Technological Forecasting & Social Change 97 (2015) 205–222

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

Integrating bibliometrics and roadmapping methods: A case of dye-sensitized solar cell technology-based industry in China

Xin Li [a], Yuan Zhou [a,*], Lan Xue [a], Lucheng Huang [b]

[a] School of Public Policy and Management, Tsinghua University, Beijing, China.
[b] School of Economic and Management, Beijing University of Technology, Beijing, China

ARTICLE INFO

Article history:
Received 17 January 2014
Received in revised form 13 May 2014
Accepted 15 May 2014
Available online 7 June 2014

Keywords:
Emerging industry
Technology roadmap
Bibliometrics
Dye-sensitized solar cell
PV industry

ABSTRACT

Emerging industries are attracting increasing attention as they engage in innovation activities that transgress the boundaries of science and technology. Policy makers and industrial communities use roadmapping methods to predict future industrial growth, but the existing bibliometric/workshop methods have limitations when analyzing the full-lifecycle industrial emergence, including the transitions between science, technology, application, and the mass market. This paper, therefore, proposes a framework that integrates bibliometrics and a technology roadmapping (TRM) workshop approach to strategize and plan the future development of the new, technology-based industry. The dye-sensitized solar cell technology-based industry in China is selected as a case study. In this case, the bibliometrics method is applied to analyze the existing position of science and technology, and TRM workshops are used to strategize the future development from technology to application and marketing. Key events and impact on the development of the new, technology-based industry have been identified. This paper will contribute to the roadmapping and foresight methodology, and will be of interest to solar photovoltaic industry researchers.

1. Introduction

In recent years, emerging industries and technologies have been attracting increasing attention worldwide, due to a series of events, such as the financial crisis, climate change, and other global issues. Many developed nations encourage the development of emerging industries to uphold their leadership position when faced with intensive global competition and also to cope with late-comers and challenges in the form of innovations. Meanwhile, several developing economies are striving to promote the emerging industries, in order to boost their economies and catch up in the global innovation race [1].

Emerging industries are being pushed by developments in the field of science and technology[1] [2]. The emergence of this new science and technology may have a profound influence on the global industrial and economic structure, leading to a new wave of industrial revolution [3]. In these circumstances, it becomes a strategic concern for all nations to identify and grasp the opportunity to develop their emerging industries, which will ultimately contribute to their international competitiveness and sustainable development when facing the wave of revolutionary industrial changes. This strategic issue raises two sub-questions: firstly, how can opportunities to develop specific technologies be identified, given the existing position and resource endowments? And, secondly, how can the emergence and growth of the technologies that will form new industries be strategized and planned? In response to these questions, this paper attempts to develop a framework for strategizing and planning the future development of these new industries in emerging countries like China, based on an understanding of the existing science and technology trajectory and the identification of the future macro-level trends in the policy, market, and industry dynamics.

* Corresponding author. Tel./fax: +86 10 62788626.
E-mail address: zhou_yuan@mail.tsinghua.edu.cn (Y. Zhou).

[1] Scholars, such as Alan Porter, define this new science and technology as newly-emerging science and technologies (NESTs).

http://dx.doi.org/10.1016/j.techfore.2014.05.007
0040-1625/

The technology roadmapping (TRM) approach is widely applied at both the firm and industrial levels, supporting the development of technological innovation, strategy, and policy. It provides a structured approach to map the evolution and development of complex systems [4], and is recognized as an effective, comprehensive tool for planning the future development of emerging technologies [5]. However, the traditional TRM methods suffer from several limitations; for example, the workshop processes rely on the intuitive knowledge of participating experts, which might be subjective and biased in some cases. By contrast, some newly-adopted quantitative analyses are using objective data, such as publications, patents, literature and commercial data, which can help to analyze the past and existing trajectory of technological innovation, which are viewed as more valid and less biased as they are supported by objective data. One of the objective analysis methods is bibliometrics. Bibliometrics helps to explore, organize and analyze large amounts of historical data, thus helping researchers to identify the "hidden patterns" and thereby assisting the decision-making process [6]. It has been widely applied to detect emerging research domains and forecast emerging technologies [7,8].

The authors believe that this bibliometric method can supplement the traditional TRM methods, like workshops. Therefore, this paper proposes a framework that integrates bibliometrics with the TRM workshop approach to strategize and plan the future development of new technology-based industries. It takes the dye-sensitized solar cell technology-based industry as a case study, against the background of the rapid development of China's photovoltaic market. Bibliometrics is applied to analyze the existing position and path of science and technology in the dye-sensitized solar energy domain, and TRM workshops are used to strategize and plan the future development of this technology-oriented industry.

The rest of this paper is organized as follows. Section 2 presents the literature review. Section 3 provides the methodology. Section 4 analyzes the case study. Finally, Section 5 concludes and discusses the paper.

2. Literature review

2.1. TRM for emerging industry

Regarding the concept of emerging industry, scholars offer various definitions from different perspectives. Forbes and Kirsh pointed out that an emerging industry represents the intersection of a unit of analysis and a temporal interval. The unit of analysis is the industry [9]. The most common definition of an "industry" is that it is a group of firms producing products that are close substitutes for one another [10,11]. Porter defines emerging industries as "newly formed or re-formed industries that have been created by technological innovations, shifts in relative cost relationships, emergence of new consumer needs, or other economic and sociological changes that elevate a new product or service to the level of a potentially viable business opportunity" [10].

However, it is difficult to study emerging industries, because it is often hard to identify them until after they have matured [12]. In addition, many emerging industries fail, and it is even more difficult to find and study failed industries [9]. Over time, moreover, scholars tend simply to stop asking theoretical questions about phenomena that are hard to study empirically [13], and as a consequence fewer scholars seek to solve the associated empirical problems. Therefore, advancing the study of emerging industries will require scholars to develop new methodologies and theories, to make more extensive use of qualitative and historical data [9].

Technology roadmapping (TRM) is a flexible technique that is widely used within industry to support strategic and long-term planning [14]. It is recognized as an effective and comprehensive tool for mapping emerging industries when studying the complex behaviors of the industrial development process [4,15], and is widely applied at both the firm and sector levels to support innovation, strategy, and policy development and deployment [5]. It provides a structured approach for mapping the evolution and development of complex systems. The TRM approach has been employed to map historical industrial emergence and thus improve our understanding of its dynamics and characteristics. For example, Phaal et al. develop more than 25 "emergence maps" of historical industrial evolution to support the development and testing of the TRM framework as a tool for historical analysis [4], and pointed out that science, technology, application and market oriented demonstrators form key milestones that demarcate the phases and transitions of industrial emergence [8]. Zhou et al. present a preliminary policy-TRM tool in order to facilitate our understanding of policy–industry interactions through the growth process of emerging industries, and undertake a systematic analysis of the policy, markets, product, and technology development throughout the process [16]. The TRM approach has also been used to map the emergence of the automotive industry [17], China's wind energy equipment manufacturing industry [16], and China's solar cell industry [2].

TRM is also a useful tool for mapping emerging technologies in an environment of disruptive change. Gerdsri proposes the concept of 'Technology Development Envelope' and attempts to make the emerging technology roadmap more dynamic, flexible and operating, in order to find the optimal path for enterprises' technology strategy [18]. Holmes and Ferrill apply TRM to help Singaporean SMEs to identify and select emerging technologies [19]. Robinson and Propp construct a "multi-path mapping (MPM)" method that is used to map the alignment strategies in the field of emerging science and technology. It can also be applied to the strategic management of research and R&D at the level of science-to-industry networks [5].

TRM has also been applied in the renewable energy sector during the creation of energy/national strategies. Lee et al. present an energy technology roadmap for South Korea for the next 10 years in order to provide guidelines for an energy technology development policy [20]. Daim et al. propose a wind energy roadmap for Pacific Northwest and consider environmental concerns, the rising cost of and dependency on fossil fuel, business opportunities, government involvement, and the availability of natural wind resources in the Pacific Northwest as the most important drivers [21]. Daim and Oliver implement a TRM process in the energy services sector, and provide details of energy efficiency roadmaps [22]. The objectives involve creating a consensus among the various stakeholders, agreeing on a common vision, providing guidelines for policymakers and decision-makers, establishing goals and targets, assessing promising technology alternatives, identifying markets, gaps and barriers, formulating strategies and action items to overcome all of these barriers, and improving communication and coordination for technology development in order to increase the future contribution of renewable resources [23].

Although TRM has been applied in many areas, it needs supporting tools to complement the strategic decision-making by using objective data analysis [8]. TRM also suffers from several shortcomings, including the fact that creating a consensus among various stakeholders during the implementation process can prove a difficult task [24]; and also because defining which technological solutions should be selected and the current situation usually depends on experts' intuitive knowledge.

We suggest that some of these shortcomings of TRM might be assuaged by the use of bibliometrics in the TRM process. Principles of bibliometrics are discussed in the following section.

2.2. Bibliometrics for emerging technologies

Bibliometrics is the measurement of literature and information data by using mathematics and statistics to explore, organize, and analyze large amounts of historical data in order to help researchers to identify the "hidden patterns" that may assist their decision-making process [6,25]. Some databases, such as the Science Citation Index and the Engineering Compendex database, can be used for bibliometric analysis [26]. Several analysis tools have been applied in the field of bibliometrics, such as simple document counting, word frequency analysis, citation analysis, co-word analysis, cluster analysis, and cooperation analysis. Some proprietary softwares have been produced for bibliometrics analysis, such as the Thomson Data Analyzer (TDA) developed by Thomson Reuters, CiteSpace [27] developed by Chen, and so on.

Bibliometrics has contributed to science and technology studies for decades [28]. It can help researchers to identify hidden patterns by classifying information according to authors, keywords, phrases, organizations, countries, collaborations, citations, and so on. It has also been widely applied to detect the taxonomic structure of a research domain [29–32] and forecast emerging technologies [7,8]. Daim et al. present a method for forecasting emerging technologies by using bibliometrics and patent analysis [6]. Kajikawa et al. attempt to detect emerging technologies by using citation network analysis, and the result offers an intellectual basis for constructing an energy roadmap [8,33]. Bengisu and Nekhili used science and technology database to forecast emerging technologies with the aid of S-curves [34].

However, one limitation of bibliometric approach has to do with the absence of interaction among experts that is vital to forecast emerging technologies. So in order to have more reliable and effective results, workshop among experts using an expert-based approach is integrated with bibliometric approach to detect emerging research domains and forecast emerging technologies. Kostoff et al. utilize literature-related discovery approach combining literature-based discovery (a bibliometric approach which produces potential discovery through analysis of the technical literature alone) with technical domain experts' knowledge to identify potentially radical improvements in water purification technology [35]. Huang et al. propose a forecasting framework combining bibliometric approach with multi-actor workshop to visualize potential innovation pathways for emerging science and technologies [36,37]. Some researchers in the past have used bibliometrics to detect emerging research domains and forecasting emerging technologies as shown in Table 1.

Some scholars point out that bibliometric approach can be a key component for science and technology roadmapping to construct a reliable roadmap [33], and that the combination of roadmapping with bibliometrics has to be addressed well in advance of the implementation of a roadmapping process [38]. Kajikawa et al. present a computer-based approach using citation network analysis to depict technology trends, and point out that the approach is a powerful tool to support roadmapping [33]. Kostoff et al. propose a systematic approach including literature-, workshop-, and roadmap-based approaches to identify disruptive technologies, and they point out that coupling literature-based discovery with a subsequent workshop/roadmap development process may amplify the strengths of literature/workshop/roadmap techniques [39].

We need to note that bibliometric approach focuses only on science or technology itself [33], while TRM is an activity covering a broader scope including products, markets, policies and strategies. The results of bibliometric analysis don't convey a fruitful insight and outcome on all of those points [33]. So when combining bibliometrics with TRM to predict the future development of emerging technologies or strategize and plan the future development of new technology-based industries, we should try to utilize TRM workshops involving various stakeholders, including technological experts, industrial experts, policy makers, and business managers.

In this paper, bibliometrics is applied to analyze the existing science research position of the technology and identify the national competitive advantage in these research knowledge domains. The adoption of the bibliometric method, which uses quantitative literature data-based analysis to visualize the science and technology status, can significantly reduce the bias due to using experts' opinions that are based on intuitive knowledge when roadmapping the future development from science to market activities. Meanwhile, we note that bibliometrics also suffers from several limitations, which may be listed as follows: (1) not all science and technology

Table 1
Bibliometrics for detecting emerging research domains and forecasting emerging technologies.

Methodologies	Description	Resources
Bibliometrics	Produces potential discovery and explores future possibilities through analysis of the academic publications.	Daim et al. [6], Shibata et al. [7], Kajikawa et al. [8,33], Bengisu et al. [34]
Bibliometrics + Experts' opinions	Produces potential discovery and explores future possibilities through both analysis of academic publications and use of technical domain experts' opinions.	Kostoff et al. [29–32], Kostoff et al. [35,38,39] Huang et al. [36], Robinson et al. [37]

developments are published, not all records are valuable, and counts do not distinguish quality [40] and (2) timely and important information may also be missing due to publishing lag times [2]. Therefore, in our framework, we will combine bibliometrics with TRM workshops to predict the industrial environments and possible events that shape the future growth of emerging technologies.

3. Methodology

Emerging industries have been propelled by science and technology innovation, which stimulate the emergence of new applications, services, or business models. Emerging industries are becoming increasingly complex and dynamic, so policy makers and investors are finding it more and more difficult to make decisions about which strategic directions to pursue and on which technological areas to focus. In order to cope with this complexity, strategic roadmapping frameworks have been widely used to forecast and plan the emergence and development of those new industries — at least 1500 public domain roadmaps have been developed during the last 15 years [41].

There are many methods or processes that can be employed to develop strategic roadmaps. Bibliometrics and the "fast-start TRM workshop" [41–44] are two recognized ones. This paper will develop a framework based on the integration of these two methods to strategize and plan the future development of new technology-based industries, when attempting to fully utilize their advantages and make this framework more valid and reliable — bibliometrics for analyzing the existing position of science and technology, and TRM workshops for strategizing the future development path from technology to application and the market. This combination tends to better address the emergence of technologies, market, industrial settings, and the dynamics between them. The analysis methods used in this paper and the industrial emergence stages are shown in Fig. 1.

Regarding strategic roadmapping, there are three essential questions [14,24,41]:

1. Where are we now?
2. Where do we want to go?
3. How can we get there?

In response to these questions, we design a 3-step framework that integrates bibliometrics and TRM workshops. For new industries that are in the embryonic and nurturing stage, the first question lays greater emphasis on the technological aspects, so we can use the data-based bibliometric method to analyze the existing position of science and technology. In addition, the latter two questions rely on our understanding of complex market and industrial settings, as well as the dynamics for developing the specific technology. This calls for the brainstorming and consensus of industrial experts, policy makers and academics. TRM workshops can provide a valid and reliable process for formulating effective planning and strategizing. The process is depicted as follows (Table 2).

3.1. Step I: Where are we now?

Many emerging industries are in their nurturing or even embryonic phase, as much of the technology is still facing the challenge of improving the reliability or price-performance of new applications [4]. In this phase, the technology should be the focus of analysis, so we use bibliometrics to analyze its R&D status — this method has significantly contributed to technology trajectory studies in recent years, while using the large dataset as an empirical base can complement and enrich the lack of validity arising due to the reliance on experts' judgments.

In this step, we search for specific keywords related to the emerging technology (such as "dye-sensitized solar cell") among the published papers listed on the Web of Science (SCI-EXPANDED) database. The analysis of the changes in the number and frequency of publications over time can increase our understanding of the R&D activity.

Therefore, the first step in our framework will help us to understand the past trajectory of dye-sensitized solar cell technology in a global sense, and to elucidate the existing position of China's innovation — is China still lagging behind and trying hard to catch up, or is it already among the leaders? The adoption of the bibliometric method, which uses quantitative-data based analysis for trajectories mapping, can significantly reduce the bias arising from using experts' opinions which are based on intuitive knowledge.

3.2. Step II: Where do we want to go?

In order to strategize the emergence and growth of a new industry, technology is not the only push factor that needs to be considered. Specifically, we may need to take into account the macro-level influential factors such as market trends, government policies, and industrial competition [4]. Bibliometric analysis can only employ the dataset of published papers (in the past) for analyzing the technology trajectory [45]; in addition, timely information may also be

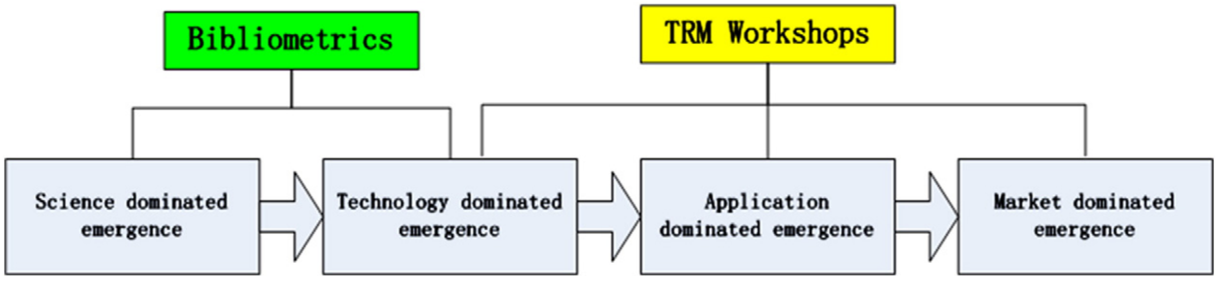

Fig. 1. Analysis methods and industrial emergence stages.

Table 2
An integrated TRM framework: combining bibliometric analysis with TRM workshops.

Methods	Objectives and analysis	Data sources and workshop experts
Step I. Bibliometric analysis	Science and technology position: R&D activity levels and key domains in the world and in China Analyze the R&D status of dye-sensitized solar cells in China	Data sources: Web of Science — SCI-EXPANDED database.
Step II. Workshop I	Industrial context: market, policy, industry dynamics. Elicit the future macro-level events and settings that might influence the PV market and the development path of the dye-sensitized solar cell technology-based industry in China, including the key scenarios of renewable energy development, and the dimensions and landscape of the roadmap	Workshop participants: experts from energy companies (e.g. Shenhua group and Huaneng group), government officers from NDRC, the State Grid, etc., academics from CAE, THU, etc.
Step III. Workshop II	Future development: roadmapping the future trajectory of dye-sensitized solar cell technology-based industries in the embryonic/nurture/mature stages 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 dye-sensitized solar cell technology-based industry in China	Workshop participants: leading Chinese experts on dye-sensitized solar cells in China, including Prof. Dai Songyuan, Dr. Sun Honghang, etc.

missing due to publishing time lags [2]. Therefore, our framework needs to compile experts' judgments to predict the future industrial environment and possible events that may shape future growth.

In this step, we use the fast-start workshop approach [42–44], which is based on existing practices that have been published, to conduct the analysis from multiple perspectives. This workshop has been used in order to identify the macro-level settings and possible future events (as opportunities, enablers, or barriers) both related to the general Chinese PV industry development, and the specific dye-sensitized solar cell technology. The workshop was organized in May 2013, and was supported by the National Institute of Clean-and-Low-Carbon Energy (Shenhua Group) and the BP center at Tsinghua University. Eleven leading experts in China on the coal and renewable energy domains were invited to contribute comments to this workshop (among those experts were Dr. Liu Ke, Dr. Tian Yajun, Dr. Wu Juanni and Mr. Lu Haiyun from the Shenhua Group, Mr. Huang Bin from the Huangneng Group, Prof. Liu Pei from Tsinghua University (THU), Dr. Zong Yusheng from the Chinese Academy of Engineering (CAE), Dr. Zhao Xingang from the National Development and Reform Commission).

During the workshop, the experts discussed the future scenarios of macro-level settings, focusing on the key impact factors and growth uncertainty that may influence the future development of the PV industry and new PV technologies, like dye-sensitized solar cells. The workshop enhanced our understanding of the potential external enablers and barriers in the future, which may propel or thwart the emergence and growth of the new solar cell technology. The employment of this fast-start workshop brings rich data and judgments about future scenarios, based on the experts' intuitive knowledge (which computers could not come up with).

3.3. Step III: How can we get there?

According to Hill et al. [46], the general strategic process includes five major steps: (i) select the mission and major goals; (ii) analyze the external competitive environment to identify opportunities and threats; (iii) analyze the internal environment to identify its strengths and weaknesses; (iv) create strategies that build on the strengths in order to take advantage of the external opportunities and counter barriers; and (v) implement the strategy. Echoing this, for strategic roadmapping, the question of "how do we get there?" can be broken down into the following sub-questions [4]: (i) what are the opportunities and resources that can help us to overcome the barriers? And (ii) what are the threats and weaknesses that prevent us from doing so?

In order to address these questions for emerging industries, we can ask experts (either on the specific technology or on the whole industry domain) to use their intuition and knowledge to strategize and roadmap the future development trajectory in the embryonic/nurture/mature stages, based on previous analyses of the external and internal settings: a review of the external industrial environment for opportunities and treats (from step II), and an analysis of the internal settings, like the existing technology path (from step I).

In this case, we asked six experts of dye-sensitized solar cell technology and industry in China to roadmap the future development of this area in the light of the identified key opportunities and past trajectory. One of the experts, Prof. Dai Songyuan has published many SCI papers related to dye-sensitized solar cells according to the results of bibliometric analysis. Other experts include Prof. Liu Pei from the BP center at Tsinghua, Dr. Sun Honghang from the Ministry of Science and Technology, etc. These experts have an in-depth understanding of dye-sensitized solar cell technology, and so are able to make judgments and forecasts based on their domain expertise. In addition, all of these experts acknowledge that the previous bibliometric analysis and workshop outputs provide a very solid basis, helping them to solidify their ideas for strategizing the future path.

4. Case study

4.1. Background: The solar photovoltaic industry in China

In the context of the growing energy demand and the progressive depletion of fossil energy, solar energy, as a clean, renewable energy, has become one of the favored new energies for human energy applications. Solar photovoltaic (PV) power generation is one of the strongest technologies for solar energy applications. The solar PV industry has been supported by many countries' government around the world, and has become one of the fastest growing new industries.

China's solar PV power generation started in the 1960s and after a long period of development, made tremendous progress, which has been particularly rapid during the last 10 years. In 1968, the first single-crystalline-silicon solar cells were developed and manufactured in China. In the early 1970s, solar cell production was developed for space. In the late 1970s, solar cell production was developed for ground use, and a few solar cell factories were set up in Shanghai, Ningbo and Kaifeng. In the early 1980s, China imported a production line for solar cells, and established the first monocrystalline silicon cell manufacturing plant. In the late 1980s, China's solar cell annual production capacity was 4.5 MWp, which capacity continued until 2002 [47]. The Suntech Company and Yingli Green Energy Company both constructed a 10 MWp solar cell production line in 2002 and 2003, respectively. Since then, China's solar cell annual production has increased significantly. According to the data from the European Commission Joint Research Centre (ECJRC) [48], in 2007, China's solar cell annual production was 1070 MW, occupying the top position among PV-producing countries, in 2010, it increased to 10.8 GW, accounting for 43% of global production.

Since 2000, China's solar PV power has been developing rapidly and the installed capacity is increasing constantly. According to data from the International Energy Agency (IEA, 2011) [49], China's solar PV annual installations in 2001 were 4.5 MW, increasing in 2010 to 500 MW, and China's solar PV cumulative installations in 2001 were 23.5 MW, increasing in 2010 to 800 MW. From 2001 to 2010, the average annual growth rate of annual installations was about 48%, and the average annual growth rate of cumulative installations was about 27%.

Although China's solar PV industry has experienced rapid progress in the last 10 years, there have been a number of problems in the PV industry. One of these is the weak PV R&D capability, another is the insufficient budget for public PV R&D. As the R&D related to elemental and next generation technologies for reducing PV costs as accompanied by technical risks and market uncertainty, many countries provide public funding for PV R&D programs. Although some public universities and public research institutions in China participate in PV R&D, the annual budgets are comparatively smaller. In 2008, the public budget for PV R&D in China was €4.54 million [50], equal to 5.45% of that in USA or 7.64% of that in Germany. Compared to other countries (IEA, 2009) [51], China was ranked 12th in the list of 17 countries [50].

The lack of sufficient public PV R&D funding led to slow progress in the cost reduction of China's PV technology, impeding the healthy, sustainable development of China's PV industry. The manufacturing technology related to purified polysilicon was lacking in China until 2007, while it was feasible to import a production line or technologies such as wafers, cells and modules from the United States, Germany, Japan or other developed countries. However, the core PV technology and key PV manufacturing technology were blocked by these countries from reaching China. Furthermore, few enterprises participated actively in R&D, and some Chinese enterprises, driven by the promise of high profits, were eager to enter the PV industry and quickly launch a PV project despite the incomplete PV manufacturing technology related to PV production, which lead the PV industry in China into a state of high energy consumption and high pollution.

The solar PV industry is a technology-based industry. If China's solar PV industry wishes to maintain its healthy, sustainable development, China needs to master the key, core technology of the industry in the global innovation race. Although, since 2000, China's solar PV power generation technology development has improved dramatically, with technological advances in the efficiency, reliability, and pollution level of PV cells and PV power generation systems, China still lags behind developed countries such as the USA and Japan in terms of cell and component efficiency, production equipment technology, and testing technology [47]. Therefore, it is first necessary to analyze the changes and future trends related to global solar PV technology and the advantages of China in the solar PV technology field in order to provide a foundation for understanding the future development of China's solar PV industry.

4.2. An analysis of dye-sensitized solar cell technology based on bibliometrics

Currently, there are different solar cell technologies employed in the solar PV industry, such as polysilicon solar cell technology, cadmium telluride solar cell technology, copper indium gallium selenide solar cell technology, gallium arsenide solar cell technology, copper indium selenide solar cell technology, and dye-sensitized solar cell technology [52]. All of these technologies have their own technological trajectory in the solar PV industry and support its development. Since solar PV technologies are rapidly evolving and China lags behind developed countries with regard to silicon-based PV technologies, it is very important for China to determine which emerging PV technology-based industries are best suited to its future development in order to achieve competitiveness and sustainable development around the world.

Dye-sensitized solar cell technology was developed by Michael Grätzel in 1991 [53]. Being low-cost, highly-efficient, simple to process and stable, it is considered a promising technology in the future PV paradigm [54]. Shibata et al. performed a case study of a solar cell to develop a method for detecting the gaps between science and technology by employing a combination of citation analysis and expert-based approaches [8]. They found that there were no patent clusters corresponding to the scientific research fronts (namely, dye-sensitized solar cells), and pointed out that the research area could have industrial potential because these academic research projects could potentially be industrialized. Their results could provide an intellectual basis for the nation to construct an R&D strategy or policy related to the solar PV industry.

Therefore, it is necessary to determine China's R&D status in the field of dye-sensitized solar cell technology. This paper applies the bibliometric method to analyze China's basic science research status in the field of dye-sensitized solar cell technology. The number of papers, research organization co-occurrence, research hot point and international cooperation analyses related to dye-sensitized solar cell technology based on the bibliometric method will be discussed in the following section.

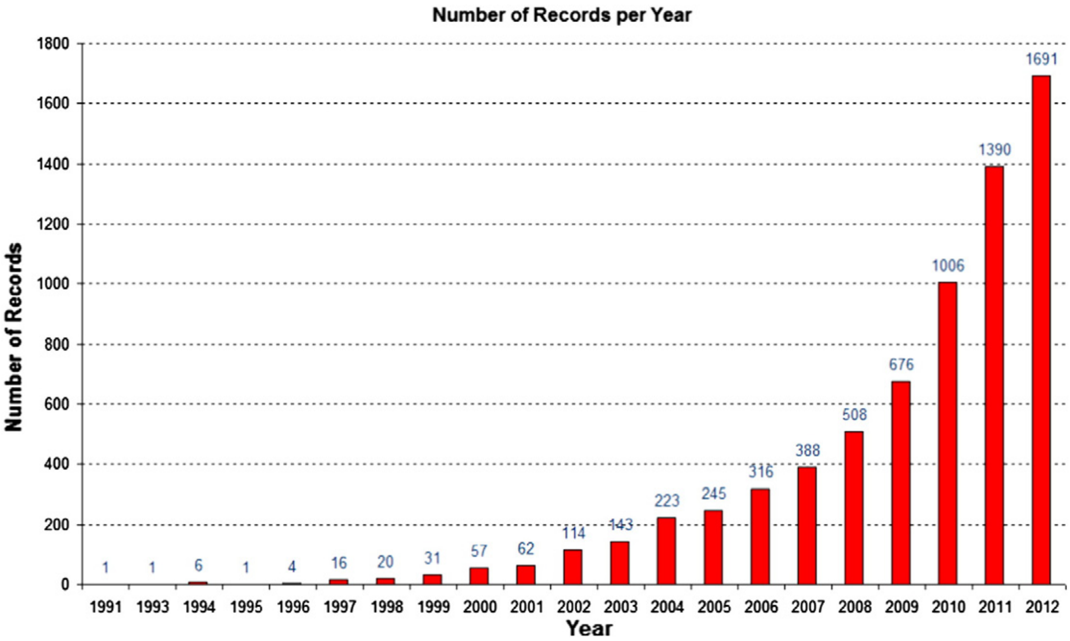

Fig. 2. Annual number of SCI papers related to dye-sensitized solar cells.

4.2.1. Data collection

This paper uses the term "solar cell" as the query to search published papers on the Web of Science (SCI-EXPANDED) database. 56,148 published papers were retrieved from the database from 1974 to 2012. After that, 6899 published papers were retrieved by using the term "dye-sensitized solar cell" as the query. The annual number of SCI papers related to dye-sensitized solar cells is shown in Fig. 2.

4.2.2. Data analysis

4.2.2.1. Paper number analysis. In order to analyze the 6899 SCI papers related to dye-sensitized solar cells, they were imported into the Thomson Data Analyzer. The years range from 1991 to 2012, and the dye-sensitized solar cell technology trend report was produced by the Thomson Data Analyzer automatically. The date of the report creation is December 11th, 2013.

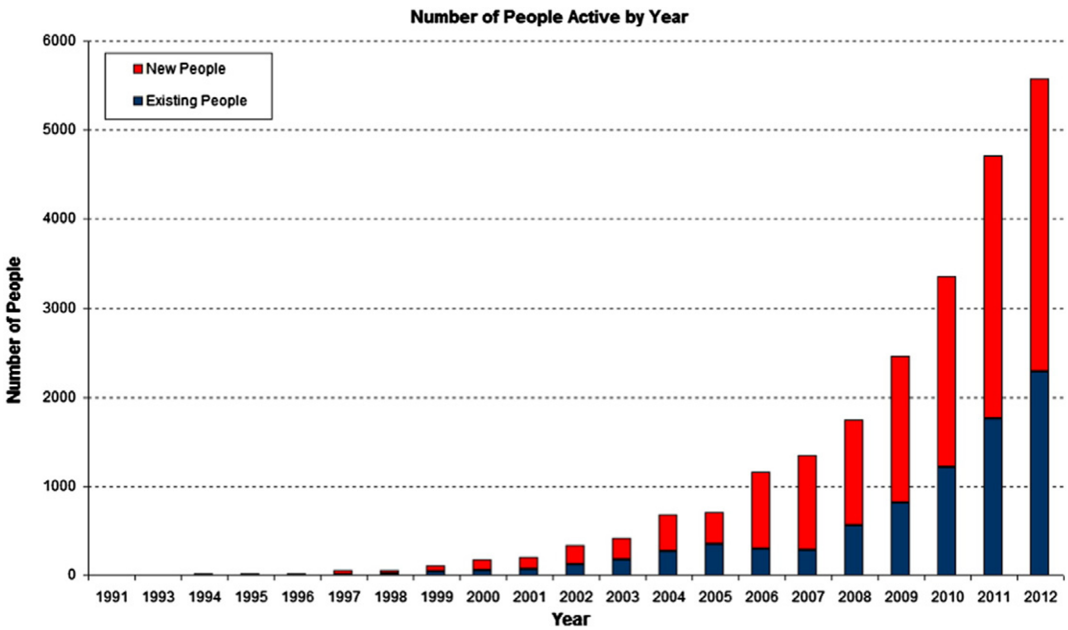

Fig. 3. Annual number of people active related to dye-sensitized solar cells.

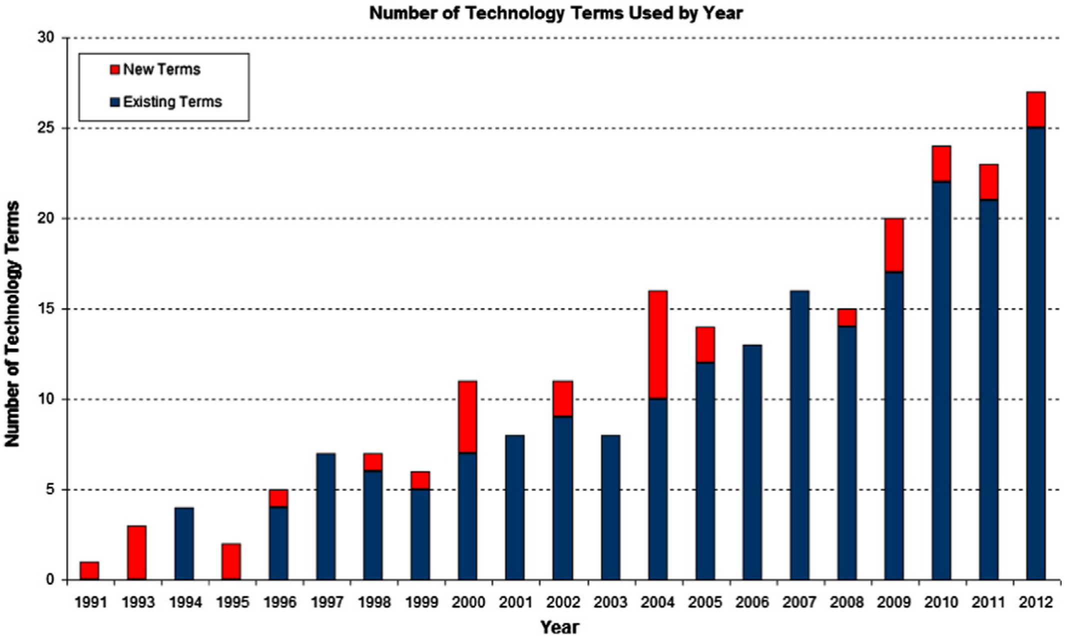

Fig. 4. Annual number of technology terms related to dye-sensitized solar cells.

The annual numbers of people active and technological terms related to dye-sensitized solar cells are shown in Figs. 3 and 4 respectively, with the SCI paper numbers related to dye-sensitized solar cells by country and year in Fig. 5. The percentage of SCI paper numbers related to dye-sensitized solar cells by country is shown in Fig. 6.

As can be seen in Fig. 3, many new researchers have studied dye-sensitized solar cells. Besides, Fig. 4 indicates

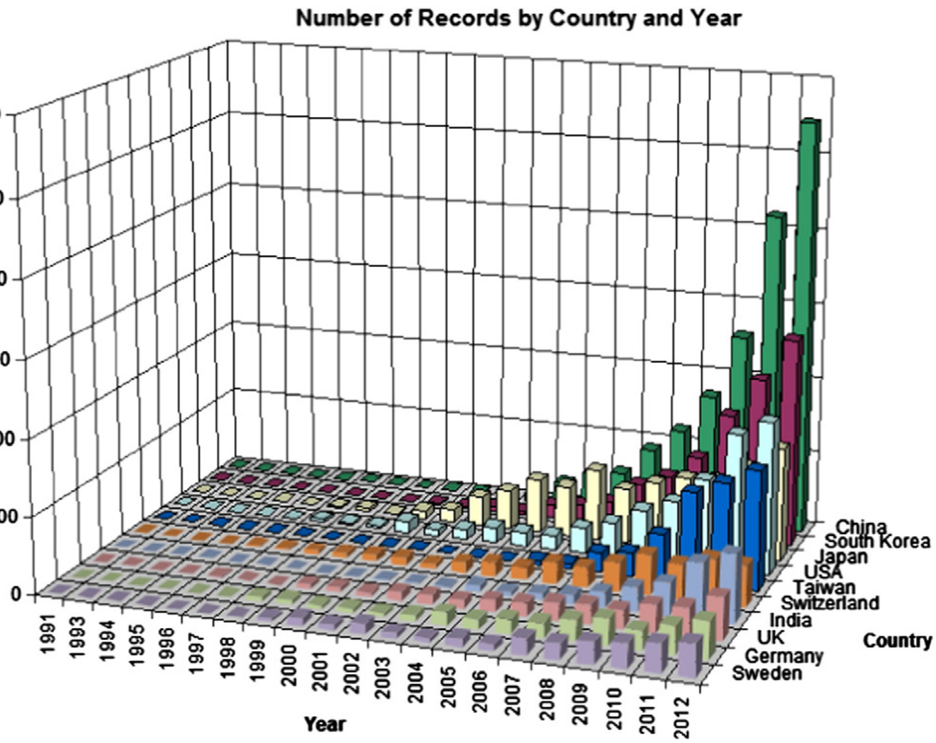

Fig. 5. SCI paper numbers related to dye-sensitized solar cells by country and year.

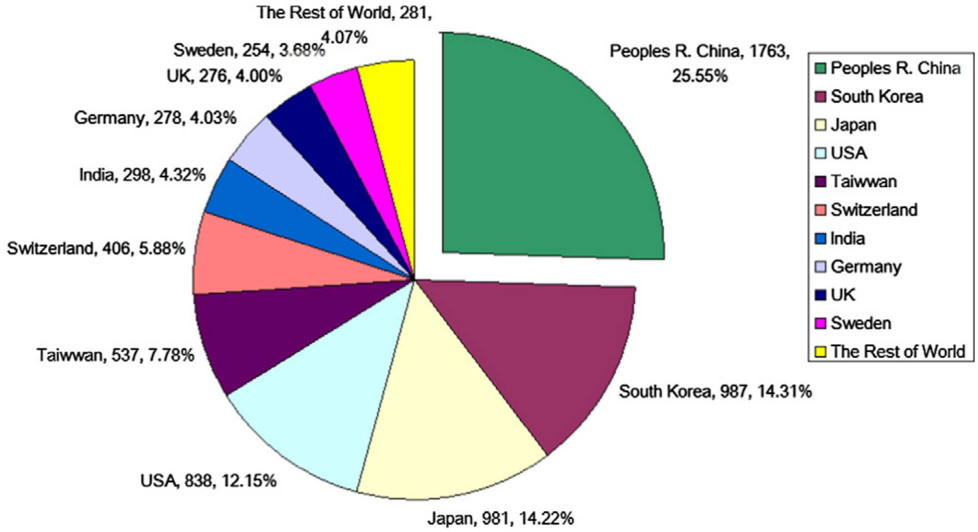

Fig. 6. The percent of SCI paper numbers related to dye-sensitized solar cells by country.

that large numbers of new technology terms appeared after 2008. This shows that the research field of dye-sensitized solar cells has been very active in the last five years.

As can be seen from Fig. 5, from 1997 to 2012, the number of China's annual SCI papers on dye-sensitized solar cells increased constantly and since 2007, has outstripped that of developed countries such as the USA and Japan. Also, from the SCI papers' publication time, we can see that China started to research dye-sensitized solar cells at almost the same time as the developed countries.

The total number of China's SCI papers had reached 1763 by the end of 2012, accounting for 25.55% of global numbers (Fig. 6).

4.2.2.2. Research organization co-occurrence analysis. In order to analyze the research organization co-occurrence and research hot point of dye-sensitized solar cells, Ucinet software was used in this paper. The steps taken to analyze the research organizations' co-occurrence related to dye-sensitized solar cells were as follows. Firstly, the 6899 published papers were imported into TDA software, and an organization co-occurrence matrix was constructed based on the organization cleared data. Then, it was imported into Ucinet software. Finally, the results are shown in Fig. 7.

In Fig. 7, the nodes represent different research organizations, and the size of the nodes represents the number of published papers. The links between the different nodes represent the cooperation existing between the organizations, and the thickness of the link represents the cooperation frequency.

As can be seen from Fig. 7, the four bigger nodes represent the Chinese Academy of Sciences, Ecole Polytech Fed Lausanne, the National Institute of Advanced Industrial Science and Technology, and the Swiss Federal Institute of Technology, respectively, which means that these four research organizations published the most SCI papers. The links from the node (the Chinese Academy of Sciences) to many different nodes shows that the Chinese Academy of Sciences engages in considerable cooperative researches with many other international research organizations, and has developed a closed cooperation with the Swiss Federal Institute of Technology and Ecole Polytech Fed Lausanne, in which both organizations are better at researching dye-sensitized solar cell technology.

As can be seen from Fig. 7, in addition to the Chinese Academy of Sciences, there are many Chinese research organizations, such as the Tsinghua University, Dalian University of Technology, and Huaqiao University, indicating that these organizations have also engaged in the study of dye-sensitized solar cell technology. In particular, the Dalian University of Technology engages in close cooperation with the Royal Institute of Technology and Uppsala University over research into dye-sensitized solar cell technology.

The top ten research organizations related to dye-sensitized solar cells are shown in Table 3, which shows that the Chinese Academy of Sciences has published the largest number of SCI papers, and that it started to research dye-sensitized solar cells in the 1990s, almost as early as the earliest organizations, such as the Swiss Federal Institute of Technology and Uppsala University. It also shows that the Chinese Academy of Sciences has published a large number of SCI papers in the last three years. The main two people engaged in the study of dye-sensitized solar cell technology at the Chinese Academy of Sciences are Wang Peng and Dai Songyuan, who have published 52 and 35 SCI papers respectively. The latter was invited to participate in our workshop as a technology expert.

4.2.2.3. Research hot point analysis. In general, the word with the highest frequency indicates that this word attracts the highest degree of concern, and represents the research hot point in the field [55].

The 4087 SCI papers were selected from the 6899 papers from 2010 to 2012. These were then imported into CiteSpace software for keyword co-occurrence analysis. The threshold in the analysis interface zone was set (35, 8, 20) in order to produce a clear display, and the analysis function of keyword co-occurrence was selected to analyze the literature. The results are shown in Fig. 8.

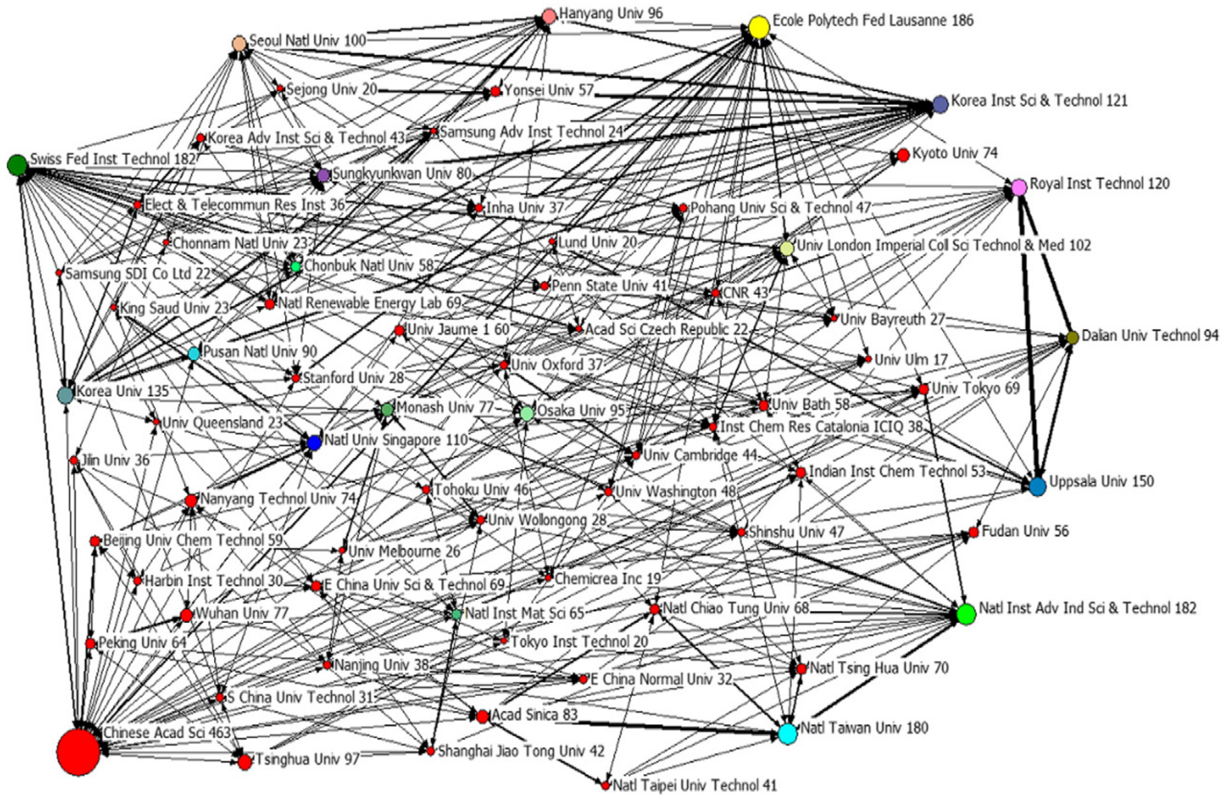

Fig. 7. The mapping knowledge domains of research organizations related to dye-sensitized solar cells.

In Fig. 8, the different colors on the top banner represent different times, and the gradation from cool colors on the left to warm colors on the right means that time is moving from the past towards the present. The nodes represent different keywords. The name of the keyword is displayed on the right side of the node. The size of the node represents the appearance frequency of the node. The link between different nodes means that co-occurrence exists between the keywords, and the color of the link represents the time at which the first co-occurrence occurred.

As can be seen from Fig. 8, the top three high frequency nodes linked with dye-sensitized solar cells are films, efficiency and performance. The top ten frequency keywords are shown in Fig. 10.

Table 3
The top ten research organizations with regard to dye-sensitized solar cells.

Number of records	Organization name	Country	Top people	Year range	Percentage of records in last 3 years
463	Chinese Acad Sci	China	Wang, Peng (52); Dai, Songyuan (35)	1997–2012	53% of 463
186	Ecole Polytech Fed Lausanne	Switzerland	Graetzel, M. (146) Zakeeruddin, S.M. (53)	1996–2012	46% of 186
182	Natl Inst Adv Ind Sci &Technol	Japan	Hara, Kohjiro (30); Arakawa, H. (27)	2001–2012	42% of 182
182	Swiss Fed Inst Technol	Switzerland	Graetzel, M. (162); Zakeeruddin, S.M. (49)	1991–2012	32% of 182
180	Natl Taiwan Univ	Taiwan	Ho, Kuo-Chuan (108); Lee, Chuan-Pei (33)	2005–2012	74% of 180
150	Uppsala Univ	Sweden	Hagfeldt, A. (72); Boschloo, G. (46)	1994–2012	44% of 150
135	Korea Univ	South Korea	Ko, J. (52); Kim, K.J. (29)	2000–2012	49% of 135
121	Korea Inst Sci &Technol	South Korea	Park, N.G. (35); Kim, K. (27)	2004–2012	59% of 121
120	Royal Inst Technol	Sweden	Hagfeldt, A. (68); Boschloo, G. (41)	2003–2012	52% of 120
110	Natl Univ Singapore	Singapore	Ramakrishna, S. (27); Liu, Bin (18)	2004–2012	83% of 110

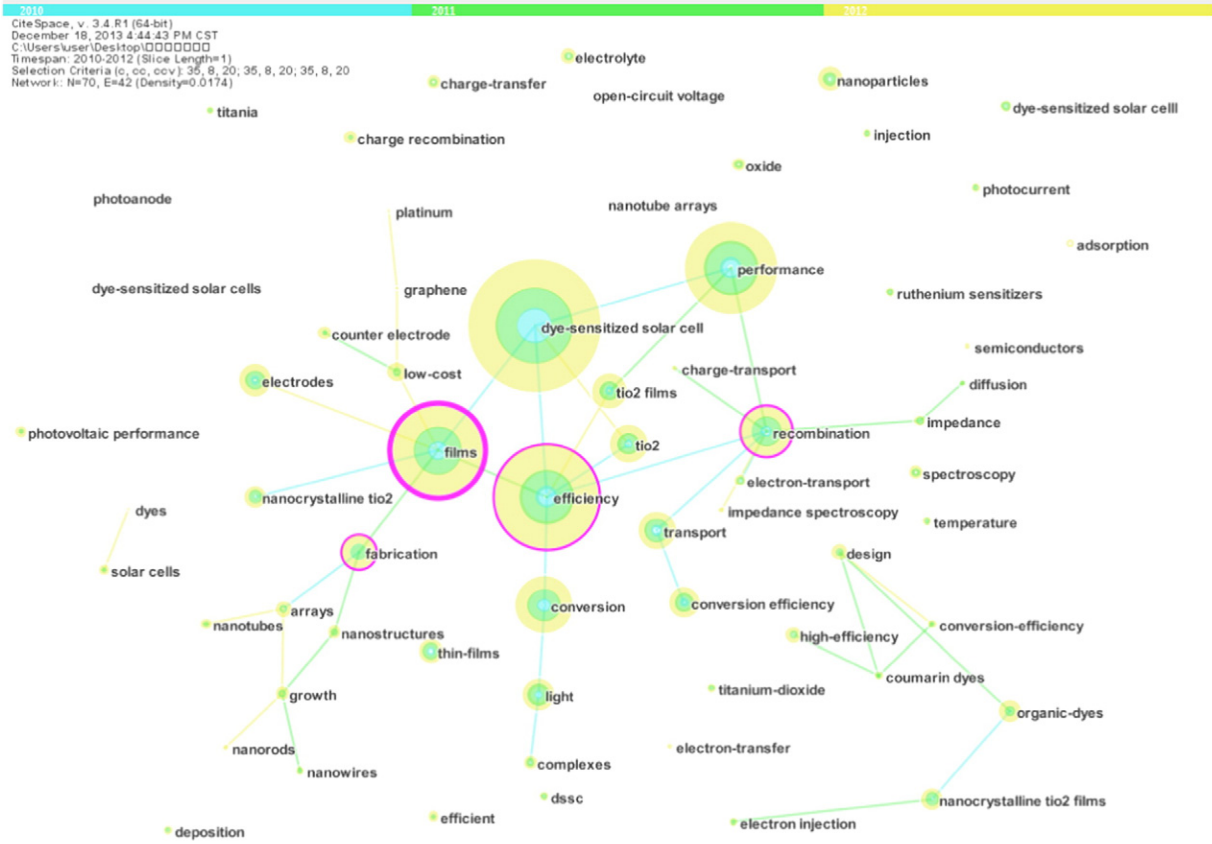

Fig. 8. The mapping knowledge domains of global research hot points related to dye-sensitized solar cells.

At the same time, China's 1224 SCI papers were selected from the 1763 papers from 2010 to 2012. The same steps as for the global research hot point were implemented, apart from a different threshold being set (20, 5, 20). The results are shown in Fig. 9, and the top ten frequency keywords are shown in Fig. 11.

As can be seen from Figs. 8–11, China's research hot points for dye-sensitized solar cells are almost similar to the global ones.

4.2.2.4. International cooperation analysis. As scientific knowledge rapidly develops, given the limitations of the national research resources of each country around the world, international cooperation research plays an important role in improving the level of scientific research and innovation capability.

In order to determine the status of China's international cooperation research in the field of dye-sensitized solar cells, it is necessary to analyze the international cooperation research network. To achieve this, Ucinet software was also used in this section. The steps were as follows. Firstly, the 6899 published papers were saved as a txt file. The author's country and the country cooperation matrix of each paper were extracted using TDA. Then, the data about the country cooperation matrix were imported into Ucinet software. Finally, the international cooperation research network of dye-sensitized solar cells was drawn using Ucinet software. The result is shown in Fig. 12.

In Fig. 12, the nodes represent countries. The name of the country is displayed to the right of each node. The size of a country's node represents the total number of countries that cooperate with it. The link between the different nodes indicates the cooperation relations between the countries, and the thickness of the link represents the frequency of the cooperation.

As can be seen in Fig. 12, the top three countries regarding cooperation frequency are China (404), the USA (370) and Switzerland (354) respectively. China has cooperated with many countries to research on dye-sensitized solar cell technology, particularly Japan, Sweden, Switzerland, the USA and South Korea. This shows that China has engaged in the highest level of international cooperation with regard to research into dye-sensitized solar cell technology.

4.2.3. Overall result analysis

From the results of the paper number, research organization co-occurrence, research hot point and international cooperation analyses of dye-sensitized solar cell technology based on bibliometrics, it is clear that the research on this field has been very active in recent years. Since 2007, China has produced more annual SCI papers than developed countries such as the USA and Japan; China started to research dye-sensitized solar cells at almost the same time as the developed countries; the Chinese Academy of Sciences has published the most SCI papers and engaged in cooperative research with the

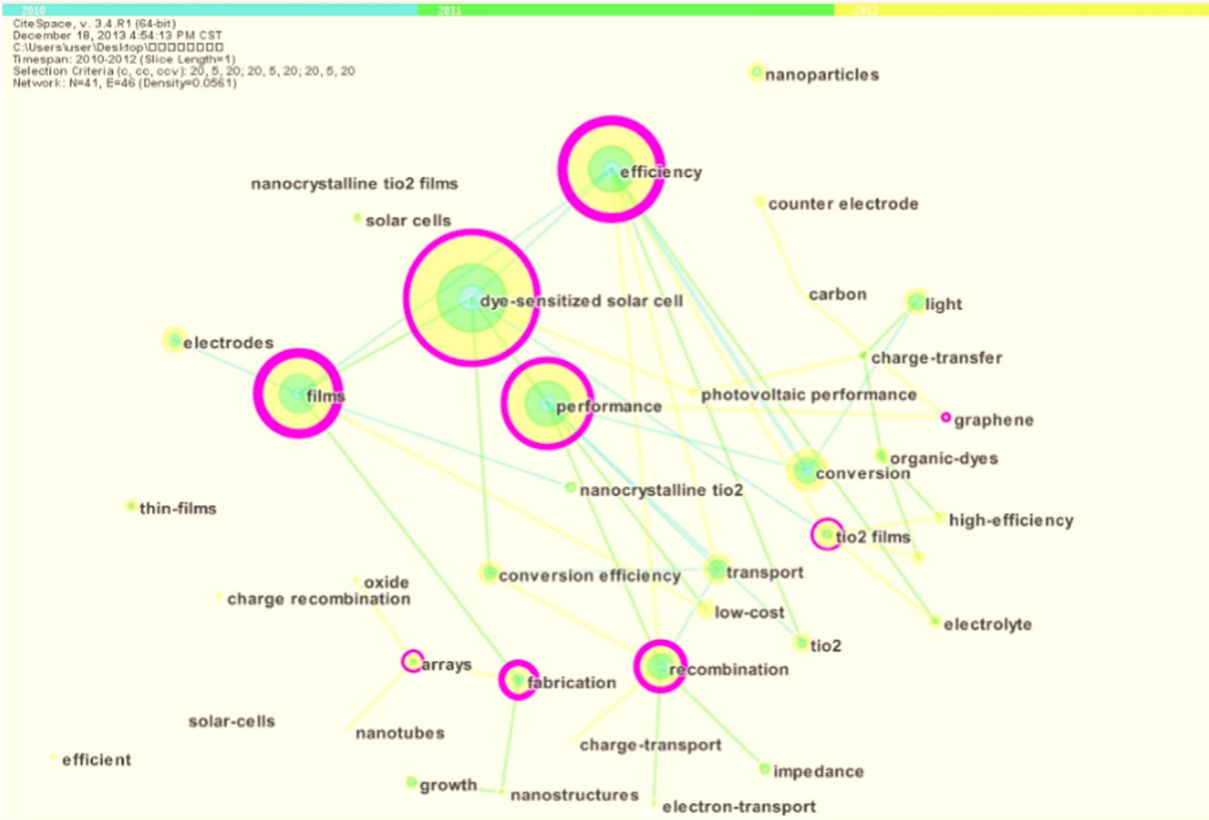

Fig. 9. The mapping knowledge domains of China's research hot points related to dye-sensitized solar cells.

highest number of international research institutions; China's research hot points for dye-sensitized solar cells are similar to the global ones; and China has engaged in the highest level of international collaboration research in this field. This means that China has been at the international forefront with regard to research into dye-sensitized solar cell technology, which has provided a solid base for it to develop its dye-sensitized solar cell technology-based PV industry in the future. Therefore,

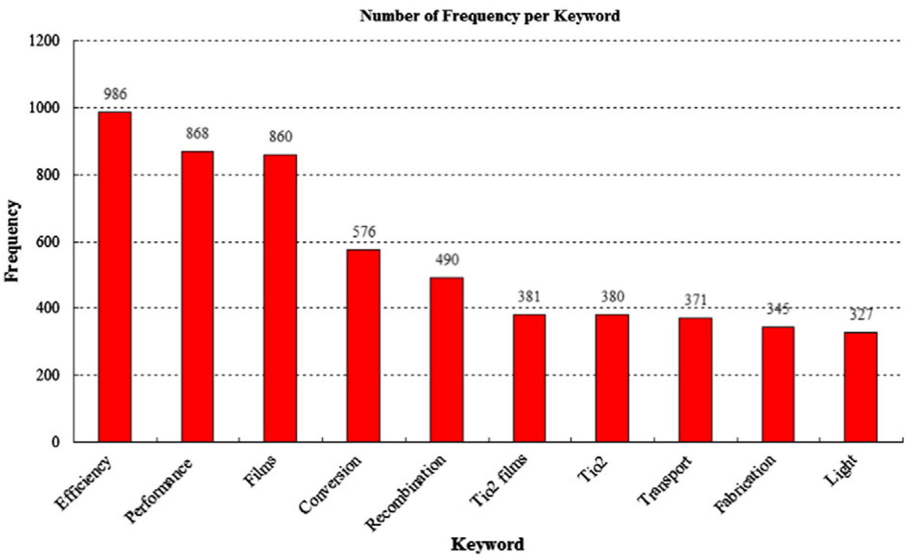

Fig. 10. The top ten frequency keywords related to global dye-sensitized solar cells.

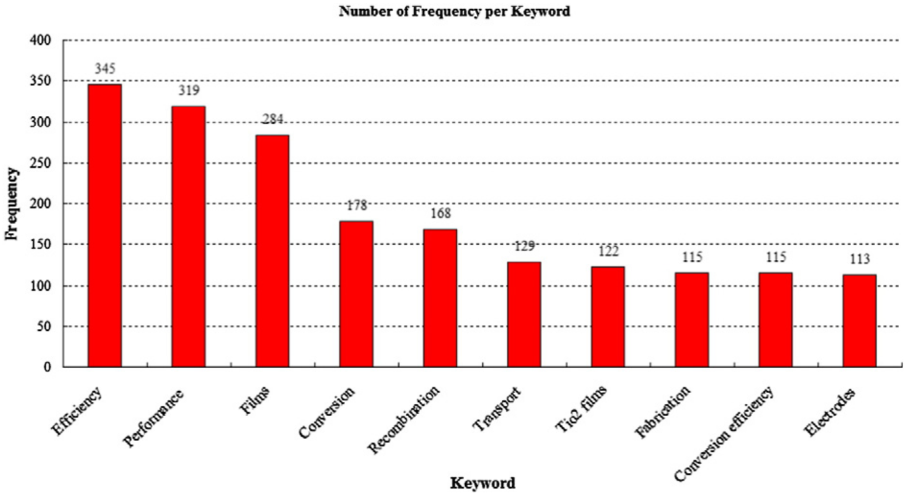

Fig. 11. The top ten frequency keywords related to China's dye-sensitized solar cells.

based on these results, we will apply TRM to strategize and plan the future development of the dye-sensitized solar cell technology-based PV industry in China.

4.3. The TRM workshop on future events in the macro-level settings: Market, policy, and industry dynamics

This half-day workshop adopted the fast-start strategic roadmapping method [43], with minor revisions to suit Chinese culture and behavioral protocols. This workshop helped to identify the key external factors that may shape the growth of this emerging industry, from which the authors compiled outputs and gathered essential information for the next step. The process is depicted as follows:

1. Planning: basic logistics and roadmap process architecture.
2. Workshop stage: developing the key dimensions for future planning; identifying and prioritizing the strategic opportunities and barriers; then discussing the opportunities and barriers in more depth;

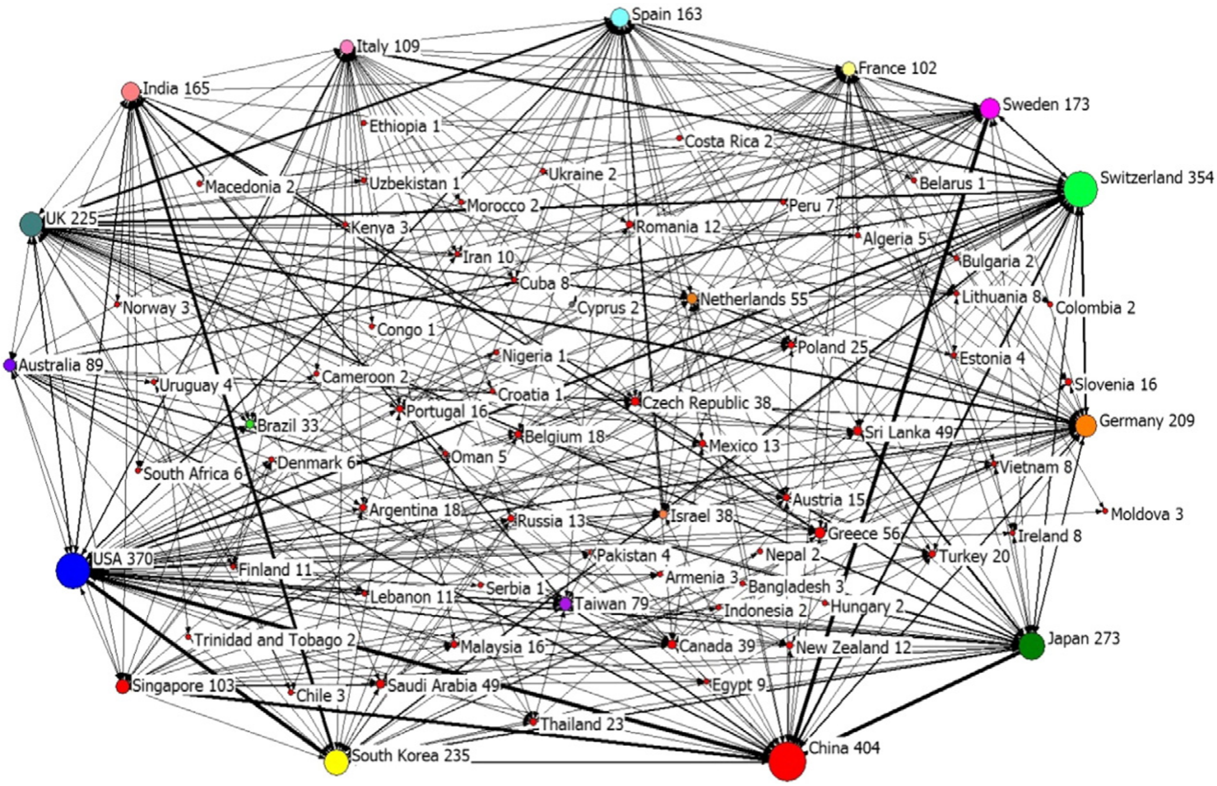

Fig. 12. The mapping knowledge domains of international collaboration related to dye-sensitized solar cells.

Table 4
Dimensions and key events (factors) of macro-level settings.

Dimensions	Key events	Controversy	Location	Time
Policy	Global energy landscape change: US rises	Low	Global	2015–2020
Policy	Strengthening the environmental policy, encouraging clean energy technologies, including clean coal (China), renewable, gas, etc.	Low	Global and China	2013–2020
Policy	Carbon tax and carbon trade exchange (open market)	High	China	2015–2020
Policy	Tight control on coal usage and other high-power consumption industries	Low	China	2013–2030
Policy	Energy price de-regulation	High	China	2020–2030
Market	Rapid energy consumption increase	Low	China	2015–2025
Market	Boom in the renewable energy market with the removal of government subsidies	High	Global	2020–2030
Market	China's finance energy and trading market link to global power trading systems	Low	China	2020–2030
Market	Energy security issue: hikes in oil prices, and import channels becoming unstable	High	China	2020–2030
Industry dynamics	Impacts of alternative energy and related products (e.g. cheap gas turbines and offshore wind power)	Low	China	2020–2030
Industry dynamics	Shale gas becomes widely exploited	Low	Global	2015–2025
Industry dynamics	Smart grid and control technologies developed and deployed, to optimize the power grid system and distributed PV network	Low	China	2020–2030
Industry dynamics	Existing PV technologies proved to have performance limits, new PV technologies need to take over	Low	Global	2020–2030

3. Review: mapping the key events (market, policy, and industry dynamics) that are important to the PV industry and dye-sensitized solar cell technology.

For the planning session, we prepared a process handbook and related domain data/information for the experts, in order to provide them with a solid basis for in-depth discussion and seeking to avoid key information being lacking. The first part of the workshop was intended to develop the key dimensions that are significant for the emerging renewable energy industry, such as the PV industry. Following the experts' opinions and our previous practice [56–58], the key dimensions of the macro-level settings (Table 4) were defined as the political and policy regulations (policy), the market trends and finance (market), and the industry ecosystem and competition (industry dynamics).

In the second part of the workshop, we encouraged the experts to brainstorm and elicit possible future events from the above policy, market, and industry dynamics perspectives. The experts did not differ significantly over the policy and market dimensions, but did have many inputs to break down the industry dynamics dimension further, as follows: industry competition (e.g. price-performance of alternatives), competing technologies (e.g. shale gas, oil, clean coal, nuclear), supporting technologies (e.g. grid connection and energy storage), and infrastructure (e.g. smart grids). Further, we asked each expert to identify the five most significant future events with details of their significance, uncertainty, location, and time, and add the notes to the roadmap template. After each expert had finished elaborating these key events, we organized a discussion session to prioritize and highlight the events according to their significance and uncertainty. More than 30 events were listed, and further processed the data to make them more succinct and easier to use in the next workshop.

In the reviewing session after the workshop, we compiled the insights that had been produced and validated by the experts' discussion. We counted those key events (or factors) that are highly likely to occur. Highly uncertain events were excluded (e.g. the maturity of nuclear fusion/carbon capture and storage technologies/energy storage technologies by 2030), although these may cause disruption that alter the path of the PV industry. These may need scenario-planning in further workshops, but were set aside at present due to the limited time. Meanwhile, we considered the specific events about which the experts disagreed — from different perspectives, experts view things differently. We attempted to facilitate discussion to resolve these controversies; however, some disparities remain with regard to the timing of events. In this case, as long as the experts agree on the significance and certainty of future events, we tend to leave discussion about the timing of these events for future research. In addition, many events have been combined (for example, the adoption of “cheap gas turbines” and “offshore wind power” have been placed together under one event: “the impacts of alternative energy products”).

The summarized output of this workshop is depicted in Table 4. As mentioned above, only the most important events (as opportunities or barriers) remain on the list. Based on this, the authors further explored and planned the future trajectory of the dye-sensitized solar cell industry in China through a second workshop.

4.4. TRM for the future development of the dye-sensitized solar cell technology-based PV industry in China

In this step, we organized a small-scale, half-day workshop (workshop II) in order to roadmap the future development of the dye-sensitized solar cell technology-based industry in China. For this workshop, we invited dye-sensitized solar cell technology experts in China with different perspectives, including technology experts, policy makers, academics, etc. (see the Methodology section). A self-organized discussion was facilitated,[2] covering technology, policy, and the market/industry dynamics, and finally we focused on the production perspective to define the emergence path when considering the impact factors and dynamics. In this case, we used IT technology and newly-developed roadmapping software to

[2] A group of five individuals can be called a small group, which can self-organize a discussion rather than a guided or orchestrated discussion [43], like in workshop I.

slightly modify the traditional stickers/posters and facilitate the discussion. The future development roadmap of the dye-sensitized solar cell technology-based PV industry in China is shown in Fig. 13.

Following workshop I, we use the timeframe from 2013 to 2030. Firstly, we shortlist the macro-level events, and remove some events that may have a less direct impact on dye-sensitized solar cell technology-based industry development. Nine events are used in our final roadmap, in the dimensions of policy, market and industry dynamics (Fig. 13). Secondly, for the technology dimension, we attempt to project the technology trajectory based on the existing science and technology background. According to the earlier bibliometric analysis (Section 4.2), China is one of the leaders in the research on dye-sensitized solar cells in the global innovation race — therefore, it is unnecessary specific to indicate the R&D progress or standard at the global or national level. According to the experts' opinions, China has a solid basis for science and technology in this domain, so it can keep up with the global development pace and possibly achieve the conversion rates of 10%–12% around 2020 and 15% around 2025. In addition, based on the keywords identified through the bibliometric analysis, the experts projected that some of these will form the subject of future R&D foci in the next 20 years (at different time phases), such as efficiency, performance, organic-dyes, and fabrication (Fig. 13).

Finally, we attempt to plot the future emergence path of the dye-sensitized solar cell technology-based industry in the production dimension of the roadmap. According to the experts' opinions and Chinese policy language, we decide to use four processes to map the industrial emergence, including industrial R&D (R&D), public demonstration projects (demonstration), early-stage commercialization with infrastructure construction (commercialization), and large-scale commercialization with rapid growth in the mass market (large-scale commercialization). These four processes may overlap in reality, but we still plot them in the time-series for clarity reasons.

On this roadmap, the industrial R&D process may be replaced by a demonstration process before 2020, and this period (e.g. 2018–2023) may be viewed as a transition between the industrial embryonic phase and the nurture phase. During this period, mass government-funded demonstration projects will be launched due to the following factors: (i) technology: the conversion rate will reach 18%–20% in labs and 10–12% in real industry, which can start to challenge the thin-film technology; and (ii) policy/market/industry dynamics: with the increasing investment flow into the PV sector, dye-sensitized solar cell technology can attract more

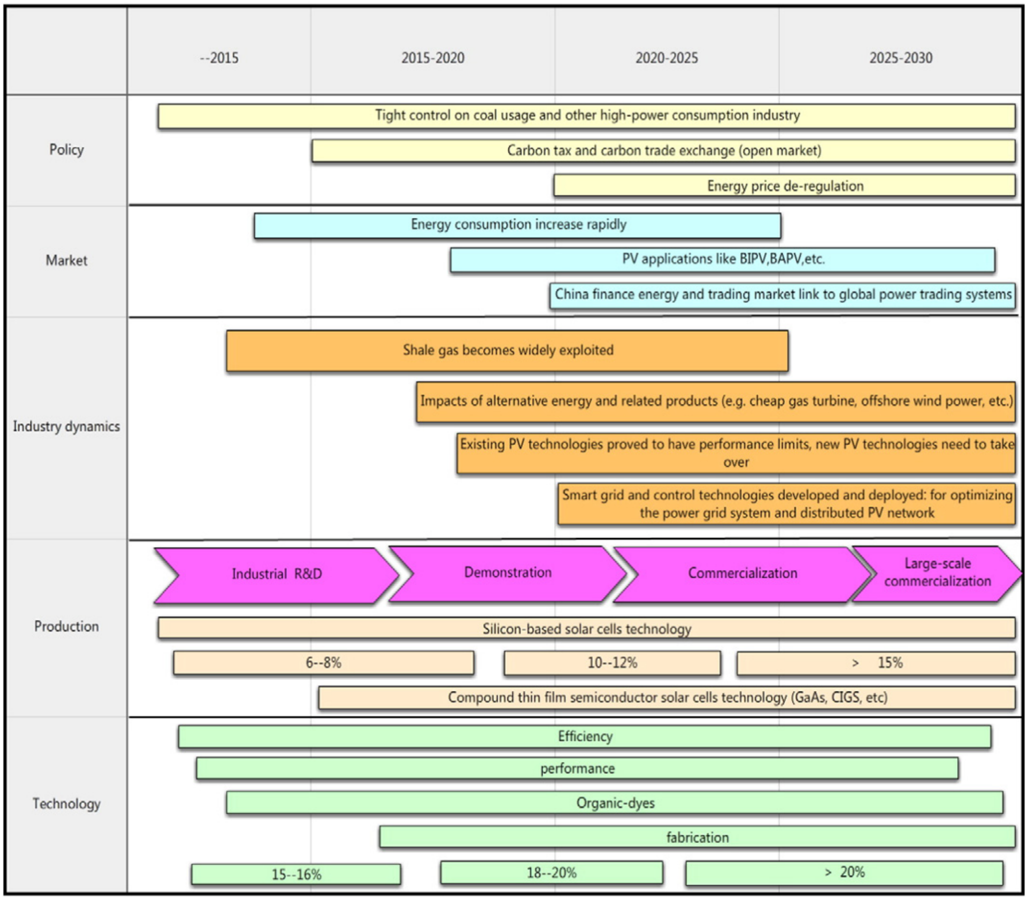

Fig. 13. The future development roadmap of the dye-sensitized solar cell technology-based PV industry in China.

investment compared to silicon-based and thin-film technologies, which have limited potential. In addition, the deployment of smart grids may lead to a boom in dye-sensitized solar cell applications, which are more suitable for distributed networks, and the dye-sensitized solar cells can be largely applied for to build the integrated photovoltaics (BIPV) and applied photovoltaics (BAPV) markets. Furthermore, the commercialization process will begin before 2025, which can be viewed as a transition period from the nurture phase to the growth phase, based on the following impacts: (i) technology: the conversion rate will reach or exceed 20% in labs and 15% in real industry, which can replace thin-film technology and challenge silicon-based PV; and (ii) policy/market/industry dynamics: energy price-deregulation, the application of carbon tax and carbon trade-exchange will significantly improve the energy market, and help to boost the deployment of distributed energy networks, specifically dye-sensitized solar cell applications. Last but not the least, a large-scale commercialization process may start before 2030, which may be seen as the growth phase, providing a significant boost to the industry.

As mentioned earlier, on this roadmap, the impact of events with high uncertainty are not counted, such as the breakthrough of energy storage technology/nuclear fusion. Therefore, there is no significant disruption to the growth trajectory. This may need further scenario planning methods. In addition, some impacts are analyzed based on the experts' intuitive knowledge, which can be further validated through an exhaustive literature review to prove the causal relationships between the possible events and growth. This also can form a subject for future research.

5. Discussion and conclusions

This paper proposes a framework that integrates bibliometrics with the TRM workshop approach, in order to strategize and plan the future development path of the new, technology-based industries. Bibliometrics was applied to analyze the existing position of science and technology in the emerging technologies' domain, and TRM workshops were used to study the future development from technology to applications and market activities. The dye-sensitized solar cell technology-based industry in China was employed as a case study, through which the proposed framework has been proven to be valid and flexible. This paper contributes to the roadmapping and foresight literature, and also sheds light on the future-oriented emerging industry studies and relevant policy analysis.

Some key findings and contributions are listed as follows:

1. The framework provides a tool for roadmapping and planning the emergence of an emerging, technology-based industry, with supporting strategy and decision-making for future development. This framework may be used specifically for developing economies that attempt to catch up in the global innovation race. We also propose a table to present the differences between the proposed framework and bibliometrics that other researchers have used to forecast emerging technologies (Table 5). As shown in Table 5, the main difference between this framework and prior bibliometric approaches is that this framework explores future possibilities based on the thorough understanding of current industrial settings and key technology trajectories. This analysis involves multi-disciplinary views from research academics, industrial experts, policy makers, and business managers — this helps to better simulate the complex industrial environments and the possible impacts that may shape the future growth of emerging technologies.
2. According to the bibliometric analysis, the research on dye-sensitized solar cell technology has been very active in recent years, and China is one of the leaders in the global innovation race with regard to this area. This provides an opportunity and solid basis for China to develop its dye-sensitized solar cell technology-based PV industry in the future.
3. A roadmap for the future development of the dye-sensitized solar cell technology-based industry in China was developed in this paper, which depicts the time-series emergence path, including four processes: industrial R&D (trials), demonstration, commercialization and large-scale commercialization. The roadmap outlined in this paper may therefore provide a useful reference for the future development of the solar PV industry in China and other developing countries.

However, there are some limitations and issues that need to be considered with regard to our approach. First of all, this paper only applies bibliometrics to analyze the existing position of science and technology in the dye-sensitized solar cell research domain. In the future, patent analysis of the technology/application development may be further integrated, which may improve the validity of analyzing the full-lifecycle industrial emergence. This is also a potential direction for future research. Second, the framework proposed in this paper is used to explore a future-oriented analysis supported by bibliometric studies, rather than to forecast a specific event with high uncertainty. Scenario-planning method may therefore be useful in further research

Table 5
A summary table of methods for forecasting emerging technologies.

Methodologies	Description	Focus
Bibliometrics	Produces potential discovery and explores future possibilities through analysis of the academic publications.	Science, technology
Bibliometrics + Experts' opinions	Produces potential discovery and explores future possibilities through both analysis of academic publications and use of technical domain experts' opinions.	Science, technology, and applications of technology
Bibliometrics + TRM workshop	Produces potential discovery, understands the current situation, and explores future possibilities through the analysis of both academic publications and TRM workshops, which brings multi-disciplinary views from research academics, industrial experts, policy makers, and business managers that can better simulate the industrial complexity.	The emergence of new technology-based industry (science, technology, application, market)

if we wish to forecast the path-independencies produced by disruptive changes, such as a technological breakthrough. Third, as for future-oriented roadmapping and planning for the dye-sensitized solar cell technology-based industry in China, in-depth interviews with entrepreneurs might prove fruitful. This would include checking whether or not China's enterprises are developing R&D cooperation with the better research institutions, which are leaders in the global innovation race with regard to dye-sensitized solar cell technology, and whether or not enterprises have participated actively in dye-sensitized solar cell technology R&D.

Acknowledgments

This paper is supported by the National Social Science Foundation of China (11&ZD140) and National Natural Science Foundation of China (71203117), and the consulting Projects of the Chinese Academy of Engineering "Nurturing and Development of Strategic Emerging Industries (2012-ZD-9). Specifically, it is supported by the EC-HVEN European framework 7 project (No. 295130) that involves the Centre of Technology Management at the University of Cambridge, which has successfully organized a series of roadmapping workshops in Europe and China that inspired the authors.

References

[1] CIEDS, A Report on the Development of Chinese Strategic Emerging Industries, Chinese Institute for Engineering Development Strategies, Science China Press, Beijing, 2013. (Chinese).
[2] L. Huang, Y. Zhang, Y. Guo, D. Zhu, A.L. Porter, Four dimensional science and technology planning: a new approach based on bibliometrics and technology roadmapping, Technol. Forecast. Soc. Chang. 81 (2014) 39–48.
[3] J. Rifkin, The Third Industrial Revolution: How Lateral Power is Transforming Energy, the Economy, and the World, Palgrave Macmillan, New York, 2011.
[4] R. Phaal, E. O'Sullivan, M. Routley, S. Ford, D. Probert, A framework for mapping industrial emergence, Technol. Forecast. Soc. Chang. 78 (2) (2011) 217–230.
[5] D.K. Robinson, T. Propp, Multi-path mapping for alignment strategies in emerging science and technologies, Technol. Forecast. Soc. Chang. 75 (4) (2008) 517–538.
[6] T.U. Daim, G. Rueda, H. Martin, P. Gerdsri, Forecasting emerging technologies: use of bibliometrics and patent analysis, Technol. Forecast. Soc. Chang. 73 (8) (2006) 981–1012.
[7] N. Shibata, Y. Kajikawa, Y. Takeda, K. Matsushima, Detecting emerging research fronts based on topological measures in citation networks of scientific publications, Technovation 28 (11) (2008) 758–775.
[8] Y. Kajikawa, J. Yoshikawa, Y. Takeda, K. Matsushima, Tracking emerging technologies in energy research: toward a roadmap for sustainable energy, Technol. Forecast. Soc. Chang. 75 (6) (2008) 771–782.
[9] D.P. Forbes, D.A. Kirsch, The study of emerging industries: recognizing and responding to some central problems, J. Bus. Ventur. 26 (5) (2011) 589–602.
[10] M.E. Porter, Competitive Strategy: Techniques for Analyzing Industries and Competitors, Free Press, New York, 1980.
[11] M. Hitt, R. Hoskisson, R.D. Ireland, Strategic Management, 8th ed., Cengage, Mason, OH, 2009.
[12] I. MacMillan, J. Katz, Idiosyncratic milieus of entrepreneurial research: the need for comprehensive theories, J. Bus. Ventur. 7 (1992) 1–9.
[13] J. Lampel, Z. Shapira, Progress and its discontents: data scarcity and the limits of falsification in strategic management, Adv. Strateg. Manag. 12 (1995) 113–150.
[14] R. Phaal, C.J. Farrukh, D.R. Probert, Technology roadmapping—a planning framework for evolution and revolution, Technol. Forecast. Soc. Chang. 71 (1) (2004) 5–26.
[15] C. Farrukh, R. Phaal, D. Probert, Technology roadmapping: linking technology resources into business planning, Int. J. Technol. Manag. 26 (1) (2003) 2–19.
[16] Y. Zhou, G.N. Xu, T. Minshall, et al., A policy dimension required for TRM: learning from the development of emerging wind energy industry in China, Technology Management in the Energy Smart World (PICMET), 2011 Proceedings of PICMET'11, IEEE, 2011, pp. 470–478.
[17] M. Routley, R. Phaal, D. Probert, Exploring the impacts of the interactions between lifecycles and other dynamics that influence the development of technology-based industries, Technology Management in the Energy Smart World (PICMET), 2011 Proceedings of PICMET'11, IEEE, 2011, pp. 1–15.
[18] N. Gerdsri, An analytical approach to building a technology development envelope (TDE) for roadmapping of emerging technologies, Int. J. Innov. Technol. Manag. 4 (02) (2007) 121–135.
[19] C. Holmes, M. Ferrill, The application of operation and technology roadmapping to aid Singaporean SMEs identify and select emerging technologies, Technol. Forecast. Soc. Chang. 72 (3) (2005) 349–357.
[20] S.K. Lee, G. Mogi, J.W. Kim, Energy technology roadmap for the next 10 years: the case of Korea, Energy Policy 37 (2) (2009) 588–596.
[21] T.U. Daim, M. Amer, R. Brenden, Technology roadmapping for wind energy: case of the Pacific Northwest, J. Clean. Prod. 20 (1) (2012) 27–37.
[22] T.U. Daim, T. Oliver, Implementing technology roadmap process in the energy services sector: a case study of a government agency, Technol. Forecast. Soc. Chang. 75 (5) (2008) 687–720.
[23] M. Amer, T.U. Daim, Application of technology roadmaps for renewable energy sector, Technol. Forecast. Soc. Chang. 77 (8) (2010) 1355–1370.
[24] O. Saritas, J. Aylen, Using scenarios for roadmapping: the case of clean production, Technol. Forecast. Soc. Chang. 77 (7) (2010) 1061–1075.
[25] M.J. Norton, Introductory Concepts in Information Science, 2001. (New Jersey).
[26] R.N. Kostoff, D.R. Toothman, H.J. Eberhart, J.A. Humenik, Text mining using database tomography and bibliometrics: a review, Technol. Forecast. Soc. Chang. 68 (3) (2001) 223–253.
[27] C. Chen, CiteSpace: visualizing patterns and trends in scientific literature, Retried 12-26-2013 World Wide Web http://cluster.ischool.drexel.edu/~cchen/citespace/current/.
[28] A.F. Van Raan, Measuring science, Handbook of Quantitative Science and Technology Research, Springer, Netherlands, 2005.
[29] R.N. Kostoff, H.J. Eberhart, D.R. Toothman, Hypersonic and supersonic flow roadmaps using bibliometrics and database tomography, J. Am. Soc. Inf. Sci. 50 (5) (1999) 427–447.
[30] R.N. Kostoff, R. Tshiteya, K.M. Pfeil, J.A. Humenik, Electrochemical power text mining using bibliometrics and database tomography, J. Power Sources 110 (1) (2002) 163–176.
[31] R.N. Kostoff, Literature-related discovery (LRD): introduction and background, Technol. Forecast. Soc. Chang. 75 (2) (2008) 165–185.
[32] R.N. Kostoff, R. Tshiteya, K.M. Pfeil, J.A. Humenik, G. Karypis, Power source roadmaps using bibliometrics and database tomography, Energy 30 (5) (2005) 709–730.
[33] Y. Kajikawa, Y. Takeda, K. Matsushima, Computer-assisted roadmapping: a case study in energy research, Foresight 12 (2) (2010) 4–15.
[34] M. Bengisu, R. Nekhili, Forecasting emerging technologies with the aid of science and technology databases, Technol. Forecast. Soc. Chang. 73 (7) (2006) 835–844.
[35] R.N. Kostoff, J.L. Solka, R.L. Rushenberg, J.A. Wyatt, Literature-related discovery (LRD): water purification, Technol. Forecast. Soc. Chang. 75 (2) (2008) 256–275.
[36] Lu. Huang, Y. Guo, A.L. Porter, J. Youtie, D.K.R. Robinson, Visualising potential innovation pathways in a workshop setting: the case of nano-enabled biosensors, Tech. Anal. Strat. Manag. 24 (5) (2012) 527–542.
[37] D.K.R. Robinson, Lu. Huang, Y. Guo, A.L. Porter, Forecasting innovation pathways for new and emerging science and technologies, Technol. Forecast. Soc. Chang. 80 (2) (2013) 267–285.
[38] R.N. Kostoff, R.R. Schaller, Science and technology roadmaps, IEEE Trans. Eng. Manag. 48 (2) (2001) 132–143.
[39] R.N. Kostoff, R. Boylan, G.R. Simons, Disruptive technology roadmaps, Technol. Forecast. Soc. Chang. 71 (1–2) (2004) 141–159.
[40] A.L. Porter, M.J. Detampel, Technology opportunities analysis, Technol. Forecast. Soc. Chang. 49 (3) (1995) 237–255.
[41] R. Phaal, Public-domain Roadmaps, Centre for Technology Management, University of Cambridge, 2011.
[42] R. Phaal, C.J.P. Farrukh, D.R. Probert, T-Plan: The Fast-start to Technology Roadmapping — Planning Your Route to Success, Institute for Manufacturing, University of Cambridge, 2001.
[43] R. Phaal, C.J. Farrukh, D.R. Probert, Strategic roadmapping: a workshop-based approach for identifying and exploring innovation issues and opportunities, Eng. Manag. J. 19 (2007) 3–12.
[44] R. Phaal, C. Farrukh, R. Mitchell, D. Probert, Starting-up roadmapping fast, IEEE Eng. Manag. Rev. 31 (2003) 54–60.
[45] X. Li, Y. Zhou, L. Huang, K. Wang, Z. Huang, Research on the development path of China's solar photovoltaic industry based on technology roadmapping and bibliometric, Technology Management in

the IT-driven Services (PICMET), 2013 Proceedings of PICMET'13, IEEE, 2013, pp. 2248–2258.
[46] C.W. Hill, G.R. Jones, Strategic Management: An Integrated Approach, CengageBrain.com, 2007.
[47] Z.Y. Zhao, S.Y. Zhang, B. Hubbard, X. Yao, The emergence of the solar photovoltaic power industry in China, Renew. Sust. Energ. Rev. 21 (2013) 229–236.
[48] A. Jäger-Waldau, PV Status Report 2011: Research, Solar Cell Production and Market Implementation of Photovoltaics, Office of Official Publications of European Communities, 2011.
[49] International Energy Agency, Trends in Photovoltaic Applications: Survey Report of Selected IEA Countries Between 1992 and 2011, 2011.
[50] M.L. Huo, D.W. Zhang, Lessons from photovoltaic policies in China for future development, Energy Policy 51 (2012) 38–45.
[51] International Energy Agency, Trends in Photovoltaic Applications: Survey Report of Selected IEA Countries Between 1992 and 2008, 2009.
[52] H.W. Xiao, Z.Y. Gu, Patent Mapping Approach and Application, Shanghai Jiaotong University Press, Shanghai, 2011.
[53] B. O'regan, M. Grfitzeli, A low-cost, high-efficiency solar cell based on dye-sensitized, Nature 353 (1991) 24.
[54] L.M. Gonçalves, V. de Zea Bermudez, H.A. Ribeiro, A.M. Mendes, Dye-sensitized solar cells: a safe bet for the future, Energy Environ. Sci. 1 (6) (2008) 655–667.
[55] C. Chen, CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature, J. Am. Soc. Inf. Sci. Technol. 57 (3) (2006) 359–377.
[56] Y. Zhou, G. Xu, Q. Zhi, F. Zhang, T. Minshall, J. Su, Roadmapping an emerging energy technology: an ex-ante examination of dimethyl ether development in China, Int. J. Prod. Dev. 17 (3) (2012) 296–310.
[57] Y. Zhou, G. Xu, T. Minshall, J. Su, A policy dimension required for technology roadmapping: learning from the emergence of Chinese wind turbine industry, Int. J. Environ. Sustain. Dev. 12 (1) (2013) 3–21.
[58] Y. Zhou, T. Minshall, Building global products and competing in innovation: the role of Chinese university spin-outs and required innovation capabilities, Int. J. Technol. Manag. 64 (2) (2014) 180–209.

Xin Li is a postdoctoral researcher at the School of Public Policy and Management, Tsinghua University, China. He received his Ph.D. degree in engineering and technology management from Beijing University of Technology in China. And he was a visiting scholar in the Department of Engineering and Technology Management at Portland State University, Oregon, USA. His recent research interests include innovation policy, energy storage technology assessment, technology forecasting and technology roadmapping.

Yuan Zhou is an assistant professor at the School of Public Policy and Management, Tsinghua University, China. His recent research interests include public policy, innovation policy and technology roadmapping.

Xue Lan is a professor at the School of Public Policy and Management, Tsinghua University, China. His recent research interests include public policy, innovation policy and technology innovation management.

Lucheng Huang is a professor at the School of Economics and Management, Beijing University of Technology, China. His recent research interests include emerging technology management and technology innovation management.