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Full paper

Emerging nanogenerator technology in China: A review and forecast using integrating bibliometrics, patent analysis and technology roadmapping methods

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ABSTRACT

Many types of nanogenerators (NGs) have been developed in a rapid pace, the technological focus and trends of this fantastic emerging technology deserve in-depth exploration. This paper presents the outcomes of a technology roadmapping study based on the research on existing position of NGs. An integrating approach that combines bibliometrics, patent analysis and technology roadmapping method (TRM) workshops was applied. The bibliometrics and patent analysis provide a means of visualizing detailed information about the past trajectory and technological focus of the NGs technology. Its results show that China has been with the international forefront regard to research into NGs since 2013, especially in the field of triboelectric nanogenerators (TENG). Based on these quantitive results, key external factors which may shape the growth of NGs-based industry have been identified according to the experts' opinions. Finally, the future development roadmap of NGs-based industry in China was proposed from technology, industry dynamics, production and market& applications perspectives. This work provides a comprehensive means for visualizing more information about the present focus and future development trends of NGs, based on a quantitive and qualitative coupling method.

1. Introduction

Emerging technologies and industries are attracting global attention due to issues such as energy crisis, financial crisis and climate change. Among the emerging technology, nano-energy was defined by Zhong Lin Wang et al. as a field of studying the small-scale, highly efficient energy harvesting, storage and applications by nanomaterials and nanodevices [1–3]. Meanwhile, as an emerging nano-energy technology, NGs present a promising application in areas including but not limited to self-powered systems, mechanical or thermal energy harvesting and smart wearable devices (SWD). The emerging of NGs from nano-energy may have a profound influence on the self-powered devices and the future development of the energy and sensing technologies, health monitoring, biomedical sensing, environmental protection, and homeland security [4–6].

Many scholars have given a very high rating in the potential of NGs for low cost energy generation for various applications [7–12]. At the same time, it is also important to predict future development and industrial growth of such fantastic emerging technology, including the transitions among science, technology, environment, application, and the public market. Li et al. [13] analyzed evolutionary trends of NGs and the promising applications, through the novel method of phased bibliographic coupling. By visualizing the characteristic research topics, issues, articles and terms, they provided a quantitative approach to understanding the evolution of the NGs research. Ahmed et al. [14] presented a detailed techno-economic lifecycle assessment of two TENG modules by ascertaining performance efficiency, manufacturing costs and environmental profile in comparison with other energy harvesting technologies. The researchers recommended that research in TENGs should focus on improving system performance, material optimization and improving the lifespan. Peng et al. [15] used "Tech Mining" to analyze the potential sensor applications of TENGs. Their findings

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shown that TENGs are mostly applicable in automation and energy-intensive industries when used as sensors.

However, no systematic reports about understanding of the existing science and technology trajectory and the future macro-level trend of NGs are available, especially through integrating bibliometrics, patent analysis and road mapping methods. At the same time, it also becomes a concern for industry dynamics and policy-makers to identify and grasp the opportunity to develop such emerging technology. There are two main questions for researchers and scholars. First, how can opportunity of developing NG technologies be identified given the existing position and resource endowments? Second, how can the emergence and growth of NG technologies forming new industries be strategized and planned?

In this work, we has developed a framework for strategizing and planning the future development of NGs technology and related industries, based on the understanding of the existing scientific and technological trajectory and the identification of the future macro-level trends in policy, market and industry dynamics. The bibliometrics and patent analysis methods were applied to analyze the existing position of NGs, and Technology Roadmapping Method (TRM) Workshops were used to strategize the future development of NGs in application and marketing. Meanwhile, key events and their impact on the development of NGs-based industry have also been identified.

2. Literature review of technology forecasting methods

There are various methods or approaches that can be employed to develop strategic roadmaps [16–19]. However, many technology forecasting methods are limited in terms of comprehending the whole ecosystem when forecasting the emerging technologies. Therefore, the use of multiple methods is proposed in this work. In this section, three recognized methodologies are firstly reviewed.

2.1. TRM for emerging industry

Carvalho et al. [18] presented a literature review relating to technology roadmapping and evolution over time, which indicated that most related studies were applied with qualitative research methods. According to former researches [18,19], TRM is recognized as an effective and comprehensive tool for mapping “new” and “emerging science” industries, which is widely used in the industry to support strategic and long-term plan. TRM is also widely applied at both the firm and sector levels to support innovation, strategy, and policy development as well as deployment [20]. Due to the emerging and rapid evolving features of nanogenerator technology, TRM can be a basic approach in this work.

2.2. Bibliometrics for emerging technologies

Based on available historical data, the use of bibliometrics can provide useful data for emerging technology forecasting, including evolution of publication, keywords, citation networks and hot topics. Bibliometric approach focuses only on science or technology itself, while TRM is actively covering a broader scope including products, markets, policies and strategies. Therefore, bibliometric approach can be a key component for science and technology roadmapping to construct a reliable roadmap, and the combination of roadmapping and bibliometrics has to be addressed well in advance of the implementation of a roadmapping process [21].

2.3. Patent analysis in emerging technologies

A patent is an intellectual property right granted for an invention in the technical field to a company, public organization, or individual by a national patent office, hence giving the owners the right to exclude others from the industrial exploitation of the patented invention for a defined number of years. Patents are useful for competitive analysis and technology trend analysis, which have always been analyzed in R&D project management to assess competitive position and avoid infringement. Patent analysis is also a valuable approach to derive information about a particular industry or technology used in forecasting [22,23]. Therefore, patent analysis of the application development was integrated in this work, to improve the validity of analyzing the full-lifecycle industrial emergence.

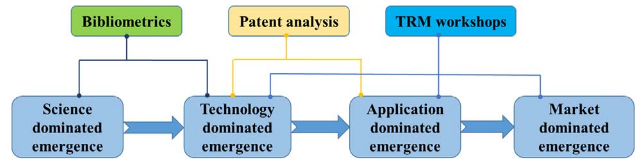

Fig. 1. Analysis methods and industrial emergence stages.

3. Methodology and data

Researchers have explained TRM needing supporting tools to complement the strategic decision-making by using objective data analysis, suggesting that some shortcomings of TRM might be assuaged by the use of other methods in the TRM process [17,18,20,22]. Based on the above literature review, in this paper, a framework will be developed based on the integration of three methods to strategize and plan the future development of NGs-based industries—bibliometric, patent methods and TRM workshops. As shown in Fig. 1, bibliometrics is applied for analyzing the existing position of science and technology, patent analysis for competitive analysis, technology trend and application analysis, and TRM workshops for strategizing the future development path from technology to application and market. The combination of three methods can better address the emergence of technologies, market, industrial settings, and the dynamics between them, which attempts to fully utilize their advantages. Regarding to strategic roadmapping, three essential questions related to the development of NGs need to be answered: (1) where are we now? (2) where do we want to go? (3) How can we get there?

In order to answer these questions, a three-step framework has been designed that integrates bibliometrics, patent analysis and TRM workshops. As NGs are in the embryonic and nurturing stage, the first question lays greater emphasis on the scientific and technological aspects. Therefore, data-based bibliometric and patent methods were used. On the other hand, the latter two questions rely on the understanding of complex market, industrial settings, and the dynamics for developing the specific technology. Hence, the brainstorming and consensus of academics, industrial experts and policy makers are needed. Such a work can be accomplished through TRM workshops, to formulate effective planning and strategizing in a reliable process. The TRM workshops process is also shown in Table 1.

4. Results and discussions

4.1. Analysis of emerging nanogenerator based on bibliometrics

The published paper number, research organization co-occurrence, research hot point and international cooperation analyses related to NGs based on the bibliometric method are discussed in this section.

In fact, after 2006, “nanogenerator” is more likely to define a small device that converts convert mechanical energy directly into electricity without using magnets and coil, first proposed by Zhong Lin Wang at Georgia Institute of Technology [1]. Therefore, we used the term "nanogenerator" to search literatures from 2006 to 2017 on the Web of Science (SCI-EXPANDED) database according to the retrieval rules in reference [13]. Then, 2021 publications were retrieved from the database.

The annual number of publications related to nanogenerator is

Table 1
An integrated TRM framework: combing bibliometric and patent analysis with TRM workshops.

Methods	Objectives and analysis	Data sources and workshop experts
Step I: Bibliometric and patent analysis	Science and technology positions: R&D activity levels and key domains in the world and China; Analyze the R&D status of nano-energy in China	Data sources: Web of Science, Thomson Innovation
Step II: Workshop I	Industrial context: market, policy, industry dynamics. Elicit the future macro-level events and settings that might influence the nano-energy market and the development path of the nano-energy technology-based industry in China	Participants: experts from technology companies, government officers, academics from CAE, THU, etc
Step III: Workshop II	Future development: roadmapping the future trajectory of NGs-based industries in the embryonic/nurture/mature stage; Given the macro-level settings and past R&D trajectory, discuss the dynamics between the macro-level settings and the technology, and plan the future development of NGs-based industry in China	Participants: leading Chinese experts on NGs in China, including Prof. Zhong Lin Wang, Prof. Haixia Zhang, etc

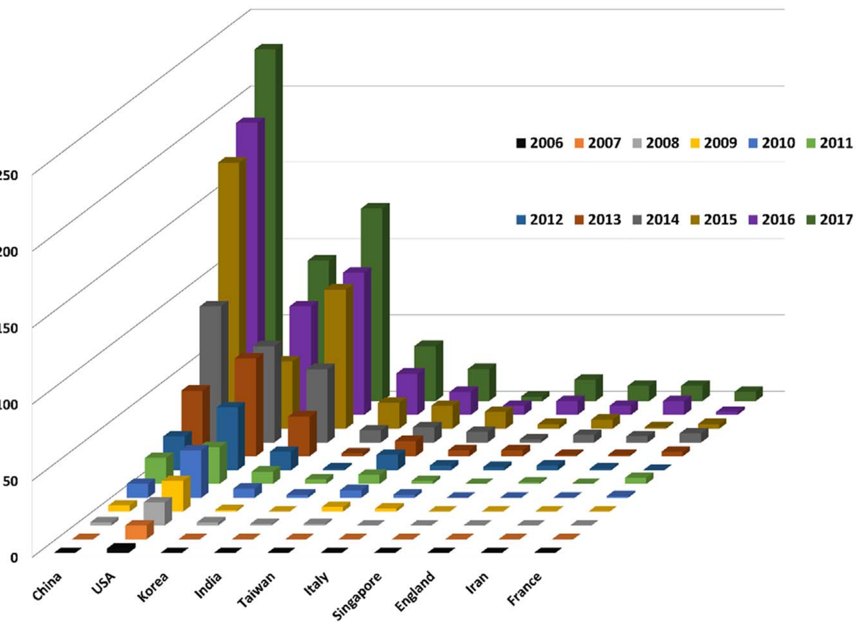

Fig. 2. Annual number of NGs SCI publications by region from 2006 to 2017.

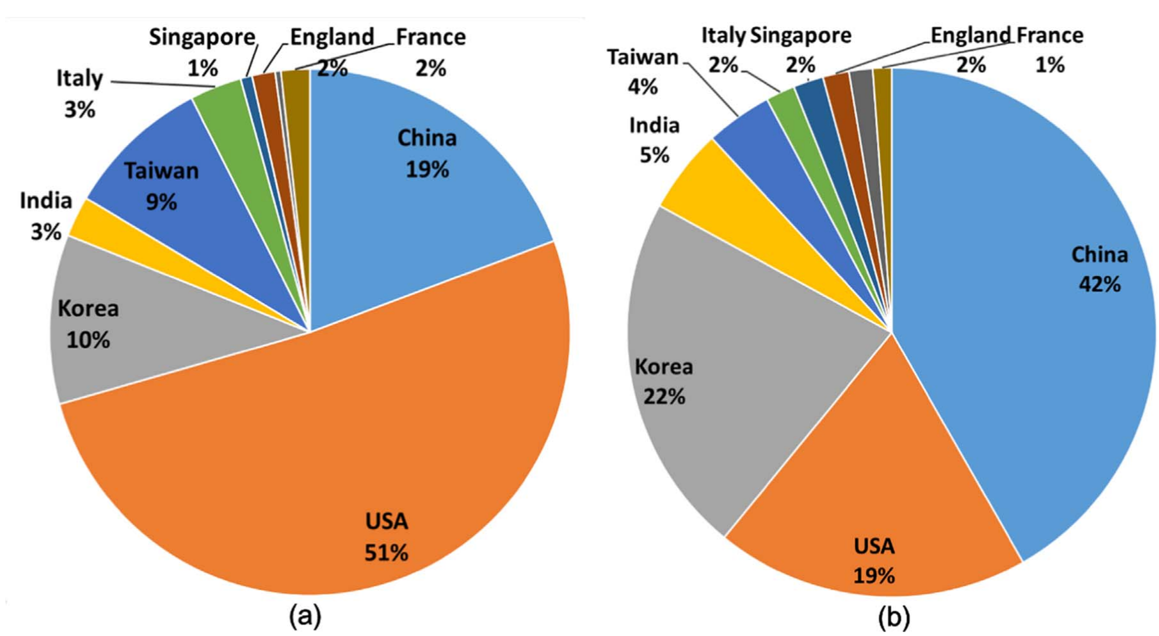

Fig. 3. The percent of SCI paper numbers related to nanogenerators (NGs) by region, a) between 2006 and 2012, b) between 2013 and 2017.

shown in Fig. 2 by regions, from 2006 to 2017. It depicts the rising trend of global publications on nanogenerator, mainly in China, USA, Korea, India, Taiwan, etc. The portion of SCI publication numbers related to NGs by region is shown in Fig. 3. Between 2006 and 2012, USA's SCI publications accounts for 51% of global numbers, which is followed successively by China, Korea, Taiwan, India and Italy, etc. However, after 2013, the number of China's annual SCI publications on NGs increased constantly, has outstripped that of USA. As a result, between 2013 and 2017, China's SCI publications account for 42% of global numbers, which is followed successively by USA, Korea, India, Taiwan, and Italy, etc. It can be concluded that China's researchers have achieved significant progress on NGs researches in recent five years. In fact, the concept of triboelectric nanogenerators (TENGs) was proposed by Zhong Lin Wang's group in 2012 [24–26], which is in the most frequent terms of NGs related research after 2012 [13].

To further explore the bibliometric indicators of China's SCI publications on NGs, the analytical tools, CiteSpace, Ucinet and TDA were used in this work [27,28]. The results are shown in following figures.

4.1.1. International cooperation analysis

Firstly, the selected publications were saved as a txt file. Then, the matrix of author's country and the country cooperation were extracted using TDA software, and a co-occurrence matrix was constructed based on the cleared data. Finally, the data matrix was imported into Ucinet software and the results are shown in Fig. 4. In Fig. 4, the nodes represent different research countries, and the size of the nodes represents published papers number. The links between the different nodes represents the cooperation relations existing among the countries. The thickness of the link represents the cooperation frequency. As can be seen in Fig. 4, the three bigger nodes represent China, USA, and South Korea, respectively, indicating that these three countries published the most SCI papers on NGs since 2006. It also shows that China engages in considerable cooperative researches with many other countries. Also, China has developed a closed cooperation with the USA, with which there are a thicker link than with any other region. As shown in Fig. 4, China has cooperated with many other countries to research on NGs, indicating that China has engaged in a high level of international cooperation on research into NGs.

4.1.2. Research organization co-occurrence analysis

In Fig. 5, the five bigger nodes represent Georgia Institute of Technology, Chinese Academy of Science, Chongqing University, Peking University, and University of Science& Technology of Beijing, respectively, meaning that these five organizations published the most SCI papers. In particular, the link between Georgia Institute of Technology and Chinese Academy of Science is the thickest indicating a very close cooperation of the two organizations. In addition to Georgia Institute of Technology, there are many Chinese research organizations linked to Chinese Academy of Science, such as the Tsinghua University, Chongqing University, Peking University, Beihang University, Xiamen University, and Lanzhou University, indicating that these organizations have also engaged in the study of NGs and engage in close cooperation with Chinese Academy of Science. The top 15 research organizations related to NGs are shown in Table 2. Georgia Institute of Technology and Chinese Academy of Sciences have published the largest and second number of SCI papers. It also shows that in the top 15 organizations, ten organizations are from China, indicating the strong research and innovation capability of Chinese organizations related to NGs.

4.1.3. Research hot point analysis

The useful SCI papers from 2006 to 2017 were selected from retrieval data. Then these publication data were imported into *CiteSpace software* for keyword co-occurrence analysis. The threshold in the analysis interface zone was set to produce a clear display, and the analysis function of keyword co-occurrence was selected to analyze the

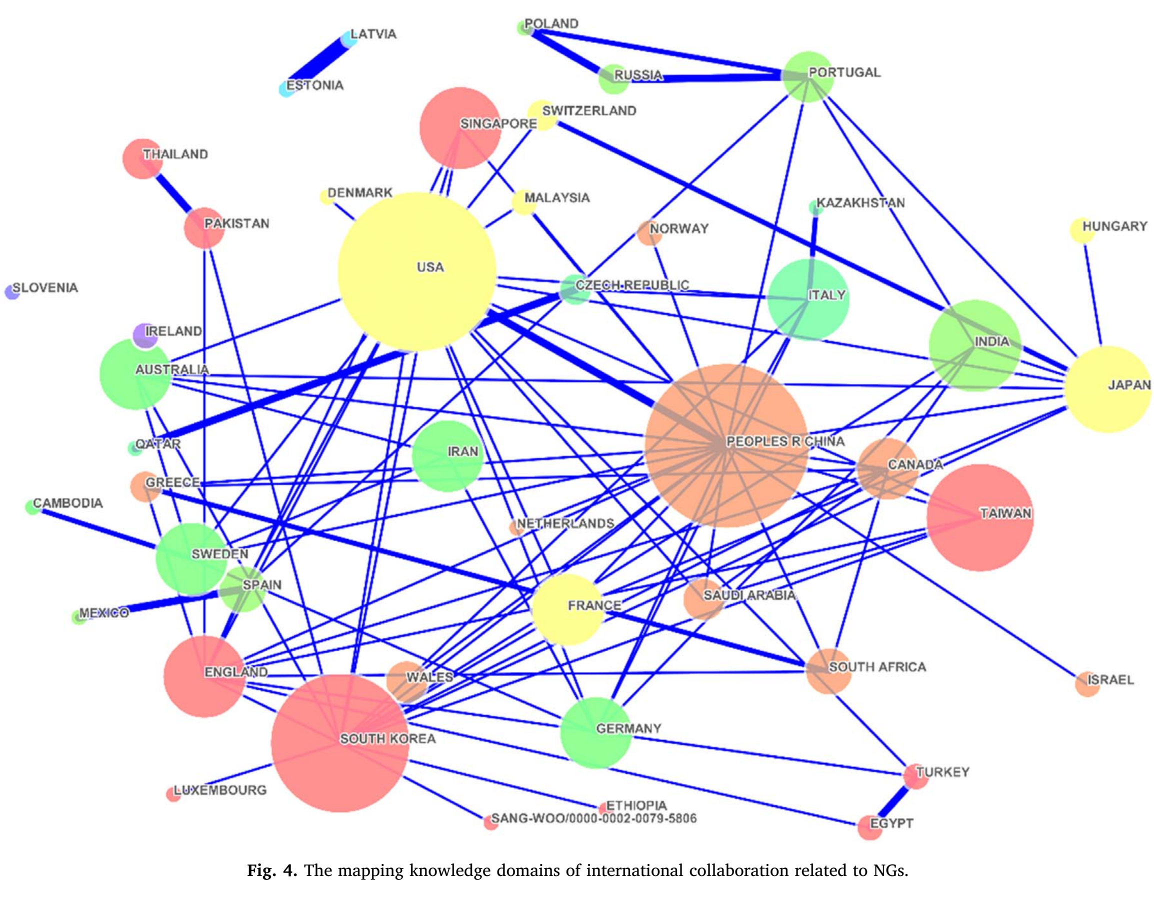

Fig. 4. The mapping knowledge domains of international collaboration related to NGs.

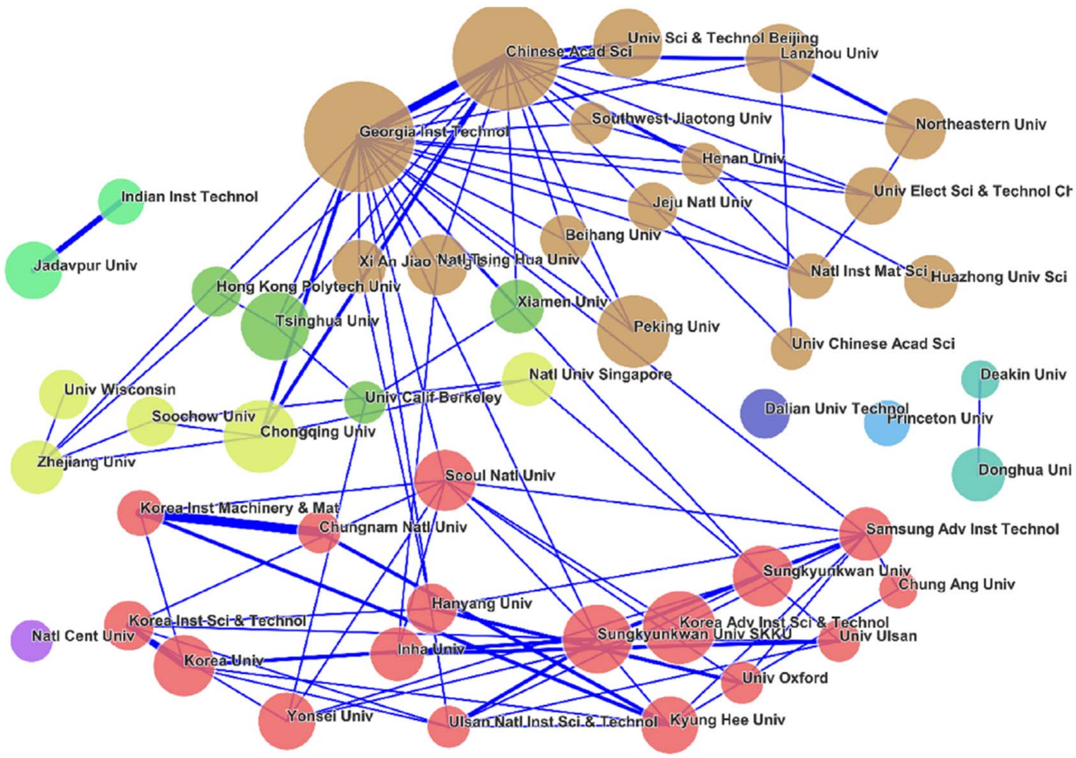

Fig. 5. The mapping knowledge domains of research organizations related to NGs.

Table 2
Profiling the top 15 organizations in R&D on NGs.

No	# Records	Affiliations	Record%since2011		Region
1	526	Georgia Inst Technol	87.26%	459	USA
2	506	Chinese Acad Sci,	98.81%	500	Peoples R China
3	77	Univ Sci & Technol Beijing	100%	77	Peoples R China
4	74	Peking Univ	89.19%	66	Peoples R China
5	73	Korea Adv Inst Sci & Technol,	98.63%	72	South Korea
6	71	Chongqing Univ	98.59%	70	Peoples R China
7	57	Tsinghua Univ,	100%	57	Peoples R China
8	57	Sungkyunkwan Univ SKKU	100%	57	South Korea
9	54	Lanzhou Univ,	92.59%	50	Peoples R China
10	48	Korea Univ,	100.00%	48	South Korea
11	43	Jadavpur Univ,	100%	43	India
12	42	Natl Ctr Nanosci & Technol NCNST	100%	42	Peoples R China
13	41	Univ Chinese Acad Sci,	100%	41	Peoples R China
14	38	Huazhong Univ Sci & Technol	100%	38	Peoples R China
15	38	Natl Tsing Hua Univ	84.21%	32	Taiwan

literature. As seen the analysis results in Fig. 6, the top high frequency nodes linked with NG are film, nanowire, array, nanopiezotronics and energy harvesting, etc. The top 10 frequently used keywords can be found in Table 3. Meanwhile, China's SCI papers were selected from the total papers from 2006 to 2017. The similar steps as for the global research hot point were implemented. The results are shown in Fig. 7, and the top ten frequently used keywords in China are shown in Table 4. It is obvious that in China the top 5 high frequency nodes linked with NGs are nanowire, array, nano-piezotronics, device and performance. As can be seen from Figs. 6–7 and Tables 3–4, China's research hot points for NGs are similar to the global ones.

From the above-mentioned results of international cooperation analysis, research organization co-occurrence and research hot point of NGs, it is clear that the research and innovation have been very active in this field in recent years. Between 2013 and 2017, China has published the most SCI papers on NGs in the world. In China, Chinese Academy of Sciences contributed to the most publications on NGs. Meanwhile, China's research hot points for NGs are similar to the global ones. The results indicate China has engaged in a high level of international cooperation and has been with the international forefront regard to research into NGs.

4.2. Patent analysis of NGs

In addition to bibliometric method, a patent analysis can reveal another aspect of innovative activities and technical competitiveness on NGs. Accordingly, we focused on the related patenting activities of different countries and organizations over time. In this step, we have built a unique database on NGs for patents granted at Derwent World Patents Index database (Thomson Innovation) from 2006 to 2016. We searched the patents with specific keyword “nanogenerator*”.

The granted patent trends in recent years have been displayed in Fig. 8. From Fig. 8, it can be seen that before 2011, the number of NGs-based patents is relatively small. After 2012, the patent number increased almost every year in a high rate. In Fig. 8, it is apparent that China's NGs-related patent number increased dramatically since 2009.

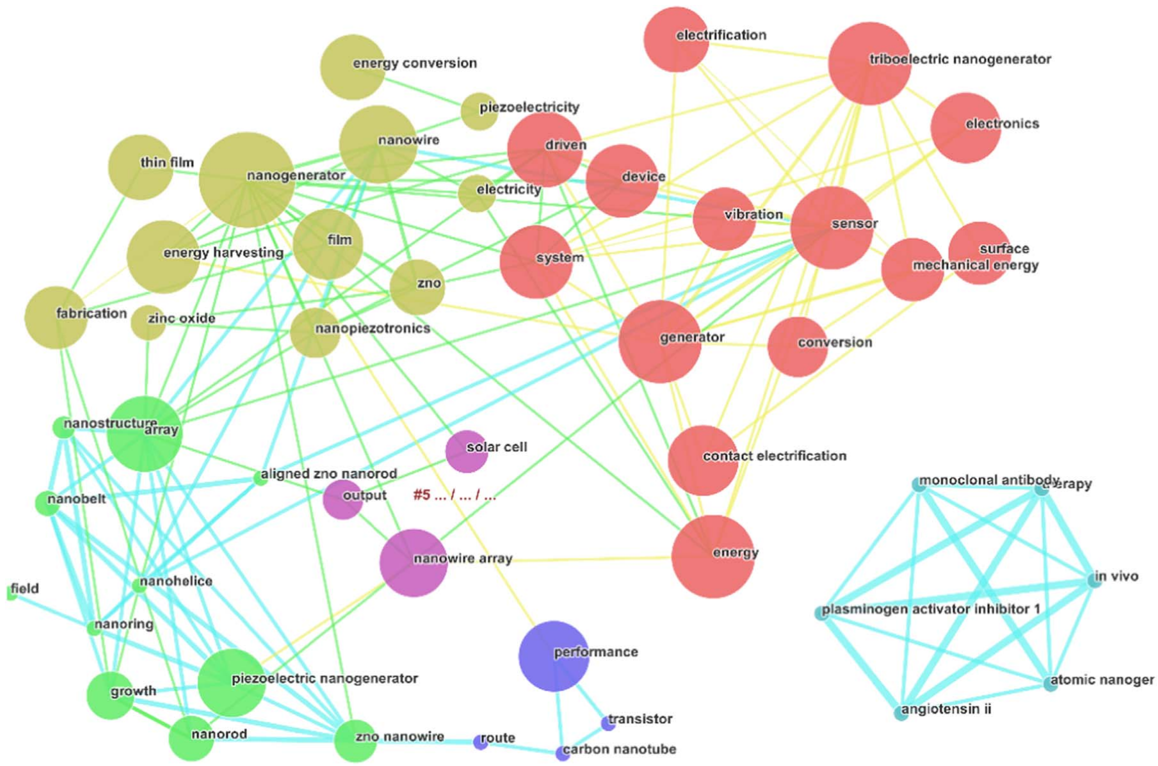

Fig. 6. The mapping knowledge domains of global research hot points related to NGs.

Table 3
The top ten frequency keywords related to global nanogenerator research.

Keywords	nanogenerator	sensor	triboelectric nanogenerator	generator	energy
Frequency	1036	493	474	455	434
Keywords	nanowire	array	performance	device	film
Frequency	307	306	271	259	257

In order to identify the significant patents, the retrieved patent data was used to generate the patent map with TDA software. Then top highest centrality patents can be identified in the patent map. In Table 5, the top 5 highest centrality patents are listed. By examining Table 5, it is possible to see the pioneering work led by Wang et al. [29–33], in contributing to the pushing of nanogenerator research to market applications. At the same time, one might conclude that TENG has technical competitiveness in future development, particularly in China.

4.3. TRM for the future development of emerging nanogenerator in China

In order to forecast emerging nanogenerator technology development in China, workshops were adopted focusing on future events in macro-level settings and future development of NGs-based industry in China.

The *workshop I* was adopted to identify the key external factors that might shape the growth of NGs-related industries. Then the authors can compile outputs and gather essential information for the next step. According to the experts' opinions and previous practice [20], the key dimensions of the macro-level settings were set as industry dynamics, market & applications and policy. Then, the experts brainstormed and elicited possible events from the above perspectives. Based on the events, authors can further explore and plan the future trajectory of NGs-based industry in China through another workshop.

The *workshop II* was adopted to roadmap the future development of the NGs-based industry in China, especially from the technology and application perspectives. In this workshop, NGs related famous experts in China were invited based on the aforementioned bibliometric and patent analysis. The future development roadmap of the NGs-based industry in China is shown in Fig. 9.

In *workshop II*, the authors use the timeframe from 2018 to 2037. Selected events are used in the final roadmap based on workshop I. In the technology dimension, we attempt to project the technology trajectory based on the existing science and technology background which is analyzed in the earlier bibliometric and patent analysis. As China is one of the leaders in the research on NGs in the global innovation race since 2013, China can lead the global development pace, according to the experts' opinions. Therefore, it would be necessary to establish standards at the global and national level. Meanwhile, based on the top keywords and important issues retrieved through the bibliometric and patent analysis, experts expected some of these can form the subjects of future R&D focus in the next 20 years, such as TENGs, sensor, fabrication and efficiency (shown in Fig. 9).

In the market and application dimension on the roadmap, the author attempted to plot the future path of the NGs-based industry in four processes, including R&D, demonstration, commercialization and large-scale commercialization, according to the experts' opinions and potential industry dynamics.

On this roadmap, nanogenerator technology would be in the R&D process before 2020. It is estimated the demonstration process will start before 2025. Furthermore, the commercialization process may begin around 2030. Last but not the least, a large-scale commercialization may start before 2037, which would provide a boost to the related industry. According to the experts' opinions, bibliometric results and patent analysis, the demonstration and commercialization may develop in several main pathways: as the self-powered active sensors, as self-powered systems, as power source for tiny devices and a wider world.

Moreover, as shown on the roadmap, the area power density of NGs may come to 200–300 mW/cm^2 around 2030. It is possible to achieve an area power density of 300–500 mW/cm^2 before 2037. It would have competitive advantages compared to some existing energy generation technologies including solar, thermal and biochemical technologies. By

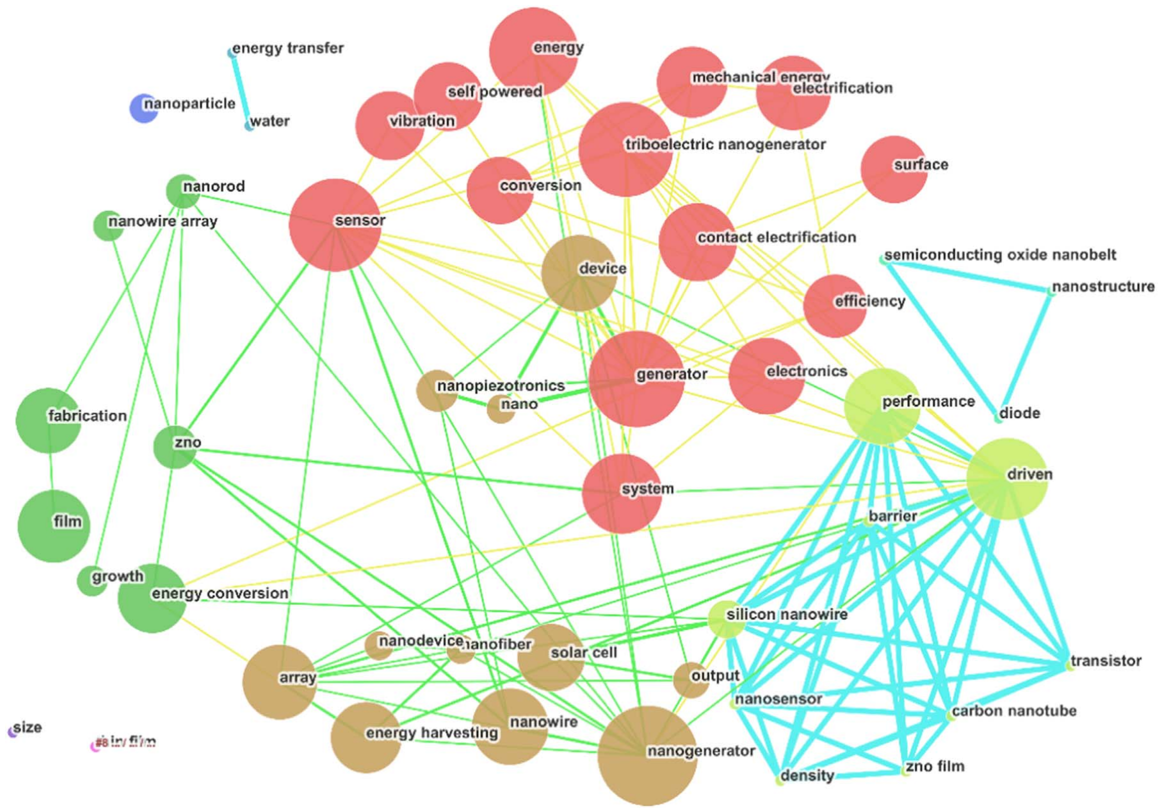

Fig. 7. The mapping knowledge domains of China's research hot points related to NGs.

Table 4
The top ten frequency keywords related to China's nanogenerator research.

Keywords	nanogenerator	generator	performance	sensor	energy
Frequency	468	330	157	315	239
Keywords	driven	triboelectric nanogenerator	system	device	film
Frequency	149	352	157	140	129

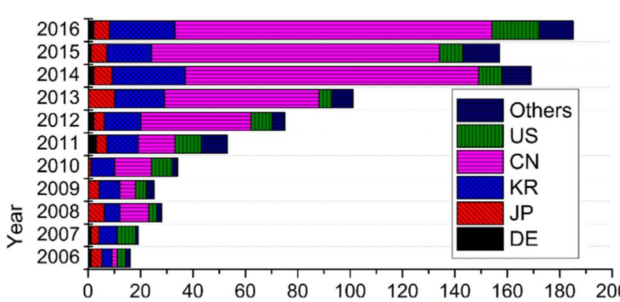

Fig. 8. Trend of patent applications on NGs.

2037, nanogenerator technology may be an effective and important part of the whole energy generation system, converting into electrical output of small-scale energies including low-frequency mechanical energies, thermal energy and chemical energy, etc. By that time, the nanoenergy involving from nanogenerator would be the *Energy for New Era* in its real sense. These results would provide important references for government decision-making on related industries and for the R&D strategies planning of related enterprises.

5. Conclusions

In this paper, the bibliometrics and patent analysis methods were applied to analyze the existing position of NGs. Technology

Table 5
Highest centrality patents.

#	Granted No.	Title	Date
1	US9595894B2	Triboelectric nanogenerator for powering portable electronics	2013–09–20
2	US20160218640A1	Triboelectric nanogenerator for harvesting energy form water	2016–01–26
3	CN104242723A	Single-electrode friction nanogenerator and generating method and self-driven tracking device	2013–06–13
4	CN104283453A	Sliding friction generator, generating method and vector displacement sensor	2013–07–11
5	CN104253561A	Sliding friction generator, power generation method and vector displacement sensor	2013–06–25

Roadmapping Method (TRM) workshops were used to strategize the future development of NGs in application and marketing.

Key findings and contributions are listed:

(1) According to the bibliometric analysis, China has engaged in a high level of international cooperation and has been located in the international forefront regard to research into NGs, providing a solid basis for China to develop its NGs-based industry in the future;
(2) A roadmap for the future development of the NGs-based industry in China was developed from 2018 to 2037. It shows NG is the possible technology that have the potential to lead to radical changes. The roadmap outlined in this work is aimed to provide a useful reference for the future development of the NGs-based research and industry in China and other countries;
(3) The framework proposed in this work is a meaningful attempt which integrates bibliometrics, patent analysis and technology roadmapping methods. This paper can be a reference to NGs related researchers and contribute to the foresight of disruptive and future-

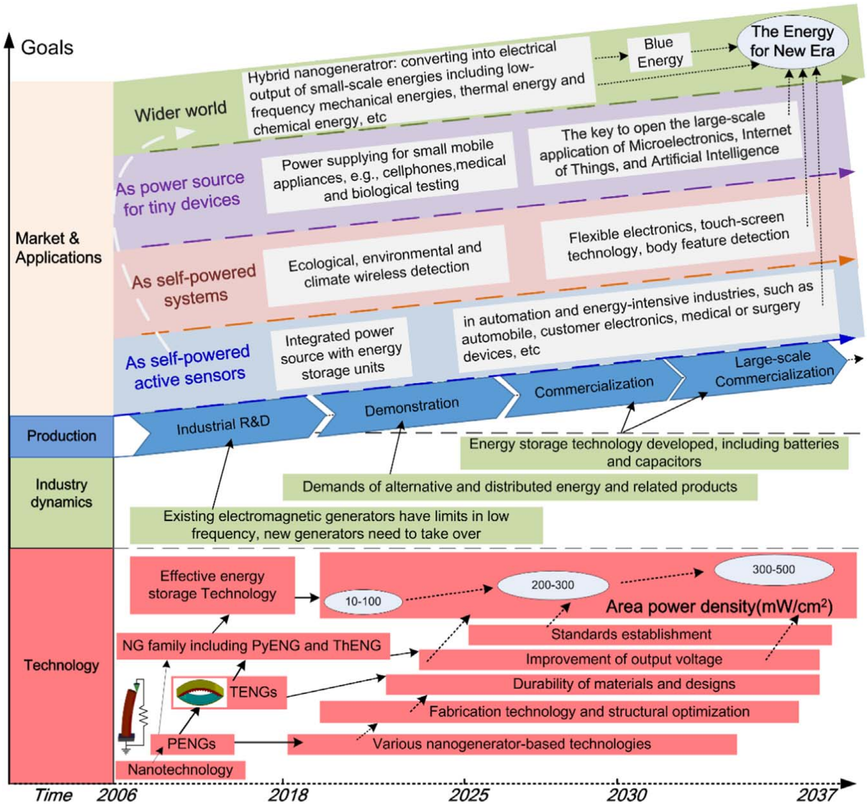

Fig. 9. The future development roadmap of NGs industry in China.

oriented technology development.

As shown in the forementioned results, the development of nanogenerator is a multi-disciplinary field with abroad potential applications. Meanwhile, there may be high uncertainties in its future path caused by unknown significant disruption. Accordingly, other methods can be useful, such as scenario-planning method, SWOT, system dynamics, and competitive features process, which can form subjects for future research. Meanwhile, government, enterprises and research institutions can deepen cooperations for related policy research on NGs to support decision making.

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