistance and sound insulation functions.

The third research frontier related to PV intelligent control systems. This technology offers the efficient and stable operation of the PV system, with real-time monitoring of the battery performance and load. This technology also allows the automatic cut-off of the power supply under the safety conditions. The resultant application of Intelligent Micro-grid in PV building systems is becoming a focal research area.

Table 5. *Highest centrality patents.*

Period	Indicator	Patent number	Patent title
1972–2007	Betweenness Centrality Closeness Centrality	US509293	Amorphous silicon film photovoltaic roof plate with flexible galvanized steel as a backplane
	Degree	US5338369	Roof-integrated photovoltaic module
2008–2011	Betweenness Centrality Closeness Centrality	US5505788	Photovoltaic roof support system with thermal regulation
	Degree	US7592537	Photovoltaic module support system
2012–2016	Betweenness Centrality	DE102005018173	Photovoltaic control system
	Closeness Centrality	US760034	A thin mounting system for mounting a solar panel on a structural surface
	Degree	US7328534	Photovoltaic shingle system

Table 6. *Research frontiers of BIPV.*

Period	Average network density	Cluster	Research frontier	Patent number
1972–2007	0.619	#1	Lightweight frameless amorphous silicon thin film solar cell module	1
		#2	Solar cell module using passive solar energy technology	1
		#3	Plate roof PV components	9
		#4	PV component integrated with roofing membrane	8
2008–2011	0.678	#1	Fixed device of glass components and construction support structures	5
		#2	Support systems on roofs/circuit connection methods between PV components/PV control system	24
		#3	Support system of PV curtain walls/support system of facade PV module	17
		#4	Support system of PV components on roofs/PV shingles/improvement of solar cell efficiency	14
		#5	PV window/support system of PV curtain walls/ventilated cavity	15
2012–2016	0.234	#1	Support systems on roofs	10
		#2	Integrated PV roofs	3
		#3	Safety protection device in PV system	4
		#4	Improved technology for electrical connection methods between PV modules and its installation	3

5 CONCLUSION

BIPV is an emerging solar power generation technology where PV materials are used to replace conventional building materials in defined areas of the building envelope. To map the evolution of this technology over time and explore the related technology frontiers, granted patents from 1972 to 2016 related to PV components and installation were collected from the DII patent database. The big data of patents were then analyzed using co-citation analysis and text clustering. Patent analysis allows researchers to efficiently obtain a comprehensive view of technological development. In this study, co-citation analysis can reveal the connection between two or more co-cited patents, establishing the foundation of the citation network. With the use of SNA, indicators such as degree, betweenness centrality and closeness centrality were applied to explore the core technologies and reveal evolutional path of BIPV. In terms of text clustering, it enables to create clusters that are coherent internally and to recognize the theme of each cluster.

According to the theory of Technology Life-cycle, the development periods of PV building were divided into three stages. The co-citation network of each period was then developed based on SNA using *Ucinet* tool.

By calculating the density of the networks, this study found that the period from 2008 to 2011 had the highest network density, which implies that the information exchange and knowledge sharing between patents were frequent during this period.

Following the development of the co-citation networks for each period, the study identified the specific research frontiers using text clustering and three key frontiers were defined: (1) light, convenient, low-cost and esthetically pleasing support systems of installed PV modules; (2) BIPV components; and finally, (3) PV intelligent control systems.

PV module support systems were highlighted by a higher degree in the network, which indicates that this technology was the main research frontier that preceded BIPV and the development of this technology was fast and mature. Methods to reduce the cost, weight and improve the esthetics were the future focus in the development of this technology. Following this, BIPV components played an intermediary role in the network, indicating that this technology still has significant potential for further research and development. PV control systems show a higher betweenness centrality in the network, which indicated that this technology is still in the initial stage of development, but is gaining researcher attention.

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