Energy Strategy Reviews 51 (2024) 101309

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

Research on the evolution of China's photovoltaic technology innovation network from the perspective of patents

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ARTICLE INFO

Handling Editor: Dr. Mark Howells

JEL classification:
L52
O33

Keywords:
Photovoltaic technology
Innovation network
Two-mode network
Social network analysis

ABSTRACT

Photovoltaic (PV) technology, as a low-carbon energy technology, is crucial to mitigating climate change and achieving sustainable development. China has the largest total number of PV technology patents in the world, but the lack of core technologies has restricted the further innovative development of China's PV industry. Therefore, it is necessary to clarify China's current PV technology accumulation to better catch up with key technology areas. To clearly describe the structural characteristics of China's PV technology innovation network, this study uses China's patent PV technology data over the past 20 years from the Incopat global patent database and analyses the structural characteristics of the network from the perspectives of one-mode and two-mode networks, using method of social network analysis (SNA). The results show that 1) the leading PV enterprises have basically formed relatively stable internal collaborations and that the scale of innovation network development has expanded rapidly, with very strong stamina; 2) with the development of China's PV industry, many innovative PV techniques have been developed by leading enterprises in the field of innovation and research and development (R&D) of PV technology, and among patent applicants with strong collaboration, kinship collaboration with investment relationships is dominant; 3) provinces participating in PV technology innovation are increasing significantly, the network is more influenced by leading nodes, and the eastern coastal provinces are pioneers in the innovation and R&D of PV technology; and 4) PV technological innovation collaboration between patent applicants and cities has changed from local collaboration to cross-regional collaboration, high-value areas are basically concentrated in the eastern coastal region of China, with scattered spatial characteristics, and cross-regional collaboration presents a "triangular" spatial structure, with the Yangtze River Delta, Pearl River Delta, and Beijing-Tianjin-Hebei as cores. The conclusions can provide patent information support for scientific research on energy conservation and emission reduction to achieve low-carbon goals, and can also provide reference for policy formulation of renewable energy development and green development strategies.

1. Introduction

As an important strategic emerging industry, the photovoltaic (PV) industry is one of the most promising renewable energy industries in the world today. The PV industry not only addresses the impending depletion of traditional energy sources but also provides an excellent path to solving problems such as global warming and environmental pollution, with its clean energy properties [1,2,3,4,5]. The Chinese government attaches great importance to the issue of global climate change and has proactively pledged to achieve a carbon peak and carbon neutrality by 2030 and 2060, respectively, demonstrating the responsibility of a major country in addressing climate issues [6]. Solar energy is an

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https://doi.org/10.1016/j.esr.2024.101309
Received 3 September 2023; Received in revised form 10 December 2023; Accepted 10 January 2024
Available online 18 January 2024

important kind of renewable energy, and one of the fastest growing renewable energy sources, with the advantages of easy installation, easy maintenance and no pollution [7], which could theoretically meet global energy needs [8]. The climate environment and energy crisis have greatly stimulated China's research, development and application of solar energy [9], and the development of the PV industry is considered an important direction for China to achieve green development and transformation and is also an important tool to achieve the "dual carbon" goal [10].

PV technology is an important technical way to achieve green development, transformation and overtaking. PV patents are innovative forms of PV technology, and research on PV patents can reflect the research and development (R&D) trend of PV technology in a country [11]. The development of China's PV industry is a typical process of technological change in a catching-up economy [12], that is, through the initial stage of acquiring foreign technologies, to vertical integration, and investing in research and development of their own technology catch-up process. Existing researches suggest that although China prefers international cooperation in the mode of technological cooperation in the PV industry [13], the total number of multinational patents in this field is relatively small [14], and China's innovative capabilities in developing PV technologies are accumulated through domestic R&D activities [15]. Despite the fact that the total number of patents applied for Chinese PV technology has ranked first in the world since 2012, the Chinese PV industry still has a large gap with developed countries in Europe and the United States in terms of fragmented patents and missing core patents, e.g., ethylene vinyl acetate (EVA) film raw materials [16,17,18]. Therefore, identifying the knowledge base of Chinese indigenous PV patents to build patent innovation synergy is a key issue.

Regarding the research on PV industry technology, scholars have mainly focused on the importance to economic development [19], how to promote technological innovation in the PV industry [20,21], and the impact of government policies on PV technology innovation [22,23,24], among other aspects. For example [25], explained the future development trend of the PV industry and the importance of strengthening PV technological innovation, and [26] and [27] propose that the impact of government support policies for PV technology on PV innovation is obvious, i.e., effective policies can reduce the R&D costs, improve the profits, and better promote the development of enterprises, but few scholars have studied PVtechnology innovation from the perspective of complex networks.

With regard to complex networks, most scholars mainly build a one-mode network to conduct in-depth studies on the trade between countries or regions [28,29], economic ties [30], innovative collaboration [31,32,33] and population mobility [34]; however, there is still a large gap in the application and depth of research on two-mode networks [35,36]. With the deepening of complex network research and the complexity of real network relationships, the two-mode network formed by associations between different types of network nodes has attracted increasing attention from scholars [37]. Compared with one-mode networks, two-mode networks can display the information of different types of nodes and inter-associations more abundantly to mine more effective information in the network model and avoid a lack of characteristic information regarding the main network structure [38]. Regarding the research on two-mode networks, scholars have mainly analyzed the structural characteristics of networks and definitions of networks [39,40]. With the expansion of research, scholars have constructed two-mode networks for different types of subjects, such as enterprise-city, actor-movie, actor-policy, listed company-non-listed company, and merger and acquisition (M&A) parties-M&A events [41,42,43], and used social network analysis to study the network density, centrality, core-edge and other aspects of two-mode networks [44,45,46]; however, two-mode networks are rarely used in research on innovation networks.

Regarding research on innovation networks, scholars have used world-renowned patent databases, such as the Derwent World Patents Index (DWPI), Incopat, European Patent Office (EPO) and literature databases such as SCI [47,48,49], and used social network analysis to investigate the network centrality and overall network characteristics of technological innovation networks in industrial fields [50,51], such as new energy vehicles [52], solar cells [53], and biological sciences [54,55]. Previous studies have not sufficiently addressed innovation networks from the perspectives of one-mode and two-mode networks; in addition, innovation network research has not been widely conducted on PV technology.

In view of this, the Incopat global patent database of Chinese local PV technology patent data to construct a mapping of the evolution of China's PV technology innovation network over the past 20 years. Specifically, we want to answer the following questions: what are the basic characteristics of China's innovation network in the field of PV technology? What is the evolutionary trajectory? And what is the correlation between provincial spaces? The potential marginal contributions are: the dual perspectives of one-mode and two-mode network break the limitation of the single-element perspective of traditional factor network research, and also make up for the lack of information caused by the single perspective, deepen the idea of evolutionary economics, and enrich the content of innovation linkage network analysis. In practical level, exploring the spatial situation of China's PV technology innovation collaboration to identify problems from a novel perspective, helping to clarify China's current PV technology accumulation pattern. In addition, an in-depth analysis of the network pattern evolution of PV technology innovation networks at different spatial scales could promote the innovation and development of China's PV industry and provide suggestions for overcoming the shortcomings of PV technology, achieving technological breakthroughs in core areas, and promoting the development of China's PV industry.

2. Research data and methods

2.1. Research data

The data used in this study were obtained from the Incopat global patent database. Drawing on the research methods of previous scholars and using the International Patent Classification (IPC) green patent code [56], PV-related IPC patents in the Incopat global patent database were searched.[1] First, the patents that are not related to PV were excluded, and second, patents with a single applicant, natural persons or companies registered outside China were excluded. In total, 6206 patents in the past 20 years, i.e., from 2002 to 2021, met the inclusion requirements. For the calculation of patent collaboration, first and nonfirst patent applicants were distinguished, and collaboration was divided into the first patent applicant (initiating) and the nonfirst patent applicant (participating), forming a directed data matrix of collaborative innovation among patent applicants. If a patent was applied for by four patent applicants A, B, C, and D, the collaborations between A and B, A and C, and A and D were all counted (3 times). To show the evolution characteristics of the PV technology innovation network as objectively as possible and to avoid sudden changes caused by special circumstances within a certain year, a multiple stage method was adopted, i.e., the research period was divided into four stages: 2002–2006 (Stage I), 2007–2011 (Stage II), 2012–2016 (Stage III) and 2017–2021 (Stage IV).

[1] WIPO. (2015). World Intellectual Property Organization. IPC Green Inventory. http://www.wipo.intclassifications/ipc/en/est/. Accessed 20 December 2015. Photovoltaic-related patent no: H01L 27/142, 31/00–31/078; H01G 9/20; H02 N 6/00; H01L 27/30, 51/42–51/48; H01L 25/00, 25/03, 25/16, 25/18, 31/042; C01B 33/02; C23C 14/14, 16/24; C30B 29/06; G05F 1/67; F21L 4/00; F21S 9/03; H02J 7/35; H01G 9/20; H01 M 14/00.

2.2. Research methods

(1) Social network analysis: Social network analysis was used to analyze the changes in the centrality, network density, mean clustering coefficient, centralization and other indicators of the PV technology innovation network to reveal characteristics of the network [57,58,59]

(2) Two-mode social network analysis: Patent applicant and city were regarded as the first and second modes, respectively, and the number of patent applicants-city PV technology innovation collaboration was used as the weight of the edge, which in turn led to a weighted and directed patent applicant-city two-mode innovation network.

3. Analysis of the overall characteristics of the innovation network of PV technology patent applicants

3.1. Basic characteristics of the innovation network of PV technology patent applicants

As seen in Table 1, there are significant gaps in the number of collaborations and the overall distribution among PV technology patent applicants. As seen in both Tables 1 and 2, Ocean's King Lighting Science & Technology Co., Ltd. (OKTECH), with the most collaborations, has basically formed a stable cooperative relationship with Shenzhen OKTECH, Shenzhen Ocean King Lighting Engineering Co., Ltd., Suzhou Canadian Solar Inc. (CSI) and Changshu CSI and has jointly applied for the most patents in 20 years, indicating that OKTECH is the core force of PV technology innovation. After No. 12, the gap slowly decreases from 96 to 1, indicating that there is a significant long-tail effect in the field of PV technology innovation. In the 20-year period, patent applicants with only 1 collaboration account for more than 50 % of all applicants, and the relationship is unstable. In addition, regarding collaborations, among the top 20 patent applicants, except for Tsinghua University and Hongfujin Precision Industry (Shenzhen) Co., Ltd., the applicants are basically companies with parent-child relationships or investment relationships, indicating that the leading PV companies have basically formed a relatively stable internal collaboration. As a university, the high rank of Tsinghua University is mainly related to China's emphasis on innovation in production, education and research, which has created a scientific foundation and a favorable atmosphere for the high-quality development of PV technology.

3.2. Evolution characteristics of the innovation network of PV technology patent applicants

Firstly, the Force Atlas algorithm plug-in in Gephi is used to generate the spatial style of the network. Then, using the ArcGIS natural breakpoint method, the node centrality and the association strength between nodes are broken, and the node association strength is divided with Stage IV as the standard, and the final formation of the visualization mapping (Fig. 1). As seen in Fig. 1, from 2002 to 2006, in the PV technology innovation network, more than 50 patent applicants participate in the network, there are 29 cooperative innovations, and the mean collaboration strength is 0.962; from 2017 to 2021, compared with Stage I, the number of associations and mean association strength increase more than 60-fold, indicating that the scale of development of the PV technology innovation network grew rapidly, with sufficient stamina.

Table 1
Number of collaborations between patent applicants from 2002 to 2021.

Indicator	Number of collaborations	Indicator	Number of collaborations
Minimum	1	Mean	3.7545
Maximum	646	Standard deviation (SD)	19.2240

Table 2
Patent applicant collaboration pairs (top 20) from 2002 to 2021.

Patent applicant	Patent applicant	Number of collaborations
OKTECH	Shenzhen OKTECH	646
OKTECH	Shenzhen Ocean King Lighting Engineering Co., Ltd.	484
Suzhou CSI	Changshu CSI	442
Zhejiang JinkoSolar Co., Ltd.	JinkoSolar Co., Ltd.	388
Suzhou CSI	CSI Solar Co., Ltd.	265
JinkoSolar Co., Ltd.	Zhejiang JinkoSolar Co., Ltd.	227
Suzhou CSI	CSI Solar Co., Ltd.	170
Shenzhen Ocean King Lighting Engineering Co., Ltd.	OKTECH	161
CSI Solar (China) Investment Co., Ltd.	Changshu CSI	139
Zhejiang Aiko Solar Technology Co., Ltd.	Tianjin Aiko Solar Technology Co., Ltd.	128
Zhejiang Aiko Solar Technology Co., Ltd.	Guangdong Aiko Technology Co., Ltd.	123
Huaneng Renewables Co., Ltd.	China Huaneng Group Clean Energy Technology Research Institute Co., Ltd.	96
State Power Investment Corporation Xi'an Solar Power Co., Ltd.	State Power Investment Corporation Upper Yellow River Hydropower Development Co., Ltd.	92
State Power Investment Corporation Xi'an Solar Power Co., Ltd.	Qinghai Upper Yellow River Hydropower Development Co. Ltd.	92
Tsinghua University	Hongfujin Precision Industry (Shenzhen) Co., Ltd.	90
Guangdong Midea Group Refrigeration Equipment Co., Ltd.	Midea Group Co., Ltd.	84
OKTECH (Dongguan)	OKTECH	75
Zhejiang Aiko Solar Technology Co., Ltd.	Zhuhai Fushan Aiko Solar Technology Co., Ltd.	68
Suzhou CSI	Yancheng CSI GCL Sunshine Power Technology Co., Ltd.	65
Zhejiang Aiko Solar Technology Co., Ltd.	Guangdong Aiko Technology Co., Ltd.	64

The node centrality of the innovation network in Fig. 1 and Table 3 indicate that in Stage I, the centrality of Tsinghua University is highest, reflecting the frontier and leading role of colleges and universities in the field of technological innovation; in Stages II and III, OKTECH and its subsidiaries enter the highest level, and the centrality of the two is far higher than that of other patent applicants; and in the Stage IV, the centrality ranking of CSI Solar, JinkoSolar, Aiko Solar Technology and many other companies is high, indicating that with the development of China's PV industry, many innovative PV techniques have been developed by leading enterprises in the innovation and (R&D) of PV technology. Level 3 patent applicants include CSI Solar and Tianjin Aiko Solar Technology, which are closely related to level 4 enterprises, and the number increased from 5 in Stage I to 9, forming secondary nodes of the patent applicant network. The numbers of level 1 and level 2 patent applicants grow rapidly from 27 to 20 to 3057 and 79, respectively.

The innovation network collaboration strength in Fig. 1 shows that the number of innovation collaboration pairs in the network increases from 29 in Stage I to 2,711, with only level 1 collaborations existing in Stage I, which indicates that the network does not have a strong internal association overall. With the development of the PV technology industry, co-operation exists at every level beginning with Stage II. In Stages II and III, level 5 associations in the network include collaborations between OKTECH and Shenzhen OKTECH. In Stage IV, there are 3 pairs with level 5 association strengths, i.e., Suzhou CSI - Changshu CSI, Zhejiang JinkoSolar - JinkoSolar, and Suzhou CSI–CSI Solar. There are 7 and 38 pairs with level 4 and level 3 association strengths, respectively. Among the patent applicants with strong collaboration strength, the

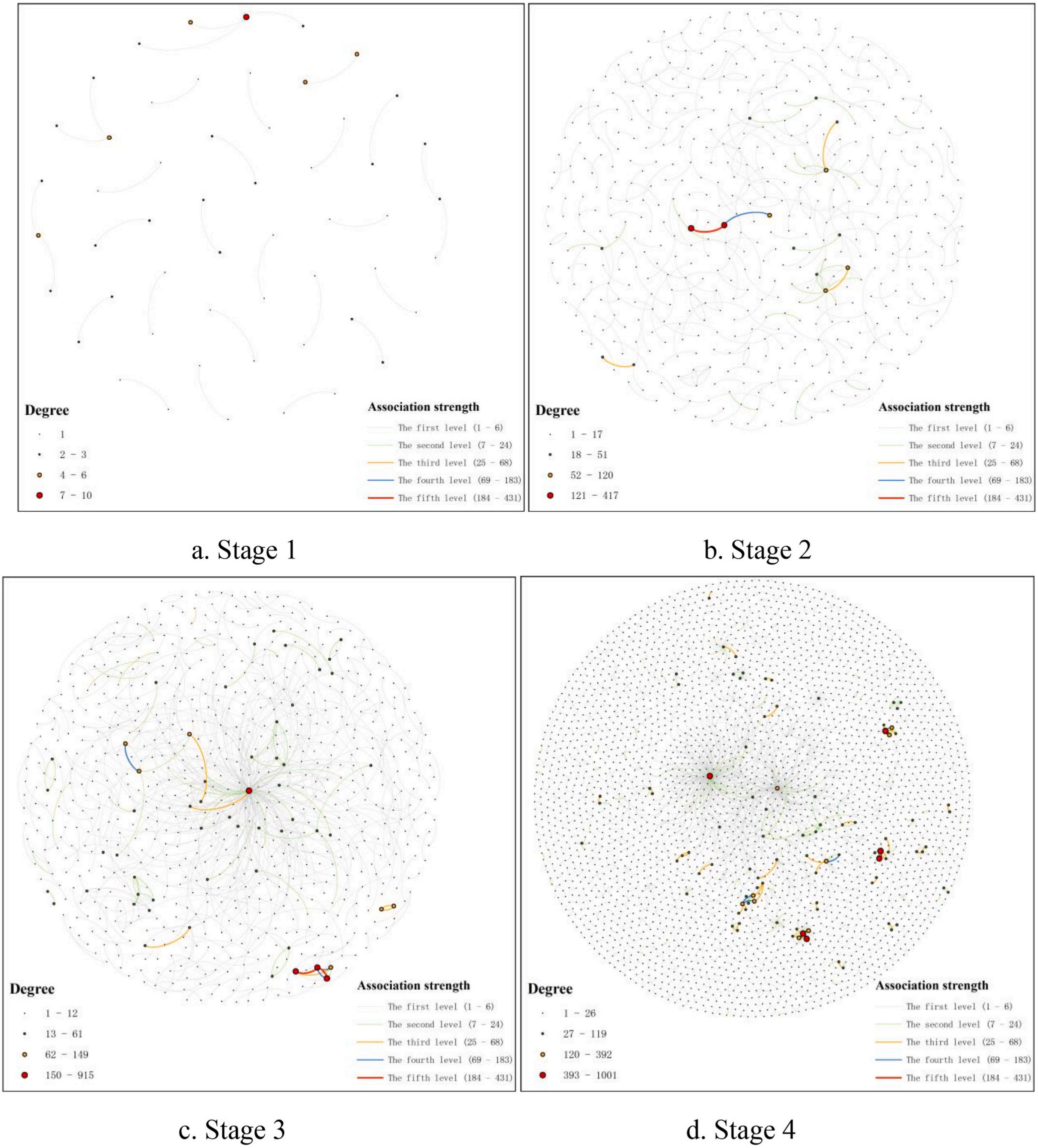

Fig. 1. Innovation network of PV technology patent applicants from 2002 to 2021.

collaboration mode is basically kinship collaboration with investment relationships.

3.3. Provincial spatial characteristics of the innovation network of PV technology patent applicants

By matching the addresses of PV technology patent applicants, a provincial PV technology innovation network is formed. Table 4 shows that the association and diversification of China's PV technology innovation network are gradually increasing. At the provincial scale, the number of nodes and associations in the network has increased significantly, indicating that the provinces participating in PV technology innovation are increasing significantly. The network out-degree centralization and in-degree centralization are declining year by year, and the out-degree centralization is greater than the in-degree centralization, indicating that the dominant nodes of the PV technology

Table 3
Patent applicant collaboration pairs (top 20) from 2002 to 2021.

Stage	Level	Node	Number
Stage I	1	Advanced Technology and Materials Co., Ltd., Central Iron & Steel Research Institute, Beijing Nonferrous Metal Research General Institute, GRIKIN Advanced Material Co., Ltd., Canton Fair Imp. & Exp. Co., Ltd., etc.	27
	2	Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Guangzhou Research Institute of Optical, Mechanical and Electrical Technologies Co., Ltd., Guangzhou Sanyuan Bearing Manufacturing Co., Ltd., Beijing Huaqi Information Digital Technology Co., Ltd., Beijing Huaqi Digital Technology Laboratory Co., Ltd., etc.	20
	3	Hongfujin Precision Industry (Shenzhen) Co., Ltd., Jianghan University, Shanxi Lebalite Technology Co., Ltd., Xi'an Jiaotong University, Military Representative Office of the Chinese People's Liberation Army in Northwest Photoelectric Instrument Factory	5
	4	Tsinghua University	1
Stage II	1	CSI (Luoyang) Co., Ltd., Kunshan Visionox Display Technology Co., Ltd., Yangjiang Nalide Industry & Trade Co., Ltd., Beijing Nonferrous Metal Research General Institute, Tianwei New Energy Holdings Co., Ltd., etc.	477
	2	Hongfujin Precision Industry (Shenzhen) Co., Ltd., Suzhou CSI, Changzhou Trina Solar Co., Ltd., Trina Solar (Changzhou) Technology Co., Ltd., Wuxi Suntech Power Co., Ltd., etc.	9
	3	Shenzhen Ocean King Lighting Engineering Co., Ltd., Changshu CSI, Tsinghua University, CSI Solar (China) Investment Co., Ltd.	4
	4	OKTECH, Shenzhen OKTECH	2
Stage III	1	Xuji Electric Co., Ltd., State Grid Gansu Electric Power Company Electric Power Research Institute, Leshan Xintianyuan Solar Technology Co., Ltd., Xiamen University, Hanghai Zhixin Electric Co., Ltd., etc.	728
	2	Zhuhai Xingye Green Building Technology Co., Ltd., Yancheng CSI GCL Sunshine Power Technology Co., Ltd., Yingli Group Co., Ltd., Zhuhai Xingye New Energy Technology Co., Ltd., Bengbu Glass Industry Design and Research Institute, etc.	43
	3	OKTECH (Dongguan), CSI Solar (China) Investment Co., Ltd., Jinko Energy Co., Ltd., Zhejiang Jinko Energy Co., Ltd., Changshu CSI., etc.	6
	4	OKTECH, Shenzhen Ocean King Lighting Engineering Co., Ltd., Shenzhen OKTECH, State Grid Corporation of China	4
Stage IV	1	Lite-On Technology Co., Ltd., State Grid Fujian Electric Power Co., Ltd., Zhejiang University, State Grid Tianjin Electric Power Company, Wuhan Ruilian Zhichuang Optoelectronics Co., Ltd., etc.	3057
	2	Guangdong Power Grid Co., Ltd., Huaneng Renewables Co., Ltd., BOE Technology Group Co., Ltd., Midea Group Co., Ltd., Guangdong Aiko Technology Co., Ltd., etc.	79
	3	CSI Solar Co., Ltd., State Power Investment Corporation Xi'an Solar Power Co., Ltd., Tianjin Aiko Solar Technology Co., Ltd., China Huaneng Group Clean Energy Technology Research Institute Co., Ltd., Guangdong Aiko Technology Co., Ltd., etc.	9
	4	Suzhou CSI, Zhejiang Jinko Energy Co., Ltd., Jinko Energy Co., Ltd., Changshu CSI, Zhejiang Aiko Solar Technology Co., Ltd., State Grid Co., Ltd.	6

innovation network are more concentrated in a few provinces, reflecting that the PV technology innovation network is more influenced by the leading nodes. The mean clustering coefficients of the network all show upward trends, indicating that nodes in the network are cooperating more closely on innovation. The network modularity and mean path length increase from 0.153 to 1.556 in the 2002–2006 period to 0.351 and 1.711, respectively, in the 2017–2021 period, indicating that on the provincial collaboration network scale, the group differentiation of the network increases significantly over time, the number of edges with complete interprovincial collaboration is increasing, and the efficiency of collaboration is declining, findings that may be related to factors such as administrative boundaries and proximity.

Table 4
Overall characteristics of the PV technology innovation network at the provincial scale from 2002 to 2021.

Indicator	2002–2006	2007–2011	2012–2016	2017–2021
Node	7	30	29	31
Edge	5	82	121	294
Modularity	0.153	0.357	0.219	0.351
Mean clustering coefficient	0.000	0.402	0.481	0.567
Average path length	1.556	2.288	2.016	1.711
Out-degree centralization	20.370	6.246	9.984	6.881
In-degree centralization	13.889	3.485	5.526	4.538

The centrality of network nodes in Table 5 shows that in the first three stages, the centrality of Beijing is higher than that of the second-ranked province; in the fourth stage, the centrality of Zhejiang ranks first, increasing from eighth in the second stage, and far surpasses Beijing. The top-ranked centrality of Zhejiang in the innovative network node demonstrates the rapid development of the PV industry in this province in the past 15 years. In recent years, driven by vigorous support by the provincial government of Zhejiang and leading enterprises such as Jinko Solar and Zhejiang CHINT Electrics Co., Ltd., the scale of Zhejiang's PVindustry and the amount of grid-connected installed capacity rank first in the country, and the PVindustry has become a landmark advantageous industry in the digital economy in Zhejiang. Guangdong and Jiangsu rank in the top five in terms of centrality beginning in Stage 2, and in Stage 4, Jiangxi becomes a sub-core node in the innovation network. In addition, most of the top ten provinces in terms of node centrality are eastern coastal provinces in China, indicating that eastern coastal provinces are pioneers in the innovation and development of PV technology.

As seen in Table 6, from 2002 to 2021, the collaboration strength of the top ten collaboration pairs in the PV technology innovation network continuously increases; however, the proportion shows the opposite trend. Specifically, the mean collaboration strength of the top ten trade pairs in the first stage is 2.4, which increases nearly seventy times to 169.2 in the fourth stage; however, the proportion decreases from 100.00 % in the first stage to 41.69 % in the fourth stage, indicating that the collaboration strength of China's PV technology innovation network continues to grow and that the node polarization effect has weakened.

For the top ten pairs, the innovation associations and collaborations slightly change, and the input-output relationships have a certain stability. For example, Beijing and Guangdong, Jiangsu and Shanghai, and Zhejiang and Jiangxi have stable cooperative relationships. Further investigation of the causes of such cooperative relationship shows that stable collaboration associations between provinces mainly occur in more economically developed provinces and that innovative collaboration is influenced by geographic proximity, the development of the PV technology industry, and other factors.

4. Analysis of the overall characteristics of the two-mode network of PV technology patent applicant-city

To more clearly identify the main characteristics of patent applicants and compensate for the lack of information caused by simplifying the cooperative innovation network of patent applicants into a one-mode network of provinces and cities, using a two-mode network of leading and participating in PV technology innovation, in this section, a patent applicant-city two-mode network is established to study the spatial flow direction and driving mechanism of patent applicant innovation

Table 5
Provincial-scale node centrality of the PV technology innovation network (top ten) from 2002 to 2021.

Rank	Province	Stage I	Province	Stage II	Province	Stage III	Province	Stage IV
1	Beijing	10	Beijing	189	Beijing	473	Zhejiang	1427
2	Guangdong	7	Jiangsu	140	Jiangsu	298	Beijing	1155
3	Hunan	2	Guangdong	95	Zhejiang	160	Guangdong	800
4	Shanxi	2	Shanghai	75	Guangdong	159	Jiangsu	731
5	Henan	1	Hebei	64	Shanghai	128	Jiangxi	712
6	Shanghai	1	Sichuan	50	Jiangxi	109	Shanghai	498
7	Inner Mongolia	1	Henan	24	Hebei	94	Shaanxi	395
8			Zhejiang	21	Shaanxi	66	Tianjin	353
9			Shaanxi	17	Henan	64	Qinghai	328
10			Gansu	15	Shandong	62	Hebei	207

Table 6
Changes in the top 10 collaboration pairs in the PV technology innovation network from 2002 to 2021.

Year	Average collaboration strength/proportion of the top 10 pairs	Collaboration pairs and collaboration strength
Stage I	2.4/100.00 %	Beijing → Guangdong (6), Beijing → Hunan (2), Shanxi → Beijing (2), Guangdong → Henan (1), Shanghai → Inner Mongolia (1)
Stage II	24.6/61.04 %	Beijing→Guangdong (62), Jiangsu→Shanghai (39), Hebei→Sichuan (25), Beijing→Jiangsu (21), Jiangsu→Henan (19), Jiangsu→Beijing (16), Hebei→Beijing (15), Sichuan→Hebei (15), Guangdong→Jiangsu (12), Beijing→Jiangxi (11), Gansu→Shanxi (11)
Stage III	40.0/42.25 %	Beijing→Jiangsu (112), Zhejiang→Jiangxi (54), Jiangxi→Zhejiang (44), Anhui→Shanghai (29), Beijing→Guangdong (29), Beijing→Zhejiang (29), Guangdong→Hunan (27), Guangdong→Jiangsu (26), Beijing→Hebei (25), Beijing→Shandong (25), Shanghai→Jiangsu (25)
Stage IV	169.2/41.69 %	Zhejiang→Jiangxi (394), Zhejiang→Guangdong (273), Jiangxi→Zhejiang (216), Shaanxi→Qinghai (192), Shanghai→Jiangsu (129), Zhejiang→Tianjin (128), Qinghai→Shanxi (98), Shanghai→Zhejiang (98), Shandong→Beijing (84), Jiangsu→Beijing (80)

collaboration.

4.1. Basic characteristics of the network

As seen in Table 7, In the nearly 20 years from 2002 to 2021, the scale of the PV technology patent applicant-city two-mode network has developed rapidly, the number of patent applicant nodes in the four stages is 24, 240, 378 and 1,623, the number of city nodes is 16, 72, 124 and 225, and the number of innovation collaborations increases dramatically from 91 to 9093, showing a rapid increase. In addition, for both degree centrality and weighted centrality, the coefficients of variation (CVs) of patent applicant and city centrality show increasing trends, indicating that the numbers of patent applicants and cities in PV technological innovation collaborations continue to rise; however, the scope and number of innovation collaborations for both patent applicants and cities show a polarization trend, but the differences are gradually diminishing.

As seen in Table 8, the PV technology innovation collaboration between patent applicants and cities has shifted from local collaboration to cross-regional collaboration. In Stage I, there are 7 local patent applicant-city pairs, mainly involving Xi'an, Guangzhou, Shanghai, Beijing and Wuhan; in Stage II, there are 5 local patent applicant-city pairs, mainly involving Shenzhen, Suzhou and Changzhou; in Stage III, there are 5 applicant-city pairs, mainly involving Shenzhen, Suzhou, Baoding and Beijing; and in Stage IV, there are 4 local patent applicant-city pairs, mainly involving Suzhou, Xi'an and Beijing. Most of these cities are provincial capitals or municipalities directly under the Central Government and are the main areas of high-tech enterprise innovation collaborations and areas with high concentrations of colleges and universities. Regarding cross-regional patent applicant-city pairs at various stages, most of the patent applicants are concentrated in highly developed eastern coastal cities, and they are more inclined to establish

Table 7
Descriptive statistics of the centrality of the 2002–2021 patent applicant-city two-mode network.

Subject	City							
time	Stage I		Stage II		Stage III		Stage IV	
Centrality	C1	C2	C1	C2	C1	C2	C1	C2
Total	28	51	291	1417	555	2989	2238	9093
Maximum	6	9	44	493	112	1073	395	1372
Minimum	1	1	1	1	1	1	1	1
Mean	1.75	3.18	4.04	19.68	4.48	24.10	9.95	40.41
SD	1.5207	2.6976	7.2139	62.6400	11.3620	100.8789	29.8656	137.4212
CV	0.87	0.85	1.79	3.18	2.54	4.19	3.00	3.40
Subject	Patent applicant							
Time	Stage I		Stage II		Stage III		Stage IV	
Centrality	C1	C2	C1	C2	C1	C2	C1	C2
Total	28	51	291	1417	555	2989	2238	9093
Maximum	3	10	6	413	53	716	30	972
Minimum	1	1	1	1	1	1	1	1
Mean	1.17	2.13	1.21	5.90	1.47	7.91	1.38	5.60
SD	0.4714	1.9432	0.5558	24.7648	2.7353	40.9911	1.3163	30.5197
CV	0.40	0.91	0.46	4.20	1.86	5.18	0.95	5.45

Note: C1 and C2 represent degree centrality and weighted centrality, respectively.

Table 8
Patent applicant-city two-mode network collaboration strength pairs (top 10) from 2002 to 2021.

Rank	Stage I			Stage II		
	Patent applicant	City	Strength	Patent applicant	City	Strength
1	Tsinghua University	Shenzhen	6	OKTECH	Shenzhen	413
2	Xi'an Jiaotong University	Xi'an	4	CSI Solar (China) Investment Co., Ltd.	Suzhou	58
3	Guangzhou Research Institute of Optical, Mechanical and Electrical Technologies Co., Ltd.	Guangzhou	3	Tsinghua University	Shenzhen	55
4	Shanghai Institute of Technical Physics, Chinese Academy of Sciences	Shanghai	3	Changshu CSI	Suzhou	41
5	Beijing Huaqi Information Digital Technology Co., Ltd.	Beijing	2	Suzhou CSI	Suzhou	37
6	Urban Waterway Branch of Guangzhou Waterway Bureau, Guangdong Province	Guangzhou	2	Changzhou Trina Solar Co., Ltd.	Changzhou	32
7	Jianghan University	Shiyan	2	Wuxi Suntech Power Co., Ltd.	Shanghai	26
8	Jianghan University	Wuhan	2	Tianwei New Energy Holdings Co., Ltd.	Baoding	15
9	Tsinghua University	Beijing	2	Tunghsu Group Co., Ltd.	Chengdu	14
10	Tsinghua University	Zhuzhou	2	Kunshan Visionox Display Technology Co., Ltd.	Beijing	14
Rank	Stage III			Stage IV		
	Patent applicant	City	Strength	Patent applicant	City	Strength
1	OKTECH	Shenzhen	716	Suzhou CSI	Suzhou	870
2	OKTECH (Dongguan).	Shenzhen	142	Zhejiang JinkoSolar Co., Ltd.	Shangrao	392
3	Shenzhen Ocean King Lighting Engineering Co., Ltd.	Shenzhen	134	Zhejiang Aiko Solar Technology Co., Ltd.	Foshan	204
4	CSI Solar (China) Investment Co., Ltd.	Suzhou	89	State Power Investment Corporation Xi'an Solar Power Co., Ltd.	Xining	190
5	Zhejiang JinkoSolar Co., Ltd.	Shangrao	54	JinkoSolar Co., Ltd.	Jiaxing	183
6	State Grid Corporation	Nanjing	52	Zhejiang Aiko Solar Technology Co., Ltd.	Tianjin	128
7	Suzhou CSI	Yancheng	48	Huaneng Renewables Co., Ltd.	Beijing	97
8	JinkoSolar Co., Ltd.	Jiaxing	44	State Power Investment Corporation Xi'an Solar Power Co., Ltd.	Xi'an	92
9	Yingli Group Co., Ltd.	Baoding	40	Zhejiang Aiko Solar Technology Co., Ltd.	Zhuhai	68
10	State Grid Corporation	Beijing	32	CSI Solar Co., Ltd.	Suzhou	64

innovation collaboration with cities with strong comprehensive strength.

4.2. Network spatial evolution characteristics

Fig. 2 shows the spatial characteristics of the local innovation collaboration in the two-mode network of PV technology patent applicant-city. Except for Suzhou and Foshan, the high-value areas of local innovation collaboration between patent applicants are basically municipalities directly under the Central Government and provincial capitals, such as Xi'an and Guangzhou. Although the number of cities engaging in innovation collaboration with local patent applicants increases from 10 to 134, the high-value areas of local innovation collaboration with patent applicants are basically dominated by cities along the eastern coast, and the number of cities is gradually increasing, involving cities with strong technological innovation capabilities, such as Beijing, Shenzhen, Suzhou and Shanghai. In cross-regional innovation collaboration, in addition to Beijing, Shenzhen, and Shanghai, there are also nonprovincial capital cities such as Luoyang, Changzhou, Wuxi, and Shangrao. Despite the low level of comprehensive economic development of these nonprovincial capital cities, these cities have become high-value areas for cross-regional collaboration in PV technology due to the strong regional PV technology industry advantages and the presence of leading PV technology companies, such as Jinko Solar Co. Ltd. in Shangrao, Jiangxi, Zhejiang Jinko Solar Co. Ltd. in Jiaxing, Zhejiang, and Guangdong Aiko Technology Co. Ltd. in Foshan, Guangdong. In summary, for both local and cross-regional innovation collaborations, the high-value areas are basically concentrated in the eastern coastal areas of China, showing a spatially scattered distribution, and the low-value areas are distributed in blocks in the central and western regions of China.

The eastern coastal area is the main location of patent applicants' cross-regional innovation collaboration, with cross-regional collaboration presenting a spatial structure with a "triangle" as the core. As seen in Fig. 3, the three vertices of the triangle are the Beijing-Tianjin-Hebei urban agglomeration with Beijing and Tianjin as the core, the Guangdong-Hong Kong-Macao urban agglomeration with Shenzhen and Foshan as the core, and the Yangtze River Delta urban agglomeration with Shanghai, Suzhou and Jiaxing as the core. These urban agglomerations are significant in the patent applicants' technological innovation collaboration network, suggesting that these urban agglomerations are the main areas for cross-regional innovation co-operation among patent applicants, and the spatial obstacles caused by geographical distance are not significant.

5. Conclusions and policy implications

5.1. Conclusions

Using China's PV technology patent collaboration data in the Incopat global patent database, this paper employs social network analysis and investigates the structure of China's PV technology innovation network from two perspectives: 1) patent applicant-patent applicant and province-province one-mode networks in 2002–2021 and 2) a patent applicant-city two-mode network in 2002–2021. The following conclusions are drawn from the results.

(1) There are significant gaps in the number of collaborations and the overall distribution among PV technology patent applicants. The leading PV enterprises have basically formed relatively stable internal collaborations, and the scale of innovation network development has grown rapidly, with strong stamina. Many innovative PV techniques have been developed by leading enterprises in the innovation and R&D of PV technology, and among patent applicants with a strong collaboration strength, kinship collaboration with investment relationships is dominant.

(3) The number of provinces participating in PV technology innovation is increasing significantly. To a large extent, the leading nodes of the innovation network are concentrated in a few provinces. The group differentiation of the network has increased significantly over time, the number of edges with complete interprovincial collaboration is increasing, and the efficiency of collaboration is decreasing. Additionally, the eastern coastal provinces are pioneers in PV technological innovation. The

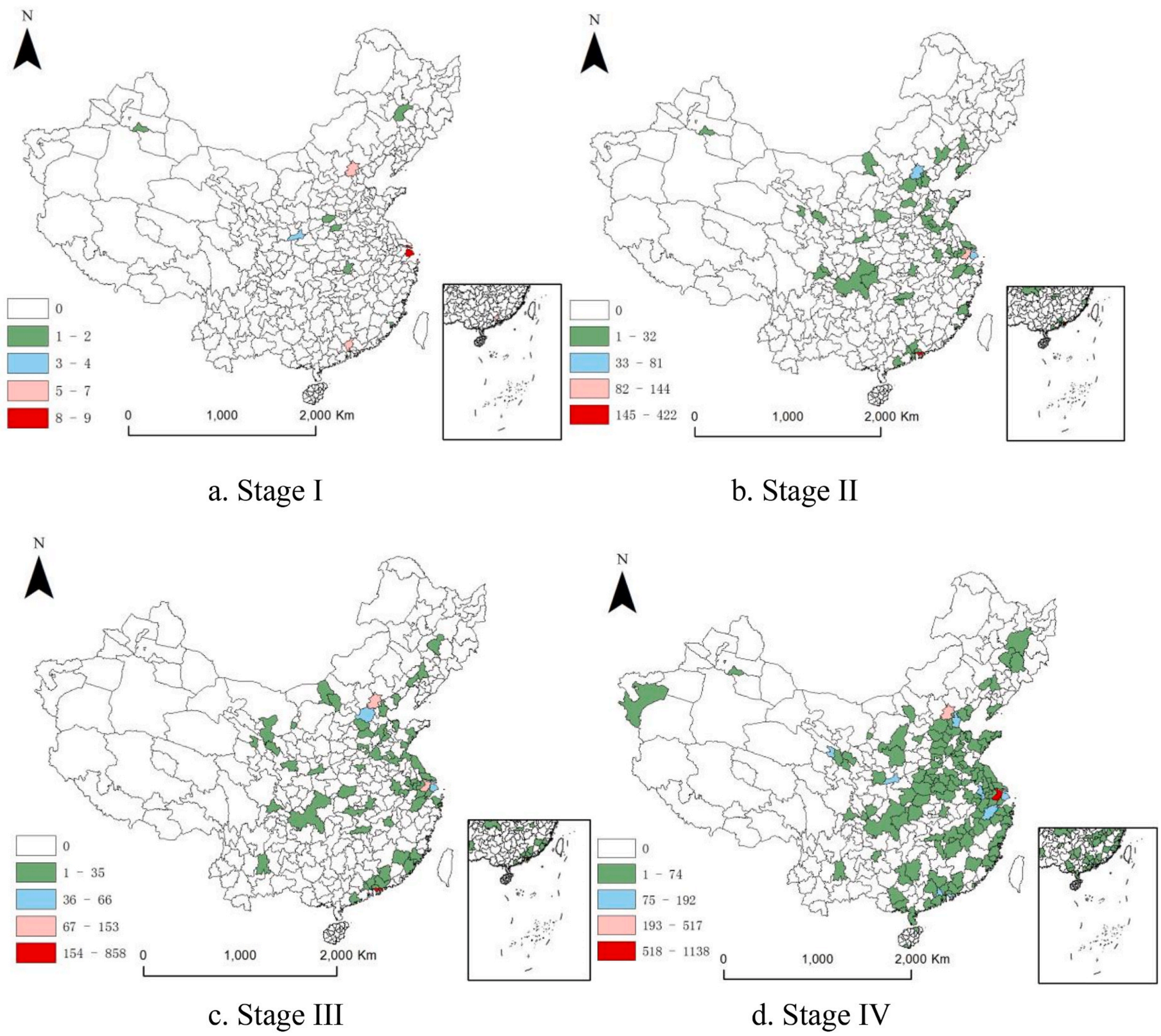

Fig. 2. The spatial characteristics of local innovation collaboration in the two-mode network from 2002 to 2021.

collaboration strength of the PV technology innovation network has continued to grow, the node polarization effect has weakened, and cooperative relationships tend to be stable.

(4) Both the scope and number of innovation collaborations between patent applicants and cities show polarization trends, but the difference is gradually weakening. Innovation collaboration has changed from local collaboration to cross-regional collaboration. Regardless of whether collaboration is local or cross-regional, high-value areas are basically concentrated in the eastern coastal areas of China, showing a scattered distribution, and low-value areas are distributed as blocks in the central and western regions of China. Cross-regional collaboration presents a “triangular” spatial structure centered on the Yangtze River Delta, Pearl River Delta, and Beijing-Tianjin-Hebei.

5.2. Policy implications

(1) The network structural characteristics indicate that the node cities on the “triangle”, i.e., Beijing and Tianjin, Shanghai, Suzhou and Jiaxing, and Shenzhen and Foshan, are core players in the PV technology innovation network and that most innovation collaborations are concentrated in these few cities. Therefore, the state should build a national-level PV technology innovation alliance with Beijing and Tianjin, Shanghai, Suzhou, and Jiaxing, and Shenzhen and Foshan as the foundation to explore the mechanism of cross-regional collaboration in PV technology innovation and promote the optimization of leadership and participation in PV technology innovation.

(2) Enterprises play important roles in the innovation and development of PV technology. The state should reduce the efficiency of information transmission caused by technological distance by establishing a technical information sharing platform and formulating incentive mechanisms [60], promote innovation collaboration among nonrelated enterprises, and promote the continuous formation of new cooperative relations between enterprises, thereby expanding the breadth of collaboration and deeply exploring the potential collaboration space in the patent collaboration network; in addition, innovation collaboration with universities and research institutes should be actively sought to realize the advantages of industry-university-research collaborations [61].

(3) The core nodes of the PV technology innovation network are mainly concentrated in core cities with administrative advantages, such as provincial capitals and municipalities directly under the central government, and cities with industrial advantages, such as Suzhou and Jiaxing. Administrative advantages and industrial advantages have important impacts on the development of PV technology innovation. The state should consider regional advantages when formulating the development strategy

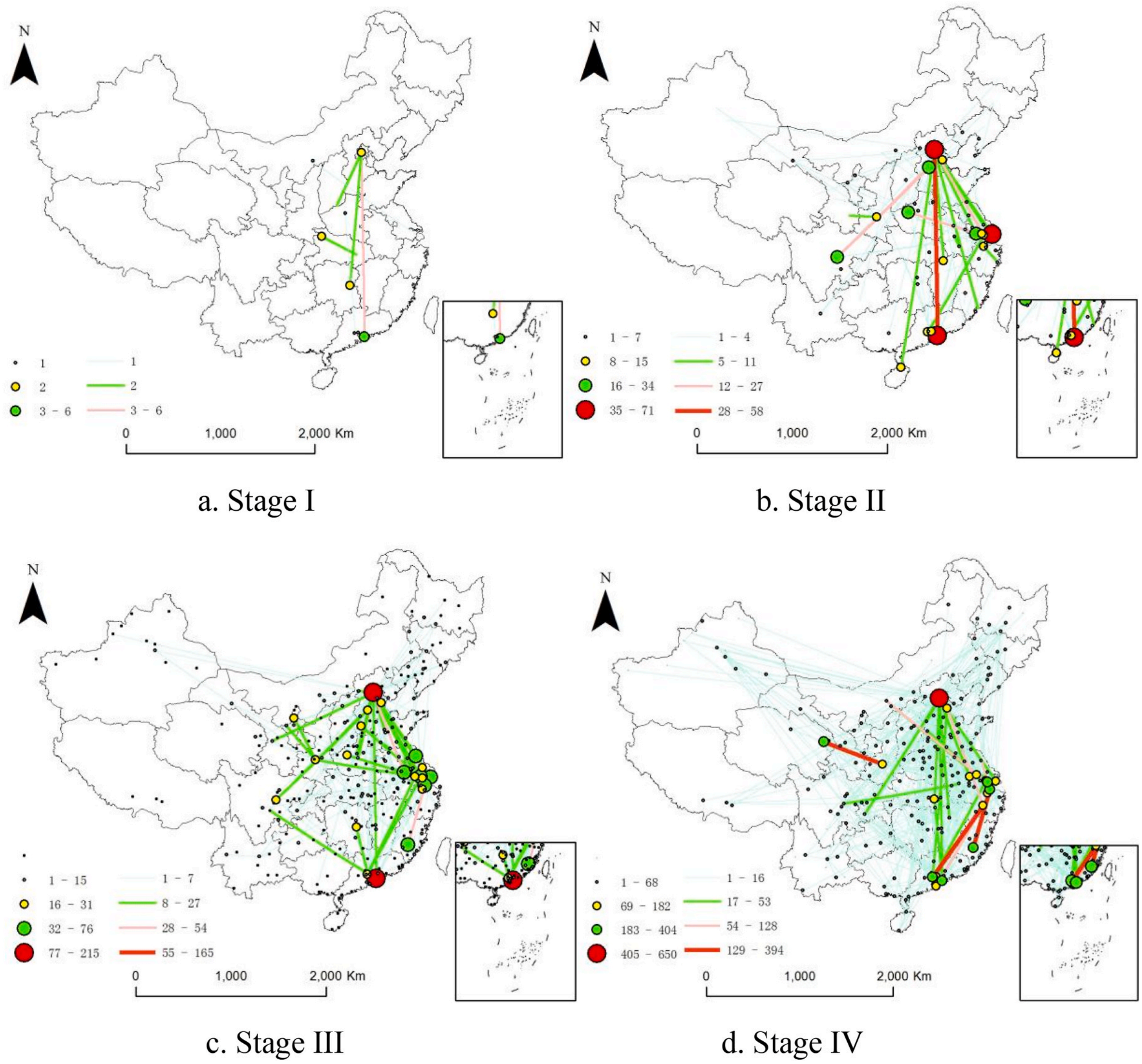

Fig. 3. Spatial characteristics of the cross-regional innovation collaboration and collaboration strength of the two-mode network from 2002 to 2021.

for the PV industry and improve the network position of cities in the PV technology innovation network.

5.3. Theoretical contributions

(1) This study uses patent applicant-patent applicant and province-province one-mode networks and a patent applicant-city two-mode network to investigate PV technology innovation collaboration; this study involves not only an in-depth analysis of the characteristics of nodes leading innovation and participating in innovation but also fills the gap regarding the lack of information caused by simplifying the cooperative innovation network of patent applicants into a one-mode network of provinces and cities [35,37,36,40].

(2) This study discusses the structure of China's PV technology innovation association network from the perspectives of provinces, municipalities and patent applicants and studies the pattern characteristics of the network from different perspectives. This study goes beyond the single element perspective of traditional element network studies, thus further expanding the understanding of innovative association networks [51,49,54].

(3) Based on evolutionary economics, in this study, PV technology collaboration patents are selected as the data source for the innovation network, not only enriching and expanding the research content of innovation networks but also providing a reference for PV technology innovation [19,22].

5.4. Research limitations and prospects

This paper studies the spatiotemporal characteristics of the PV technology innovation network; however, limited by the length of the article, there are still several aspects to be further studied. First, this paper uses patent applicants to study the PV technology innovation network and does not address the attributes of patent applicants, such as universities, colleges, research institutes and enterprises, a limitation that can be optimized in future studies from the perspective of industry-university-research collaborations. Second, due to the length of the article, the influencing factors for China's PV technology innovation network are not analyzed. In future research, the mechanism of network evolution can be further investigated with the results of this study serving as a foundation. Third, for research on PV technology innovation networks, in this paper, the PV technology innovation network is only analyzed from the perspective of patent collaboration; in future research, the evolution pattern of PV technology innovation networks can be comprehensively and synthetically investigated by means of journal paper collaborations and questionnaire surveys, combined with patent analysis, network mapping, technology trajectories and hotspots, policy evolution, and outlook prediction, which will provide more valuable insights for policy makers, industry stakeholders and researchers in the field of renewable energy.

Credit Author Statement

Feng Hu: Supervision, Conceptualization, Writing – original draft. Saiya Mou: Writing – review & editing, Investigation. Shaobin Wei: Methodology, Software. Liping Qiu: Writing - Reviewing and Editing, Validation. Hao Hu: Data curation, Visualization. Haiyan Zhou: Data curation, Writing – original draft.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant number 72373135), the Humanity and Social Sciences Foundation of Ministry of Education of China, China Ministry of Education of China , China (Grant number 22YJAZH027), the Zhejiang Province Philosophy and Social Science Planning Project, China (Grant number 24NDJC067YB).

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