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Triple Helix innovation in China's dye-sensitized solar cell industry: hybrid methods with semantic TRIZ and technology roadmapping

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Abstract In recent years, the Triple Helix model has identified feasible approaches to measuring relations among universities, industries, and governments. Results have been extended to different databases, regions, and perspectives. This paper explores how bibliometrics and text mining can inform Triple Helix analyses. It engages Competitive Technical Intelligence concepts and methods for studies of Newly Emerging Science & Technology (NEST) in support of technology management and policy. A semantic TRIZ approach is used to assess NEST innovation patterns by associating topics (using noun phrases to address subjects and objects) and actions (via verbs). We then classify these innovation patterns by the dominant categories of origination: Academy, Industry, or Government. We then use TRIZ tags and benchmarks to locate NEST progress using Technology Roadmapping. Triple Helix inferences can then be related to the visualized patterns. We demonstrate these analyses via a case study for dye-sensitized solar cells.

Keywords Triple Helix model · Semantic TRIZ · Technology roadmapping · DSSCs · Text mining · Emerging technology

Abbreviations

CAS	Chinese Academy of Science
CTI	Competitive technical intelligence
DII	Derwent innovations index

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DSSCs	Dye-sensitized solar cells
FTA	Future-oriented technology analysis
NEST	Newly Emerging Science & Technology
NLP	Nature language processing
P&S	Problem & solution
PCA	Principle components analysis
SCI	Science citation index
SME	Small and medium enterprises
ST&I	Science, technology & innovation
THM	Triple Helix model
TRM	Technology roadmapping
WoS	Web of science

Introduction

Newly Emerging Science & Technology (NEST) represents progressive, sometimes explosive, developments within a new or existing field. NESTs are vital in terms of competitive advantage for firms or even countries (Soares et al. 1997). The apparent acceleration in NESTs is not only an obvious global feature of today's Science, Technology & Innovation (ST&I) scene but is also becoming a key factor in national R&D programs (Zhang et al. 2012a).There are increasing efforts to plan and integrate ST&I activities to address NEST issues collectively, instead of trying to approach them only from single perspectives (Bengisu 2003).

Profiling historical development patterns for NESTs can help understand key technological system components. "Tech Mining" (Porter and Cunningham 2005) directly contributes to Competitive Technical Intelligence (CTI) by illuminating current R&D emphases and key players. CTI especially concerns the "who" and "what" of external R&D (Porter and Newman 2011)—who are the key competitors and what technologies are they pursuing (*Competitive Intelligence*); and what is happening in a given technological arena (*Technical Intelligence*).

In a relatively separate literature, the Triple Helix model (THM) was proposed and introduced to address the dynamics of university, industry, and government relations (Etzkowitz and Leydesdorff 1995). Triple Helix discourse directs attention to the interchange of research knowledge among these institutions (Etzkowitz and Leydesdorff 2000). It is challenging to extend such analyses to measuring science and technology innovation in different domains (Park et al. 2005).

Over the past year, we have focused on "Term Clumping" steps to improve cleaning and consolidation of phrases and terms (Zhang et al. 2012b). Also, we are combining qualitative and quantitative methodologies to compose Technology Roadmapping (TRM) models, useful instruments to indicate technology development trends visually (Zhang et al. 2012a). In this paper, we draw on topical factors that are elucidated by term clumping, to generate a TRM to explore the relations of academy, industry, and government at the national level. Especially, we introduce "Semantic TRIZ" (Verbitsky 2004), the methodology applying TRIZ theory with bibliometric techniques, as the bridge to help combine term clumping results with TRM visualization. The prospect is that semantic TRIZ conceptualizations may help to identify system components and to track evolving problem solutions by way of text analyses (e.g., extracting nearby phrases to get at semantic relationships).

Usually, general Triple Helix emphasizes statistical analysis and three-dimension measurement (Leydesdorff 2003). Park et al. (2005) applied semantic analysis with title words to compare the different academic emphases between South Korean and Dutch research. However, it is challenging to engage semantic TRIZ and its framework with term clumping and TRM. This paper addresses the case of China's dye-sensitized solar cells (DSSCs) industry, and tries to apply our new methodology in the THMs. Significantly, (1) the term clumping approach retrieves value-added phrases from massive ST&I document sets; (2) semantic TRIZ not only pays attention to the "words," but also their related sentences, seeking to deepen semantic understanding; (3) TRM describes the dynamics of Problems and Solutions (P&S) in a visualized way. These concepts and methods are new for Tripe Helix studies, and also, extend the current research on Triple Helix along a different angle. This paper is organized as follows: "Literature review" section summarizes key literature on THMs, TRIZ and semantic TRIZ, and TRM. Our DSSC data and the methodology of the Triple Helix Innovation study in China's DSSC industry are described in "Data and methods" section. Finally, we draw conclusions and discuss these in fourth section.

Literature review

Concepts and applications of the Triple Helix model

Research providing insight into the interrelationships of university and industry is important to consideration of R&D management and, furthermore, with regard to technology transfer facilitation. For example, Barbolla and Corredera (2009) assessed some of the most influential factors for success or failure in research contracts and pronounced that features related to the corporate partner's strategic and functional characteristics can be decisive. Giuliania and Arzab (2009) explored the factors driving the formation of "valuable university—industry linkages" that may facilitate a higher potential to diffuse knowledge to other firms in the economy. Also, the "government" factor has been added. Boardman (2009) sought to detect how different types of university research centers affect individual university-industry interactions. Based on different research questions or targets, these research efforts paid attention to one or two of the categories: university, industry, or government.

Noting the stability of the double helix model for the structure of DNA, Etzkowitz and Leydesdorff (1995) introduced the THM to present the relations of university, industry, and government. Leydesdorff (2003) also identified the three dimensions of measurement in a Triple Helix configuration and their combinations, and measured these relations in both internet and science citation index (SCI) data. The THM has become an important instrument for ST&I management and policy studies.

Researchers have introduced the THM for comparisons in the ST&I domain at the national level. Park (2005) elaborated a THM for measuring the knowledge-based innovation systems in the economies of South Korea and the Netherlands. Fogelberg and Thorpenberg (2012) investigated the development of innovation policy and development organizations in regions or countries where Triple Helix research is conducted and analyzed the data of two cities in Western Sweden. Various new ideas, concepts, and methods have been added to extend and upgrade the THM. Etzkowitz (2012), one of the founders of the THM, discussed the importance of permeability among university, industry, and government boundaries with research on the experience of many world-famous universities and regions. Kim et al. (2012) noticed the significant limitations of the relations based on the THM and the environment of research while investigating regional entrepreneurial activities. They offered several effective suggestions based on empirical study of birth and death rates of U.S. firms, at the state level.

TRIZ theory and its extension with bibliometrics—semantic TRIZ

Defined by G. S. Altshuller, the term “TRIZ” comes from a Russian expression that means the “theory of inventive problem solving.” TRIZ theory affords many tools for the development of systems, such as Quality Function Deployment (QFD), Theory of Constraints (TOC), and Six Sigma for problem identification and analyses (Rantanen and Domb 2008; Kremer et al. 2012). TRIZ also establishes new views for the system of technology by orienting research toward both abstractness and concreteness as a new approach to technology analyses, revealing laws of evolution of technical systems, and summarizing 40 principles of invention (Nakagawa 2001). The concepts of Contradiction, Evolution, Resources, and Ideal Solution could be considered as the main building blocks of TRIZ (Savransky 2000). Rantanen and Domb (2008) also presented the model of TRIZ theory (shown as Fig. 1), which is useful for summarizing the structure of the TRIZ model.

Several attempts have been made to connect TRIZ theory with bibliometric methods. Soo et al. (2006) intended to develop a cooperative multi-agent platform to integrate patent analysis with TRIZ by extracting structural information from patent documents with the aid of ontology and Natural Language Process (NLP) techniques. Cong and Tong (2008) categorized patent documents according to the inventive principles of TRIZ theory. Kim et al. (2009) extended TRIZ theory to the task of technological trend discovery with patent records. Li et al. (2012) provided a means for classifying patents with the level of invention (LOI), which was defined in the TRIZ theory and can be used as an approach for ranking patents.

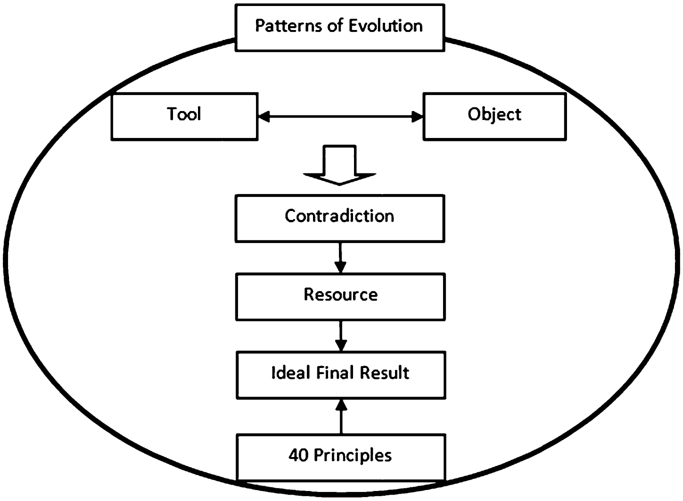


Fig. 1 Model of TRIZ theory (based on Rantanen and Domb 2008)

This study attempts to answer two key questions regarding patent analyses:

1. Are the Contradiction Matrix and Technology Evolution Trend statistically stable?
2. How best can we connect a general recommendation of TRIZ to a specific innovative idea?

Verbitsky (2004) defined "Semantic TRIZ" as applying software with sufficient intelligence to "understand" terms in reading millions of ST&I documents. Semantic TRIZ is based on semantic indexing, and its application launches a novel approach to the innovation process. Verbitsky noted that by using this systemic relationship of components to analyze the terms of a patent or a scientific article, a series of relationships between substantive phrases and their verbs (actions) can be extracted. This enables one to analyze term (concept) usage or function, and so help better understand the evolution of the inventive system or technology under study.

Technology roadmapping (TRM) and technology opportunities analysis (TOA)

TRM provides a structured means for exploring and communicating the relationships among evolving and developing markets, products, and technologies over time (Phaal et al. 2004). In general, TRM identifies (1) a particular industry's common product and process performance targets, (2) the technology alternatives and milestones for meeting these targets, and (3) a common technology path for R&D activities (Garcia 1997). Currently, bibliometric and text mining techniques are also more and more closely combining with TRM methods. Based on patent analysis, Lee et al. (2009) proposed a TRM process that originated from capability analysis for technology planning and resulted in business opportunity analysis for marketing planning. We have provided a more detailed literature review on TRM theory and TRM with bibliometrics in one of our previous papers where we presented a hybrid TRM composing model (Zhang et al. 2012a).

TOA (Porter and Detampel 1995) performs value-added data analysis for CTI studies. On a macroscopic level, TOA contributes to two fields: automated ST&I intelligence extraction and visualization and Future-Oriented Technology Analysis (FTA). More recently, Porter and Cunningham (2005) have offered the "Tech Mining" approach that applies text mining to bibliometric search results, likewise with the aim of devising CTI and informing FTA. We adapt a number of ideas and tools from these approaches.

Comparison with previous work

This paper differs from other research as described in Table 1.

Data and methods

We have focused on the DSSC domain for several years and have formulated a multi-step Boolean search algorithm, adapted and applied via search interfaces to two leading, global ST&I databases—the SCI Expanded of Web of Science (WoS) and EI Compendex. However, in this paper, considering the close connection of patents and TRIZ theory, we apply a corresponding search algorithm to the patent database Derwent Innovation Index (DII), accessed via the Web of Knowledge site.

We chose DII for several reasons: (1) DII has collected about 30 million patents from more than 40 patent organizations all over the world, which makes it an especially

Table 1 Differences between our approach and related work

Research	Reference	Purpose of research	Differences
Triple Helix model (THM)	Etzkowitz and Leydesdorff (1995, 2000); Leydesdorff (2003); Etzkowitz (2012)	Etzkowitz and Leydesdorff introduced the THM to identify the relations among university, industry, and government, and, also, worked continuously to enrich THM (e.g., measurement methods, boundary permeability, etc.)	Our paper uses THM to analyze ST&I related to China's DSSC industry, and evaluates the relations among the 3 institutions. However, we emphasize the application of semantic TRIZ and TRM to THM, but not the THM theory itself. In addition, we extend the "University" category to "Academy," which now includes both universities and institutes
Empirical studies with Triple Helix indicators	Park et al. (2005); Kim and Park (2012); Khan et al. (2012)	Park and other researchers (especially Korean researchers) enthusiastically engaged in empirical studies of THM on both regional and national levels. Triple Helix indicators are used frequently with knowledge-based innovation system measurement, social network analyses, and comparison studies for various domains	In some ways, this paper also could be considered an empirical study that applies THM to China's DSSC industry studies. However, the difference between our work and Park's is that we do not only focus on THM but also on other theories (e.g., semantic TRIZ and TRM)
TRIZ theory	Rantanen and Domb (2008)	This book could be considered as a guidebook for all TRIZ researchers as it includes almost all TRIZ concepts and models (e.g., Contradiction Matrix, Technology Evolutionary Trends, 40 principles of invention)	TRIZ theory is really a "big" system, and we just adopt a few ideas to combine with bibliometrics. Moreover, we do not address theoretical TRIZ concepts research
Semantic TRIZ	Verbitsky (2004)	Verbitsky connected TRIZ theory with bibliometrics, and defined "semantic TRIZ" methodology. Particularly, he also presented how to analyze patent documents with semantic indexing technology in details	We follow Verbitsky's semantic TRIZ methods, and use the software, *Goldfire Innovator* (Arel 2004), to retrieve "problem–solution" patterns with semantic TRIZ techniques. Here, we emphasize applying semantic TRIZ as an instrument for Triple Helix innovation research
Technological Trend Discovery (TTD)	Kim et al. (2009)	Although Kim did not mention any TRIZ concepts in his paper, we classified his work into the category "semantic TRIZ," more specifically in the category that combines semantic TRIZ and TRM. Kim located the "problem–solution" patterns in the time dimension and tried to describe "when problems occurred" and "when and how problems are solved" with TTD studies	This is an important reference for our work. On the one hand, we enhance the theoretical evidence by framing with TRIZ theory. On the other hand, we combine this simple demonstration with our previous TRM research (Zhang et al. 2012a). Furthermore, in this paper, we use this "hybrid" approach to THM studies

comprehensive patent database across categories: chemical, electrical, electronic and mechanical engineering; (2) DII affords value-added patent information with its 60 years of patent indexing experience, where patent abstracts in different languages are re-written into English, seeking to clarify obscure and legalistic terminology (especially important given our text mining interests); (3) DII identifies the Patent Assignee Code for patent assignees, which makes the classification and cleaning work much easier, especially for international companies or national academies (e.g., Chinese Academy of Science, CAS) that have so many different names in the "big" patent database; (4) DII also has its own classification and citation system, which may not be important for this paper but is a really significant feature.

The resulting 4,116 patent abstracts and titles cover the time span from 1991 (DSSC was first announced in *Nature* by the two Swiss scientists O'Regan and Grätzel in 1991) through November 18, 2012. We collected 568 records whose patent number starts with "CN," because we tried to avoid obstructions from the "confused" patent family and only wanted the patents from the Chinese Patent Office (SIPO). After the NLP process had been conducted on the combined "abstract+title" field via VantagePoint (see References), 11,202 phrases and terms were retrieved.

The framework of the Triple Helix innovation study in this paper is shown in Fig. 2. We explain the various components in the following sections.

Record classification

We retrieved 254 patent assignees from the 566 records and reduced the number to 217 by the fuzzy matching routine in VantagePoint. In this step, the "Patent Assignee Code"—as mentioned this Derwent field is particularly helpful here—helps consolidate duplicate assignees. Further, we used the organization filter in VantagePoint to classify these

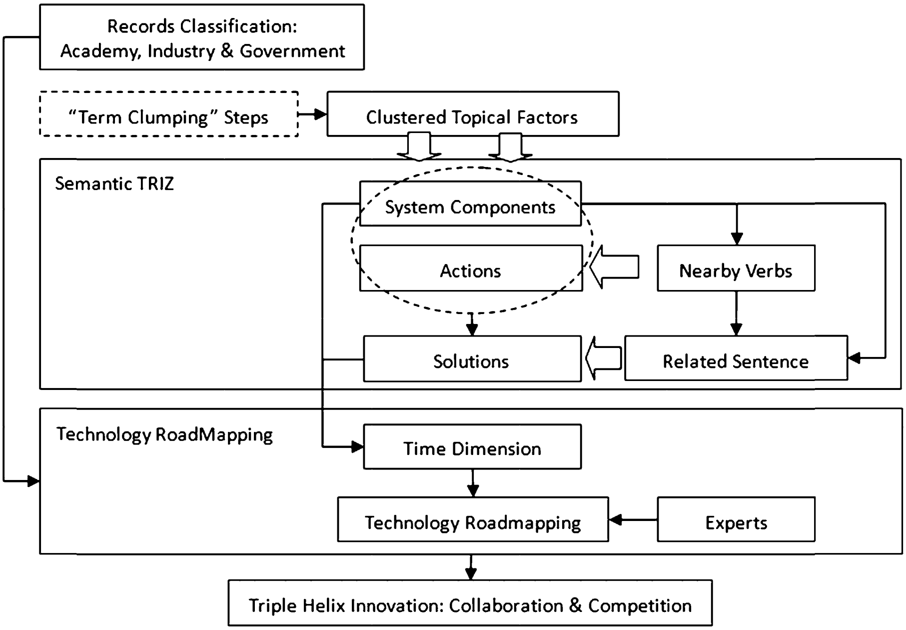


Fig. 2 Framework of Triple Helix innovation with semantic TRIZ and TRM

assignees into the categories “Academy (110 patents),” “Industry (76 patents),” “Government (0 patent),” and “Individual (32 patents).”

Term clumping steps

As detailed previously, term clumping is the series of steps to clean and consolidate rich sets of topical phrases and terms in a collection of documents relating to a topic of interest (Zhang et al. 2012a, b). We applied such term clumping steps to the DSSC Derwent patent dataset for China. The stepwise actions are noted in Table 2.

In Step 5 we generated a Factor Map (Fig. 3) via VantagePoint based on “term co-occurrence analysis” using principle components analysis (PCA).We asked several Ph.D. students who focus on DSSCs research at the Beijing Institute of Technology for informed suggestions. The four topical factors in the large oval in Fig. 3 are suggested to be consolidated, and the other three factors are retained.

Based on the literature review for DSSCs and the experts’ aid, we distinguish 4 solar cell subsystems, as defined by knowledgeable DSSC researchers—“photo anode,” “sensitizer,” “electrolyte,” and “counter electrode.” In this case, we consolidated the 7 topical factors into 4 clusters, which are shown in Table 3. The terms—“photosensitive dye” and “ruthenium dye”—marked by a star in Table 3, belong to the “sensitizer” sub-system.

Semantic TRIZ

As shown in Fig. 2, the “contradiction between object and tool” and the “ideal final result” could be considered respectively as the Problem and its Solution. In this paper, we

Table 2 Term clumping stepwise results

China’s DSSCs 568 records (derwent innovations index)	
Field selection: title+abstract	Phrases+keywords
Initial phrases	11,202
Step 1. Basic cleaning	
Remove terms starting with numbers, e.g., “1.5 %,” “20 degree”	10,038
Remove stopwords, common terms, academic terms (e.g., “what,” “detailed description,” “methodology”)	8,457
Step 2. Further cleaning	
Fuzzy Matching: Consolidate terms with similarities (e.g., “efficient and efficiency,” “dye sensitized solar cell,” “dye sensitive solar cell,” and “dye-sensitized solar cell”)	7,443
Step 3. Pruning	
Remove terms only appearing in single records	1,379
Step 4. Top term selecting	
Term frequency inverse document frequency analysis (TFIDF): rank terms and select the top 50/100 terms	50/100 (for different purposes)
Step 5. Clustering	
Principle components analysis (PCA)	7 Topical factors
Step 6. Knowledge modification	
With the knowledge from literature review on DSSCs and semi-formal expert interviews, modify the results	4 Topical clusters

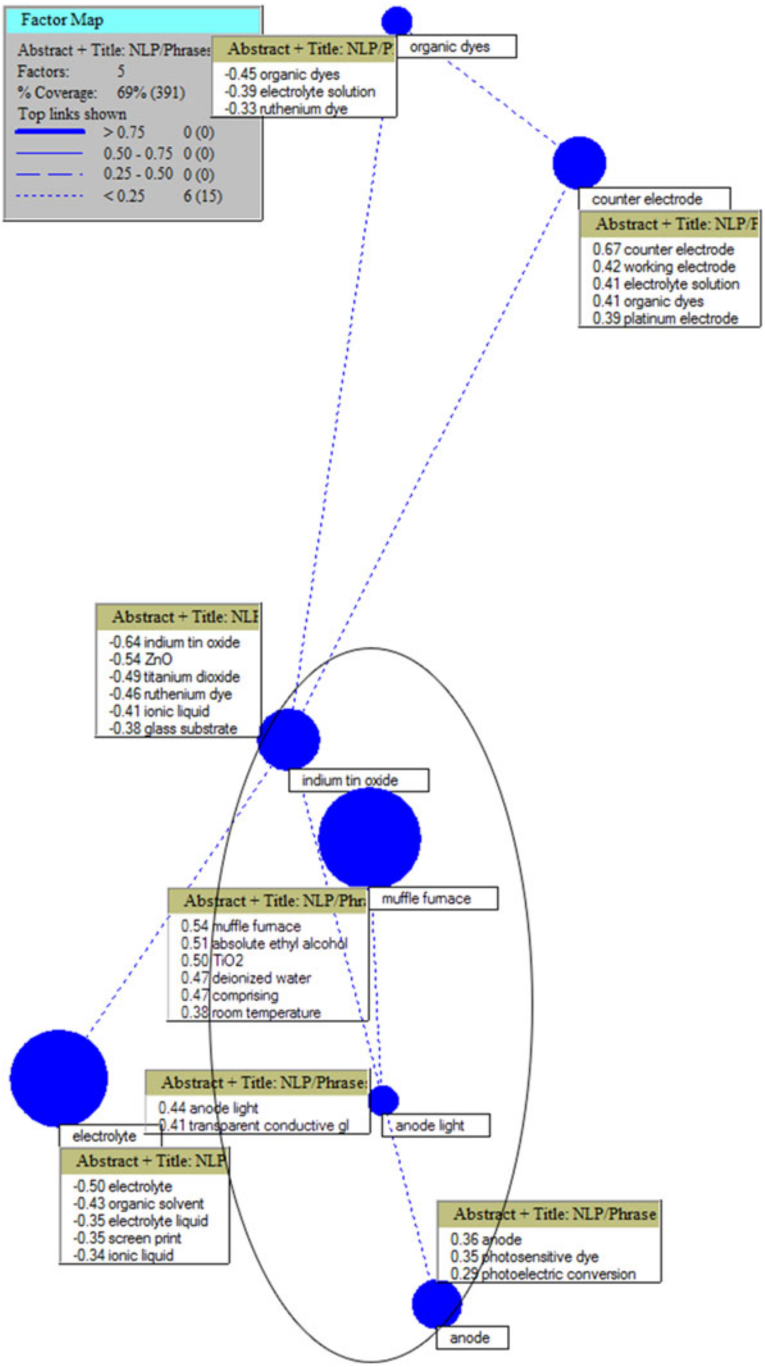


Fig. 3 Factor mapping of DSSCs (for the top 50 terms)

Table 3 Topical clusters and related items

No.	Clusters	Topical factors	Related items
1	Photo anode	Anode	Photoelectric conversion efficiency; anode; photosensitive dye*
2		Anode light	Anode light; transparent conductive glass
3		Muffle furnace	TiO_2; deionizer water; absolute ethyl alcohol; Room temperature; muffle furnace; comprising
4		Indium tin oxide	ZnO; titanium dioxide; glass substrate; ionic liquid; indium tin oxide; ruthenium dye*
5	Sensitizer	Organic dyes	Electrolyte solution; organic dyes; ruthenium dye
6	Electrolyte	Electrolyte	Electrolyte; organic solvent; ionic liquid; screen print; electrolyte liquid
7	Counter electrode	Counter electrode	Counter electrode; working electrode; electrolyte solution; organic dyes; platinum electrode

The terms with star appear in more than one clusters

emphasize the Problem & solution (P&S) patterns using semantic TRIZ. With our long-term research experience on "phrases and terms" behind us, we noticed that misunderstandings would likely occur if we only have these terms without more bases for sifting through them.

For example, at that point, we knew that "organic dyes" is a key term within the field of DSSCs, but we don't know how the "organic dyes" take effect in DSSCs. Thus, in the first step, we pay attention to the importance of verbs. In the last example, we retrieved several verbs that appeared nearby "organic dyes," for example, "using." Accordingly, we guessed that someone or something may "use" the "organic dyes," in other words, "organic dyes" are probably important materials for some components or products. For further studies, we looked at the whole sentence, the origin of "using" and "organic dyes," which was "Fabrication of working electrode for dye-sensitized solar battery, involves… secondary dye-absorption using organic dye." At this point, meaning became clearer, and this also gave us the hint to extend the terms analysis to "object-verb" phrases or related sentences.

We undertake to estimate relationships between the topical clusters/factors and the P&S patterns. As shown in Fig. 4, the topical factors are "system components" that could be considered as one part of the "problem" in the P&S pattern, while their nearby verbs are problem-related "actions." Furthermore, the topical factors plus their nearby verbs (or related sentences), which are Verb-Object (V–O) phrases (or Object-Verb-Object phrases) could be considered as the "solutions."

We retrieved the 4 topical clusters with 7 topical factors and about 20 items in the term clumping steps. The 4 topical clusters also could be symbols for the 4 subsystems of DSSCs. We then use *GoldFire Innovator* (semantic TRIZ software, see References) to treat the subsystems as "problems," retrieve their related "actions," and combine them as "solutions."

TRM

We construct a hybrid model for TRM using bibliometrics and text mining techniques, where we locate the topical factors in the time dimension and describe the technology trends based on the time-based occurrence pattern of the topical factors (Zhang et al.

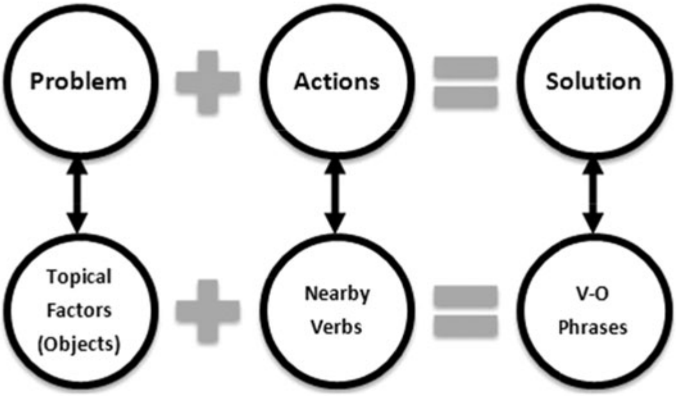


Fig. 4 Mapping between P&S patterns and topical factors

2012a). In this paper, the P&S patterns that we obtain with semantic TRIZ methods take the place of the topical factors. We locate the "problems" and "solutions" at the time when they occurred, and link them with the "relations" (as shown in Fig. 5). In this instance, we seek to understand the following questions in the form of a TRM visualization: (1) which problem was addressed, and when? (2) How the problem was solved (new techniques, new materials, or something else), and when? (3) Which organizations (Industry, Academy or Government) work together on these issues?

In addition, the ordinate axis of TRM presents the technology development phrase. This time, however, going beyond previous qualitative definitions, we are able to identify 3 or 4 important phrases by hybrid quantitative and qualitative methods (Zhang et al. 2012a). After locating each problem and solution, we work to delineate the technology trends with the potential relations among these P&S patterns—these are shown as the blacked & dotted line in Fig. 5. We also define four kinds of relations among the P&S patterns, which are shown in Table 4.

Triple Helix innovation study

Overview of Triple Helix innovation in China's DSSCs industry

According to general statistical analysis, we present the proportions of Assignees and Academy as follow: (1) among the 568 patents, 50 % of them are from the "Academy," 35 % are from "Industry," and 15 % are from "Individual," and no government's patent; (2) We also looked further into the "Academy" part—72 % of them are from "University" sources and others (e.g., research institutes) include, especially, CAS with 19 %; ITRI has 1 %; and others, 8 % of the patents. We note the top 10 institutions in Table 5, and several interesting discoveries derive from these:

(1) Until 2012, the Chinese government did not have any special national DSSC R&D programs that emphasized patenting; accordingly, no government units appear in the patent assignee list.

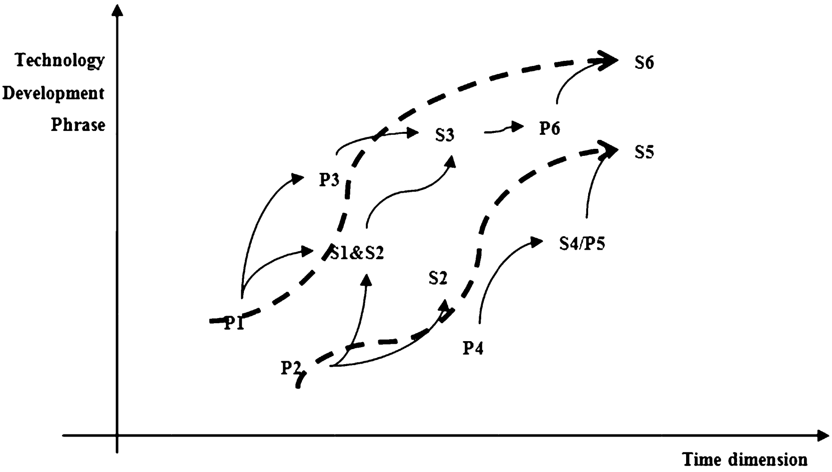


Fig. 5 P&S pattern technology roadmapping

Table 4 Relations in the P&S patterns

No.	Relations	Relations
1	Problem to problem	Relate: there are relations between the two problems, e.g., the same subsystem
2	Problem to solution	Solve: problem is solved by the solution indicated
3	Solution to solution	Relate/upgrade: there are relations between the two solutions, e.g., the same subsystem; or the "next" solution upgrades the previous one
4	Solution to problem	Evolve: solution evolves to new problems (we mark this relation as S/P in the TRM)

(2) Academies, which constitute the largest proportion of the patent assignees, also play the most important role in China's DSSC research. [Note our adaptation of the "Academy" category to distinguish important special research institutes in addition to universities.]

(3) In emphasizing the proportion of the academy we find that, currently, universities head China's DSSC research; "Wuhan University," "Tsinghua University," and the "University of Southeast" comprise the Top 3.

(4) We also notice that CAS (there are some 21 CAS branches appearing in the patent assignee list) is another leading institute, which should not be ignored. The total proportion of CAS (19 % in Academy, and 9 % in total), along with the number of its related patents (73) makes it the leading contributor of all institutions. In other words, considering the importance of CAS in China's ST&I enterprise and its national ties, this prominent R&D activity suggests that the government is attuned to solar cell development, even though direct government agency patenting is absent.

(5) The Industry Technology Research Institute (ITRI) of Taiwan is the only Taiwanese institution with official connections there and applied permissions in SIPO. So, ITRI's notable patent activity conveys significant policy interest as well.

Table 5 Top 10 universities and research institutes patenting DSSCs in China

No.	University	#P	No.	Institute	#P
1	Univ. Wuhan	20	1	CAS Physics Inst.	19
2	Univ. Tsinghua	16	2	CAS Plasma Physics Inst.	16
3	Univ. Southeast	16	3	CAS Chem. Inst.	16
4	Univ. Fudan	13	4	Ind. Technol. Res. Inst. of Taiwan	8
5	Univ. Nanjing	13	5	CAS Changchun Applied Chem. Inst.	7
6	Univ. Peking	13	6	Beijing Soltex Energy Tech. Inst.	3
7	Univ. Beijing Sci. & Technology	9	7	CAS Shanghai Inst Ceramic	3
8	Univ. Electronic Sci. & Technology	8	8	Anhui Optics. & Fine. Mechanics Inst.	3
9	Univ. Huazhong Sci. & Technology	8	9	CAS Hefei Inst. Physical Sci.	2
10	Univ. Nankai	8	10	CAS Inst. Semiconductors	2

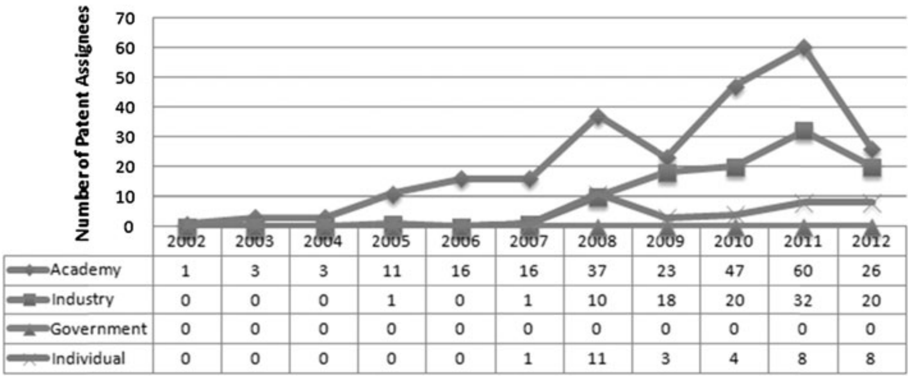
#P no. of related patents

We also describe the trends of DSSC patent applications by Academy, Industry, Government and Individuals. Figure 6 indicates that China's industry lagged behind academy patenting in the field through 2012. As shown in Fig. 6, although DSSCs were first introduced in 1991, the first DSSC-related patent in SIPO was applied for in 2002 by an academy unit (Dalian University of Technology).On the "Industry" side, the application year of the first patent is 2005 (Hongfujin Precision Ind. Shenzhen Co. LTD).

Triple Helix collaboration and competition in China's DSSC industry

We are interested in cross-sector collaboration. This is particularly so in China, given the prominence of university and research institute patenting. Recognizing that co-patenting among institutions is relatively rare in general, we explore this for Chinese DSSC patents. The collaboration between academies and corporations is shown below: Ten patent records were applied for by both academies and corporations, and, among them, 6 academies and 8 corporations collaborate.

We take a closer look at the universities collaborating with industry, as shown in Fig. 7. It is interesting that all these relations occur in the same regions or neighborhoods, except



	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Academy	1	3	3	11	16	16	37	23	47	60	26
Industry	0	0	0	1	0	1	10	18	20	32	20
Government	0	0	0	0	0	0	0	0	0	0	0
Individual	0	0	0	0	0	1	11	3	4	8	8

Fig. 6 Trends of patent applications in China's DSSC industry

for Nankai University and East China Normal University, which also collaborate with two foreign companies (Delta Inc. and Singapore Polytechnic). Notice that "ShangyuJinteng Medic. Chem. Ind. Co." is the firm most closely collaborating with East China University of Science and Technology (ECUST), and ECUST collaborates with two other firms in Shanghai through its subsidiary. In this instance, we draw two conclusions on current Triple Helix Collaborations in China's DSSCs industry:

(1) Geo-advantage plays an important role in the collaboration between academy units and corporations;
(2) Sometimes academies, especially universities, do not collaborate with corporations directly, but their subsidiaries may do so.

CTI focuses on the key competitors and their key technologies. We link the CTI exploration to Triple Helix innovation studies, particularly in terms of collaboration and competition in R&D. We chose the Top 100 terms with the Top 30 Academy & Industry Group (from Term Clumping results) to generate the Cross-correlation Map using VantagePoint (Fig. 8). In this map, we associate institutions according to the key terms that came up in their patent records. We group the institutions based on the similarity of their research interests (not based on co-patenting per se). Certainly, the key terms in patent records are not the only way to represent institutions' research interests. However, these do provide usable intelligence on organizations' emphases. As mentioned in the "semantic TRIZ" section, these key terms also could be considered as "system components."In this instance, we are able to explore potential collaborative or competitive relationships based on shared interests.

Relations within the Academy or Industry categories are common (marked in the real cycles), such as the BYD Co. and the Chery Automobile Co., University Dalian Technology and Nankai University (Fig. 8). Of special interest, note the relationship between Nanjing University and the Industry Technology Research Institute of Taiwan. We also find two clusters with both Academy & Industry represented (marked in the dotted cycles):

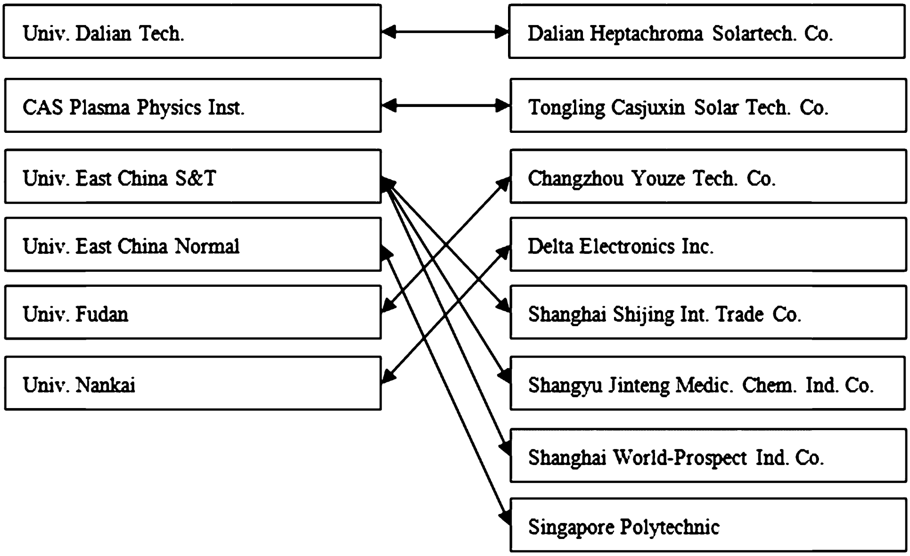


Fig. 7 Collaborations between academies and corporations in China's DSSC industry

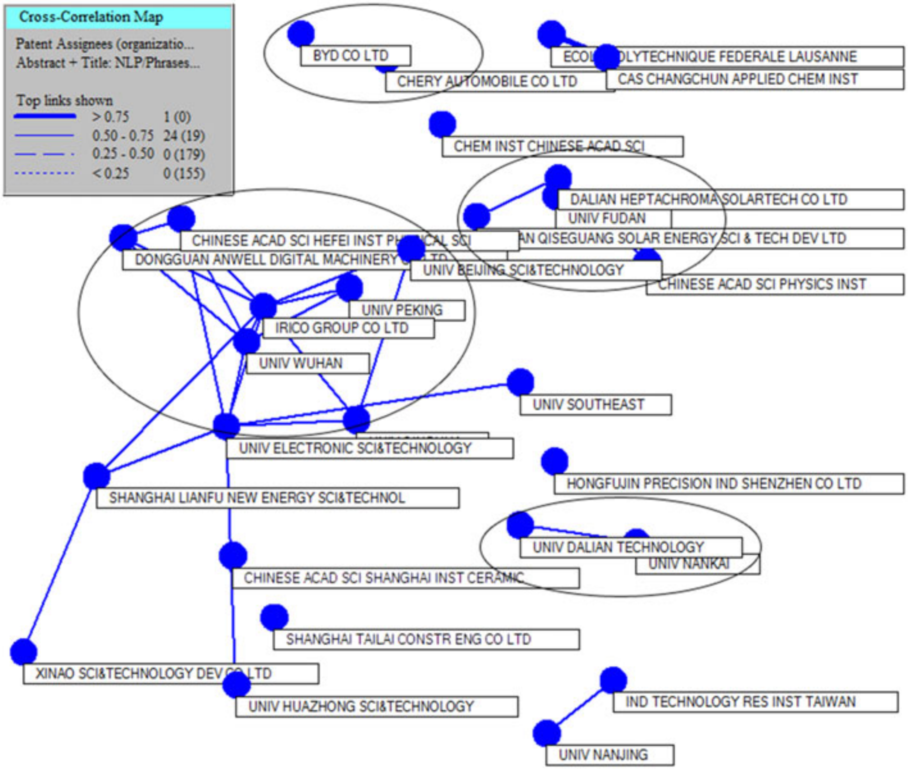


Fig. 8 Correlation map of academy & industry with similar research interests

(1) The first one has at its core Irico Group Co.(IRICO) and includes Peking University, Wuhan University, and CAS—Hefei Physical Science Institute;
(2) The second includes Fudan University, Dalian Heptachroma Solar Tech. Co. and Dalian Qiseguang Solar Energy S&T LTD.

We took a closer look at a core institution on the map (high centrality)—IRICO—by gathering more information from literature and the internet. We notice that IRICO is an old nationalized corporation known for its LED techniques. In order to avoid or reduce the loss during the financial crisis in 2008, IRICO adjusted its industrial structure, and one of its new directions was photovoltaic. Interviews with the head of IRICO, which was presented on the website, indicate a strategic industry in bolstering development of the photovoltaic industry. Initiatives include efforts to merge some small and medium enterprises (SME) in southern China based on their complementary technologies. Since 2009, IRICO has applied for nearly 70 patents in the photovoltaic field.

Problem & solution (P&S) patterns identified by semantic TRIZ for China's DSSC patenting

For this analysis, we divide our data into Academy (376 records), Industry (187 records), and "Academy & Industry" (10 records), and retrieved the P&S patterns separately via GoldFire Innovator software. Selected sample of the results are shown in Table 6. We focus on 4 items from

Table 6 P&S patterns of semantic TRIZ in China's DSSC industry

Clusters	P&S patterns	Years	Type	THM
Photo anode—photoelectric conversion efficiency	…for solving the problems of bad soakage of dye and semiconductor material in dye sensitized solar energy battery and **low** *photoelectric conversion efficiency* in **existing** technique….	2005	P	I
Photo anode—indium tin oxide	The **conductive layer** is **composed** of optional one of *tin indium oxide*, tin fluorine oxide, ZnO–Ga_2O_3, ZnO–Al_2O_3, tin-base oxide, tin stibium oxide and zinc oxide, mean grain size…	2008	S	I&A
Sensitizer—organic dye	A *photosensitive dye* e.g. *organic dye* is attached on a pipe wall of the nanometer pipes	2011	S	I
Electrolyte	In the solar cell, the medium holes oxide quasi solid *electrolyte* is set to **replace** the liquid *electrolyte* at the surface of the wide-gap semiconductor…	2005	S/P	A

Triple Helix model (THM) participants are coded as A (academy organizations, including universities and research institutes) and I (industry)

Terms in Bold: Actions

Terms in Italic: Subjects or Objects

3 sub-system clusters: "photoelectric conversion efficiency" (Photo Anode), "indium tin oxide" (Photo Anode), "organic photosensitive dye" (Sensitizer), and "electrolyte" (Electrolyte).

According to semantic TRIZ studies with GoldFire Innovator, we analyze the items and their related sentences, and track patent activity annually. For example, we notice that both academies and corporations focus on the "liquid electrolyte" and "gel electrolyte" continuously in the "Electrolyte" sub-system of DSSCs. We find several related P&S patterns, such as "solid electrolyte is set to replace the liquid electrolyte," "liquid electrolyte is used for preparing gel electrolyte," and so on. Such information indicated by the P&S patterns offers rich CTI potential to track overall and individual organization interests over time (Table 6).

TRM for China's DSSC industry

Based on the previous analyses, we now move to depict the P&S patterns in a Technology roadmap (TRM). We engage persons knowledgeable about solar cell technology and industry in China to help interpret the empirical findings. Our small patent dataset of China's DSSC industry only contains 568 records and DSSCs constitute a small sub-domain in the overall solar cell and renewable energy system. Phrases and terms we extract have high similarities and are not easy to classify into different levels via automatic software. Therefore, it is not appropriate to identify the technology development phases based solely on the empirical methods, as we did in our previous TRM work (Zhang et al. 2012a). In this case, we distinguish three general technology development phases - materials, techniques/components, and products. Experts then help us to modify the P&S patterns to make the description succinct and fit for TRM rendition. They also help interpret these patterns. The TRM for China's DSSCs Industry is shown as Fig. 9.

We asked 3 experts[1] to review Fig. 9, and they endorsed the trends depicted. The following findings reflect their inputs:

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[1] Dr. Chen Xu, who graduated in Materials Science and Engineering, Georgia Tech and works in IBM; Ms. Tingting Ma, PhD student at the School of Management and Economics, Beijing Institute of Technology, who has been analyzing DSSCs for three years; and Dr. Jud Ready, principal research engineer in nanotechnology and materials engineering, Georgia Tech Research Institute, who reviewed and agreed with our results finally.

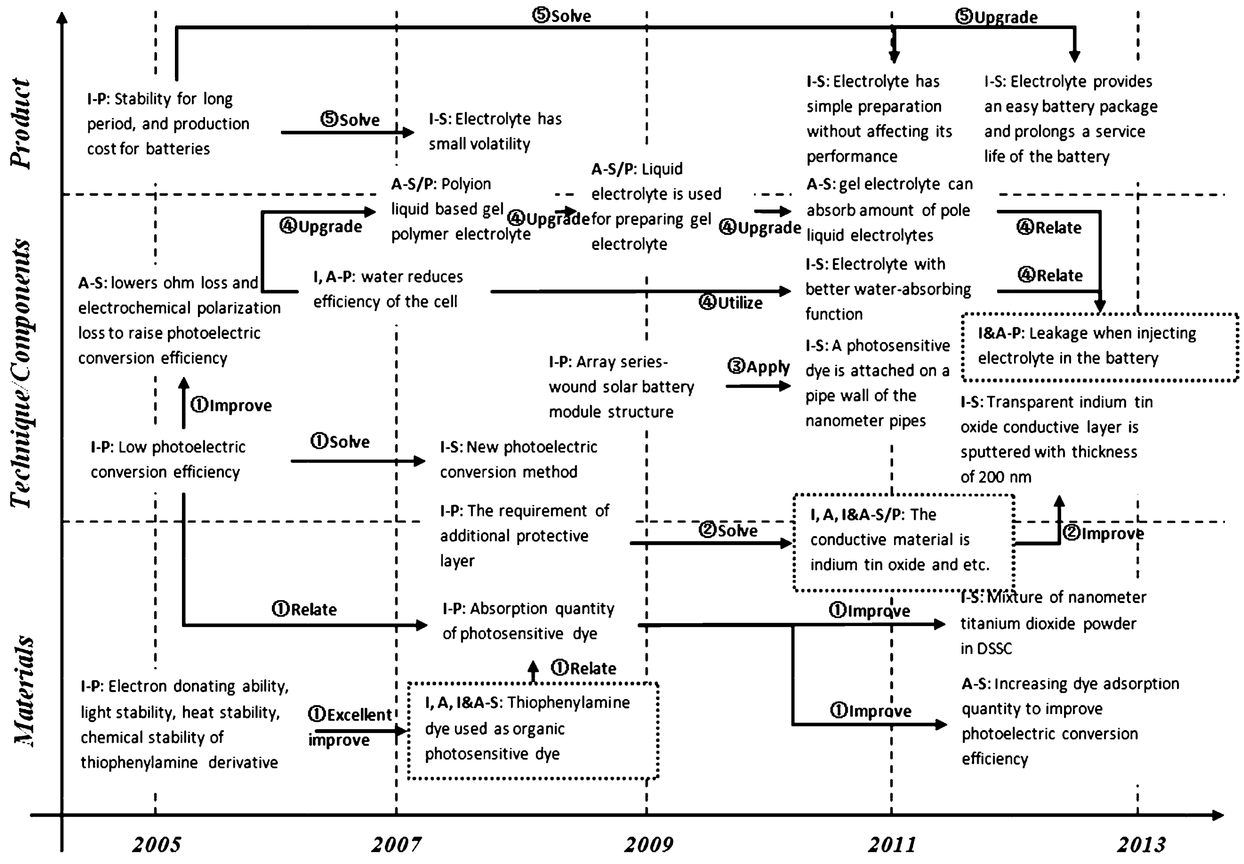

Fig. 9 Technology roadmap for China's DSSC industry

(1) The ① trend: Academies and corporations of China have focused on the "low photoelectric conversion efficiency" problem for a long time, which also relates to "the absorption quantity of photoelectric dye" problem. Solutions of these problems have mostly involved advances at the materials level, and, also, some new techniques have been involved.—*Both agree; h*owever, this is considered a fundamental issue of DSSC research, and academies and corporations have different approaches because of different purposes;

(2) The ② trend (*2 passable agreements from experts*): Both academies and corporations emphasized this material related problem, where indium tin oxide conductive layer was improved. Our experts commented that this trend should not be limited to contact materials, and Indium tin oxide is the issue because of the shortage of Indium, while ZnO and other metal oxides are potential replacements;

(3) The ③ trend: Only corporations had this kind of patents, focusing on a technique attaching photoelectric dye to nanometer pipes. Our experts offered *1 objection and 1 abstention*. One commented that it is a fair competition because academies always contribute through either articles or patents; thus, the conclusion should be both academies and corporations have great interest in dye loading related processes.

(4) The ④ trend: It is interesting to discover the different research interests of academies and corporations. Academies paid more attention to upgrading the materials and technical components from liquid electrolyte to gel electrolyte, while corporations added better water-absorbing functions in the battery. Additionally, a leakage problem occurred when injecting electrolyte to battery—our experts offered *1 agreement and 1 abstention*. One commented that gel electrolyte is the most used electrolyte form, showing better stability and conductivity than liquid and solid electrolytes. However, because of the different final system behaviors, academies would not care about the reliability issues too much.

(5) The ⑤ trend: These address problems in the "product" level, which relates heavily to corporate concerns. Problems evolved slowly, with ongoing production cost concerns, and some advanced electrolyte related package and preparation methods being invented—*1 expert fully and 1 possibly agreed*. One comment is that corporations should also be concerned with stability problems.

Significantly, we find three P&S patterns evolving with collaborations between academies and corporations:

- Thiophenylamine dye is used as organic photosensitive dye;
- Indium tin oxide is used as the material for a conductive layer;
- Leakage problem when injecting electrolyte to battery.

In this case, it indicates that collaborations between Chinese academies and corporations in DSSC development focus heavily on the materials and techniques (the two more basic developmental layers, as per Fig. 9), and the commercially oriented collaborations involving battery product development (the top layer) are much weaker.

Discussion and conclusions

Discussion of Triple Helix innovation in China's DSSC industry

Statistical analysis of China's DSSC patents is relatively novel. Semantic TRIZ and TRM analyses here show some interesting Triple Helix aspects concerning innovation in China's

DSSC industry. Since 2002, DSSC patent activity in China has accelerated (Fig. 6). It is interesting, and potentially salient to national industrial policy, to identify the relative roles of universities, research institutes, government agencies, and companies. In this paper we focus solely on patent activity (elsewhere, as noted, we continue to study R&D and business-related publication activity).

DSSCs represent a NEST—a newly emerging technology, albeit one that competes in an existing energy marketplace. The renewable energy technology subset of that market is undergoing rapid development. And within that subsector, solar cell (photovoltaic) technologies of many types are being pursued.

Given such flux, it is worthwhile to locate China's DSSC developmental efforts. Somewhat surprisingly, our analyses find that Academy patenting has been considerably more extensive than corporate patenting on these solar cells in China. We discuss the absence of Governmental patenting, noting the important role of research institutes, especially the Chinese Academy of Sciences (that we locate in the Academy, but note strong governmental ties). We also call attention to the interesting engagement of ITRI of Taiwan in patenting in SIPO.

Although Chinese governmental units have not been active in patenting, we note significant presence in funding DSSC research. The annual program lists of the National Science Foundation of China (NSFC) show nearly 100 DSSC—related projects. That support has gone to the Academy—universities and research institutes—not to Companies. Other governmental funding (e.g., Ministry of Industry and Information Technology, Ministry of Science and Technology) also goes mainly to Academy organizations, although some photovoltaic companies appear to receive government funding for DSSC R&D. This suggests a focus on fundamental R&D, and that appears consistent with the Academy patenting record that concentrates in the more foundational materials and techniques layers of the TRM profile (Fig. 9).

We try to conclude the Triple Helix relationships in China's DSSC development as follows: (1) Collaborations between Academy units and Industry organizations are limited, based on co-patenting data, but interesting; (2) Academies afford the more fundamental materials and technique development, while Companies bring to bear more Product issue resolution interests and capabilities; (3) Future research might well explore the strategic partnering (both that in place and potential) between Academy and Industry institutions via in-depth consultations and case studies. Investigating what factors contribute to successful Academy-Industry partnering could be rewarding.

Conclusions

This paper presents a novel combination of analytical approaches—Tech Mining, semantic TRIZ, technology roadmapping (TRM), and Triple Helix Modeling (THM). Figure 2 shows how these interrelate. We present a case analysis for DSSC patenting in China. This serves to illustrate how the analytical approaches can complement each other. Tech Mining (combining bibliometric activity counting with text analytics) provides a rich resource on topical content and key players (especially at the organizational level in this case analysis). Term clumping techniques help consolidate the topical information (Table 2) to get to fruitful conceptual units for further analyses (Table 3). This reflects a novel extension of these techniques from analysis of research publication to patent records. Semantic TRIZ methods help relate "clumped" terms to purposive meaning—the Problem& Solution (P&S) analyses illustrated by Table 6. We think TRM visualization enriches understanding by providing perspective on topical R&D emphases evolving, and these can be associated with the key actors engaged with each, over time. That, in turn, complements Triple Helix analyses.

Further studies to extend these results can take several directions. In terms of data, we are updating our Derwent patent data, and we believe that it will atone for the disadvantages of our current small size dataset on DSSCs. In addition, it would be valuable to complement patent analyses with R&D publication analyses, which particularly extend our fundamental understanding on R&D levels.

We feel it also would be interesting to combine TRIZ technology evolutionary trend analyses with the Triple Helix concepts to compare different kinds of NESTs at different development levels. On one hand, addressing one or two specific technical questions, comparing the different development trends in the THM, and understanding the emphasis of different institutions and the potential collaboration opportunities should be meaningful. On the other hand, especially in the R&D levels, we aim to keep working to engage R&D factors (e.g., policy, governmental funding, and business model) into the THM, to deepen understanding of the collaborations and competition patterns.

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