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Four dimensional Science and Technology planning: A new approach based on bibliometrics and technology roadmapping

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ABSTRACT

Seemingly endless new technologies are emerging. Mapping out Science and Technology (S&T) planning correctly on the national level would help innovation shareholders remain current on technological development trends and gain an advantageous position among the fierce future competition of the global market. Thus, formulating effective S&T planning is significant for a nation, especially for new and emerging technologies. This paper proposes an industry S&T planning framework. Different from previous frameworks, this methodology's dynamic is directed in four dimensions (nation, technology, industry, risks and impacts), tries to find the key elements in a specific technology area, and aims to aid in national S&T planning. China's solar cell industry is employed as the case study.

1. Introduction

As globalization continuously advances, so does technology. This leads to the frequent appearance of candidate new technologies and the blossoming of some of those as Newly Emerging Science and Technologies [NESTs]. Compared to traditional technologies, emerging technologies are fast developing and have uneven and limited applications in the marketplace. Yet, one NEST may profoundly impact the global industrial and economic structures. The strategic importance of technology in delivering value and competitive advantage becomes more critical as the cost, complexity, and rate of technology change increase, even as competition grows and sources of technology globalization multiply [1]. These circumstances drive the need for nations to identify and grasp potential technology opportunities [2]. This paper presents an approach to set up planning for NESTs based on understanding national priorities in order to enhance technological innovation and international competitiveness.

Our four dimensional (nation, technology, industry, risks and impacts) approach seeks to integrate future-oriented technology analyses [FTA] into a national Science, Technology and Innovation [ST&I] policy framework. Regulation and policy instruments need support systems to augment their targets—a variety of (and often shifting) industrial contexts. This emphasizes the requirement for relevant and timely strategic intelligence to enable effective decision-making and strategy development for national S&T planning. Considering this, governments ought to seriously consider the following questions:

(1) How best to capture emerging technologies' development situation? Many existing approaches focus on exploring future possibilities, neglecting to make sure that we understand key “forces and factors” of the current situation [1,3–5].

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(2) How to build upon the current analyses to address the emergence and evolution of technology for the nation? Which dynamics are important? (This has implications for point 1.) What sorts of data and analyses are needed [5] to evaluate and prioritize NESTs?
(3) How best to evaluate not only the technology per se but also the industry to deliver that technology in the form of innovative products or processes?
(4) Considering social and environmental consequences that have indirect, externality, or unintended impacts, for good or bad, how does the NEST fit within the risk and regulation landscape?

These four points summarize many complex practical issues. We explore these four requirements, in different contexts and in projects that variously lean more on some elements rather than others. Our intent is to construct a hybrid innovation management model aiming to help a nation implement Science and Technology planning of an emerging technology with both qualitative and quantitative methodologies.

A number of additional questions are critical in analyses of target technologies. What is the current situation with respect to a given NEST for the nation? Most FTA approaches favor expert engagement, but identifying experts is a non-trivial task. In many cases, the types of actors to be engaged vary. Qualitative and quantitative methodologies must be combined into useful intelligence to feed into multi-actor engagement approaches.

This paper is organized as follows: Section 2 describes a four dimensional Science and Technology planning framework for emerging technologies. An empirical study of China's solar cell industry is used to verify the scientific and practical value of the model in Section 3. Finally, Section 4 presents conclusions.

2. Four dimensional Science and Technology planning approach framework

2.1. A tailored approach

Analysis of an emerging technology should elucidate technology policy and management issues and questions. Porter and Cunningham listed 39 tech mining questions and more than 200 indicators based on 13 Management of Technology (“MOT”) issues [7]. These are just suggestions; the technology analysts need to work with the intended study users to determine what information would be most valuable in managing the technology in question and in what form. For emerging technologies, aiming for different targets, the questions could vary. Does this technology offer realistic innovation potential? What is driving such innovation? Are there potentially unintended consequences of manufacturing and introducing the resulting products (or processes)? The first two questions lay more emphasis on the technology while the latter question emphasizes industrial and societal factors.

To answer the spectrum of questions, we construct the framework in four levels for Science and Technology planning following the four dimensional idea. These four levels are 1) the national context for the target technology, 2) the target technology, 3) that technology's industry, and 4) potential impacts of target innovations. In this framework, each level provides the background and analysis base for the following one. We try to find the key elements in each level by answering the MOT questions to help set up the Science and Technology planning for an emerging technology.

Nations operating in competitive environments demanding process improvements, new product introductions, or technology-enhanced services must obtain and use information on emerging technologies [1]. Bibliometrics – counting activity levels and identifying patterns in R&D bibliographic records, plus patent analyses – has contributed to Science and Technology studies for decades [6]. With the expansion of databases that compile abstract records and of desktop computing power, text mining of those records further enriches the empirical base. “Tech Mining” [2] is our shorthand for such activities. It can help researchers and research managers understand the “research landscape” to identify what is already heavily studied and to help ascertain the best opportunities for further research.

However, limitations of bibliometrics also should be listed: (1) not all R&D is published or patented, and counts do not distinguish quality [2]; (2) not all publications or patents are similarly valuable; for example, patent barriers could have more business value than the technology itself; (3) timely and important information may be missing due to publishing lag times. At the same time, qualitative methodologies (e.g., Delphi) provide chances to compile diverse experts' opinions. They depend on experts' intuitive knowledge, but they may be biased since the opinion of experts may be influenced by subjective elements and limited cognitive horizons [8–10]. Accordingly, various researchers are working to combine qualitative and quantitative methodologies. Based on a national R&D program in Korea, Lee and Song selected the key research area in nanotechnology by fuzzy clustering methods with a questionnaire of 600 experts from government, enterprises, and institutions [11]. In our framework, we will employ qualitative analyses or quantitative analyses, or the combination of the two, for different levels based on their respective characteristics.

2.2. A Science, Technology and Innovation (ST&I) planning framework

The research framework is constructed as per Fig. 1.

Level 1—National Context for the Target Technology: In order to conduct strategic S&T planning, understanding the country's technological innovation environment is the first important step. The environment may include the current competitive situation, global and national technology policies, and market development. All of this information is required to determine whether the

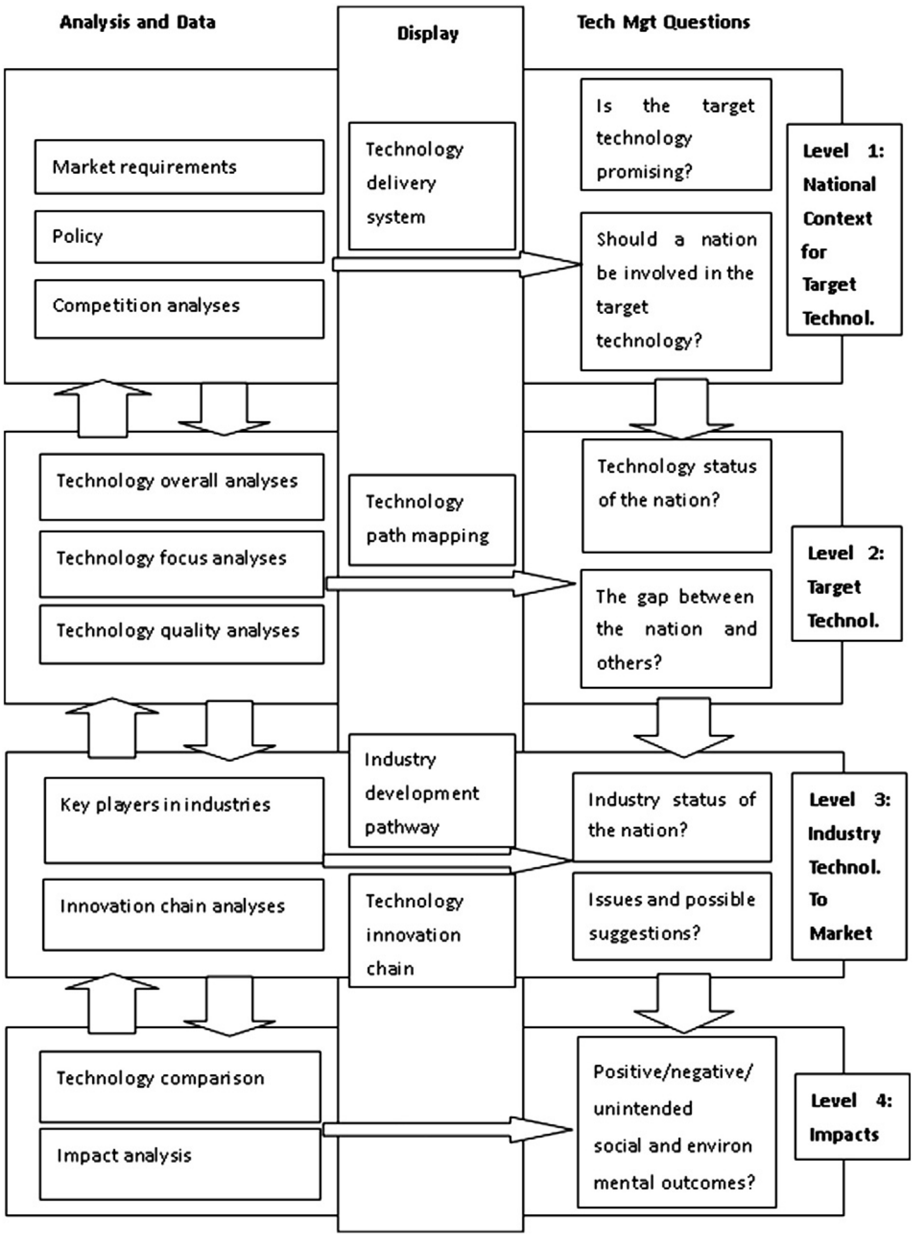

Fig. 1. Four dimensional "Up-to-down" Science & Technology Planning Framework.

nation should pursue this technology and therefore undertake planning for it. In this paper, we use the Technology Delivery System ("TDS") to reflect contextual dynamics because of its suitability for "emerging" technologies by distinguishing the key contextual factors affecting the success of that innovation process [14,15]. In this level, the qualitative analysis, namely the experts' knowledge, forms the major method of data gathering.

Level 2—Target Technology: The NEST under consideration is the core for product development and attendant industry; if the conclusion from Level 1 is that "the target technology is promising and the nation should be involved in the related industry," then this level aims to reveal the current situation of the emerging technology and define the gap between one nation and the most advanced international level. Patent data can contribute to characterize a nation's status for the target technology overall, and regarding focus (its emphases) and quality (how its capabilities compare to international competitors). Combining empirical results with experts' knowledge, this section yields the development trends and future direction for this emerging industry by applying technology path mapping.

Level 3—Industry (to deliver the technology to market): After understanding the current situation of the NEST and the gap between one nation and the advanced level, the key technology management objective at this level is to grasp the current situation of a nation's industry to produce innovative products or processes using the NEST in question. This section aims to identify the nation's industry leaders and knowledge-sharing networks, and to analyze the industry's future direction by monitoring the activities of major players. At the same time, through in-depth research on the industry innovation chain, this section tries to identify any bottlenecks impeding successful commercialization and to subsequently offer ideas for their solution. We do note that there will likely not be a one-to-one mapping between a target NEST and "an" industry—obviously, an industry draws upon multiple technologies and, conversely, one technology is likely to be applied in multiple industries.

Level 4—Impact: The analysis then should be followed by identification and analysis of potential impacts of the innovations involved. These might include attendant safety and environmental control developments in the manufacturing or other supporting innovations or to help mitigate negative impacts. Technology Assessment draws attention to issues beyond the technology itself, to expand selection criteria beyond technical functionality to consider cost, infrastructures, and compatabilities—i.e., impact assessment. We especially want to identify potential hazards and side-effects, including environmental, health, and safety concerns that could arise. We also are very interested in secondary effects, potentially involving economics, social changes, and so forth.

3. Case study: Four dimensional Science and Technology planning for China's solar cells industry[1]

As a sustainable use of clean energy, solar energy has great potential for future development and application. Solar technology development began in the 1950s. Although the current cost for solar power generation is high, in the long run, as the technology advances, solar energy is promising to become the mainstream of energy use with an immeasurable potential for development. In recent years, the energy situation has achieved high priority throughout the world. Thus, sustainable photovoltaic (solar) energy has been developing rapidly, and in some developed countries such as Germany and Japan, solar photovoltaic energy has advanced into extensive production. Driven by the international market and domestic policy, China's solar cell industry has risen gradually and has quickly become a new star. The emergence of a large number of outstanding solar companies – such as Wuxi Suntech, Changzhou Trina, and Tianwei Yingli – has initiated business development at many stages of the solar cell industry; thus China's solar cell innovation chain is emerging [13].

However, compared to the leading countries, whether in terms of technology, or production and market, the development of China's solar cells industry is still not mature. Therefore, understanding the current technical status and industrial development is important for making a preliminary summary and a reasonable forecast for China's solar cells industry potential. This information is particularly meaningful for Science and Technology planning—i.e., to what extent should China devote resources to solar cell development?

Based on this background, employing the four dimensional planning framework, we take China's solar cell industry as the case study. We try to find out the key elements at the four levels, detect the relationships and future directions of the key elements, and aid in S&T planning for China's solar cell industry. This research is undertaken on behalf of the Ministry of Science and Technology of China. The Ministry is interested both in the results for solar cells and as a model methodology to consider for general NEST planning.

We use State Intellectual Property Office of China (SIPO) patents as the primary data source for technology mining and for other analyses.

3.1. Level 1—National context analysis for China's solar cell industry

This section attempts to find the driving forces and potential sources of resistance for China's solar cell industry and to clarify the need and basic background for technology planning in this technology area. We use "technology delivery system (TDS)" ideas here. The TDS approach is akin to other technology innovation systems approaches, but we favor its distinct treatment of (1) the enterprise (organizations with requisite capabilities) to develop the innovation and take it to market, and (2) the key contextual factors (actors, trends and events) affecting the success of that innovation process. The TDS approach has been successfully employed by Ezra to analyze the USA Solar Photovoltaic and Solar Thermal Industries which was used for technology management and policy development for the US Department of Energy Solar Energy Program [12]. In this section, we set up the TDS for China's solar cell industry (Fig. 2), mainly emphasizing key national contextual factors, including the competitive environment, the international situation, China's market for solar cells, and China's policy by combining expert knowledge and a literature review.

(1) Competitive environment: although solar energy is an inexhaustible source of renewable clean energy, achieving effective and convenient use of solar energy resources remains a largely unfinished task; therefore, the study of solar cells has become increasingly important. The current development of solar cells is experiencing various problems: it satisfies only a small part of the world energy consumption; the cost is much higher than other energy sources. However, the world has reached a consensus that, with improvements to manufacturing technology, solar cells will eventually be a more feasible approach for human large-scale renewable energy applications.

[1] There are three generations for solar cells. In China, especially for industry, the first generation is dominant, with some attempts within the second and third generations, which are considered to be the future direction for solar cell industry. Also, the solar cell industry not only emphasizes the products, but also stresses the materials, production process, etc.

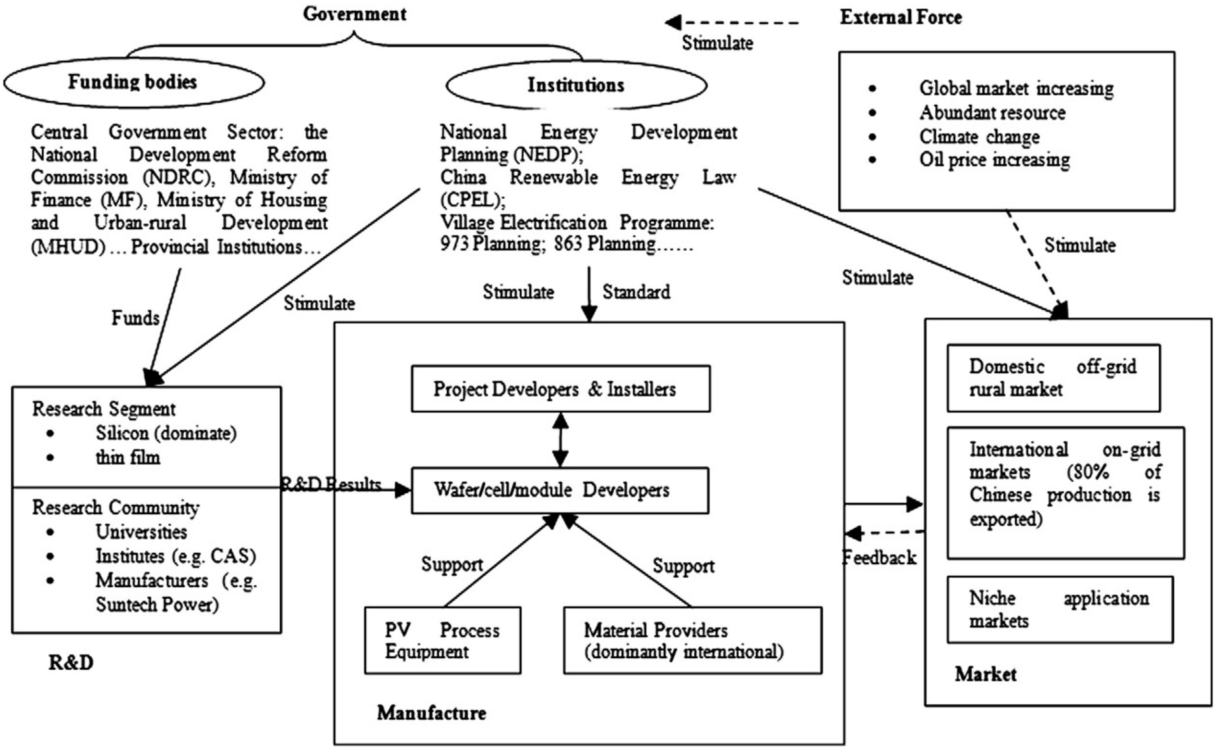

Fig. 2. Technology delivery system for China's solar cell industry.

(2) International situation: Europe is the world leader and the main force in the renewable energy market and industry. The average annual growth rate is more than 2%. One of the important reasons why Germany and other European countries, as well as the United States and Japan, lead in the solar cell area is the comprehensive impact of government goals, price incentives, financial subsidies, tax incentives, supportive credits, export promotion, and R&D funding. Germany, Spain, and other European countries employ the policy of compulsory acquisition with a fixed price system. Germany's Renewable Energy Act requires that the monopoly energy companies, primarily power companies, must follow state rules for prices in order to purchase renewable energy products. Under the support of governments, the solar cell industry has developed rapidly; the annual average growth rate for solar cells and module production has reached up to 33% in the last 10 years, 43% in the last 5 years. It is noteworthy that, in 2006, China's solar cell production reached 369.5 MWp, following Japan and Germany, making it the world's third largest producer of solar cells [13].

(3) China's market: China has extremely rich solar energy resources. From 1971 to 2000, nearly 30 years, solar energy reached between 1050 and 2450 kWh/m^2; the average amount of solar radiation for 96% of the land area reached more than 1050 kWh/m^2. Each year, China's land surface solar radiation is equivalent to that of 1.7 trillion tons of standard coal. Therefore, extensive application of solar cell technology could hold great significance for China's economic and social development. At the same time, as China's coal, oil, and other traditional energy resources become increasingly scarce, development and utilization of solar and other new energy sources are more in demand [13].

(4) China's energy policy: the main policy framework to support China's solar cell industry is reflected in two aspects: one is the national energy development plan, including the “Eleventh Five-Year Plan” and the long-term development of renewable energy planning, etc.; the other is implementation of the “Renewable Energy Law” in 2006. Those policies make provisions for subsidies, R&D support, technology demonstration construction, and other aspects [13].

From the analysis above we recognize both advantages and disadvantages of solar energy, as compared to other energy sources. However, the international community generally recognizes its potential; therefore, all major countries have introduced policies to make up current deficiencies for solar cell technology to encourage the industry's development. This international consensual climate has facilitated development of China's solar cell industry. We also explore the impact of the domestic environment to China's solar cell industry development. Significant demand, abundant resources, effective policy to support R&D, and subsidies for remote areas are effective factors promoting the progress of China's solar cell industry.

The analysis above shows the importance and urgency for China's solar cell technology development and also demonstrates the need for science and technology planning. On this basis, Level 2 analysis is warranted—to assess the specific attributes of solar cell development for China. Technology analysis can be used to grasp China's current technology level and the strengths and weaknesses of its solar cell industry, to help plan the future of China's solar cell technology.

3.2. Level 2—Technology analysis for China's solar cell industry

Keeping the national context analysis of the last section in mind, this section explores the innovation pathway for China's solar cells technology. The analysis will mainly employ bibliometric approaches to Chinese patent data to uncover the current situation of China's solar cell technology. In this part, technology roadmapping is used to describe the technology trends and foci, looking both backward and forward in time.

Based on different classification standards, we can divide the phases of the technology development cycle into different parts, and the specific features of different technologies are also able to influence the classifications. Aiming to distinguish the differences among solar technology fields, we attempt to define the technology development phases by extracting core terms in the solar cell patent abstract set and analyzing the prominent International Patent Classifications [IPC]. In this step, we generate objects-associated mappings in successive time periods with the help of bibliometrics software. Experts then summarize the phases of the technology development cycle by reviewing the evolution of terms. More than other steps, qualitative methodologies provide the foundation for the "Construction of Technology Roadmapping." According to the objects and relationships (Objects-Associated Mappings), experts locate each object on the phases and time axes of the roadmap (Fig. 3).

Expert input was completed in two rounds. First, we read overview papers, executed an initial database search, and text-mined the database search results. We did preliminary searches to identify local expertise to help guide us. One professor invited us to meet, and a Ph.D. student helped during analysis. The face-to-face interview with him provided input to allow a first evaluation of our analyses.

A second round focused on identifying workshop participants to develop the technology roadmap. Again, our collaborating material science doctoral student helped the social science organizers identify and encourage participation by two professors and four doctoral students with expertise in nanomaterials, organic solar cell, and silicon solar cell. In addition, a faculty member with expertise in innovation processes and nanotechnology joined. The workshop focused on mapping likely innovation avenues. Our collaborating expert, Chen Xu, helped interpret results from the workshop (which entailed abundant note-taking).

We can see the following from Fig. 3:

(1) Between 1985 and 2000, China's solar cell industry focused on basic research; some of the research was not strictly related to the solar industry.
(2) About 2000, China's solar cell industry entered into a stage of rapid development. In this stage, component research and product research were conducted almost simultaneously, but component research began a little earlier than product research and reached a peak between 2000 and 2005; however, it showed a slightly shrinking trend after that.
(3) In 2004, the terms "battery," "light-emitting diodes," and "semiconductor" first appeared among high-frequency technology words of China's solar cell patents, which also marks the official entry of China's solar cell industry into the product research stage. After 2005, both basic research and component research slow on a relative basis, showing that product research has become mainstream to the industry.

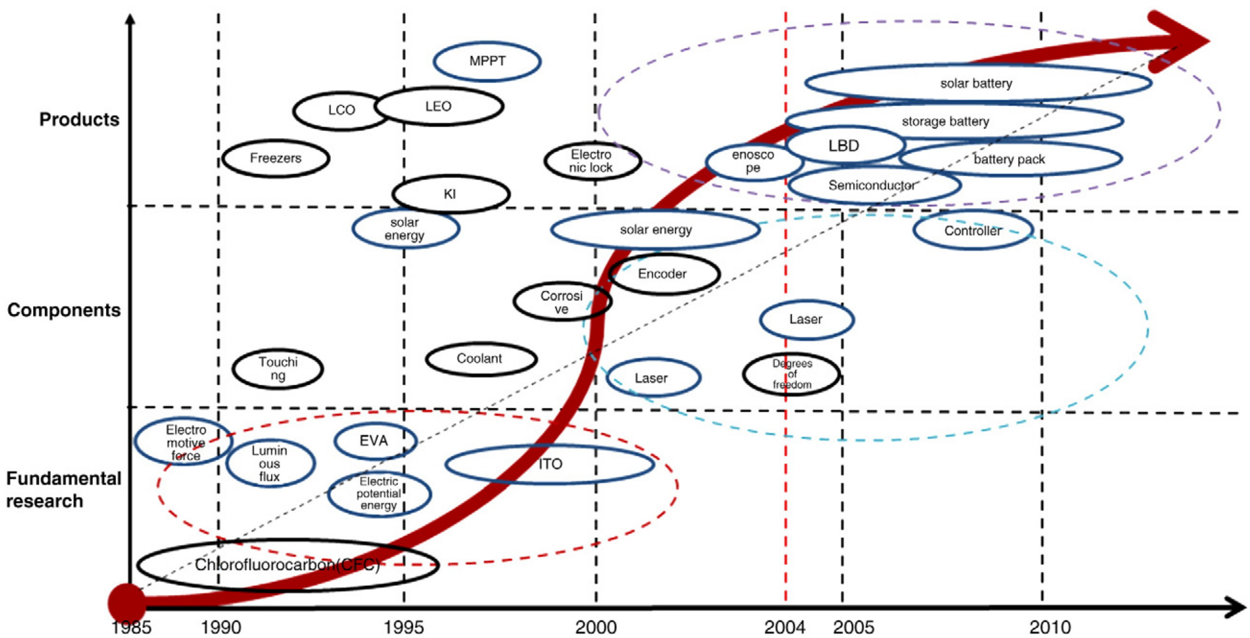

Fig. 3. Technology roadmapping of China's solar cell industry.

We also analyze technology quality by exploring how long a patent is maintained. The analysis in this section is performed bearing in mind that, if the patent is deemed to be valuable and the maintenance fee is reasonable, the owner will pay to maintain the patent as long as possible. We can see that in SIPO, the maintenance period of patents granted to Chinese assignees is not as long as those granted to key foreign nations (Fig. 4, top portion). Foreign applicants are actively patenting in China; indeed, most high-quality patents (i.e., those maintained for many years) are held by non-Chinese applicants. A large proportion of patents granted to Chinese assignees (more than 50%) are maintained for less than 5 years. Furthermore, China's patents take a smaller percentage among the high-quality (long maintenance) patents, while Japan's percentage among these patents is quite high. All these observations show that the important patents, as well as the key technologies, still belong to Japan, even in China.

In the lower portion of Fig. 4, we explore the 30 patents maintained in force for more than 12 years. Among that group, two patents lead: one applicant is Tianjin University; the other one is Jianli Wang. They both are 23 years old and remain in force. In comparing countries, two Japanese enterprises (Canon Inc. and Sharp Corp.) take the top rank, having several patents with long

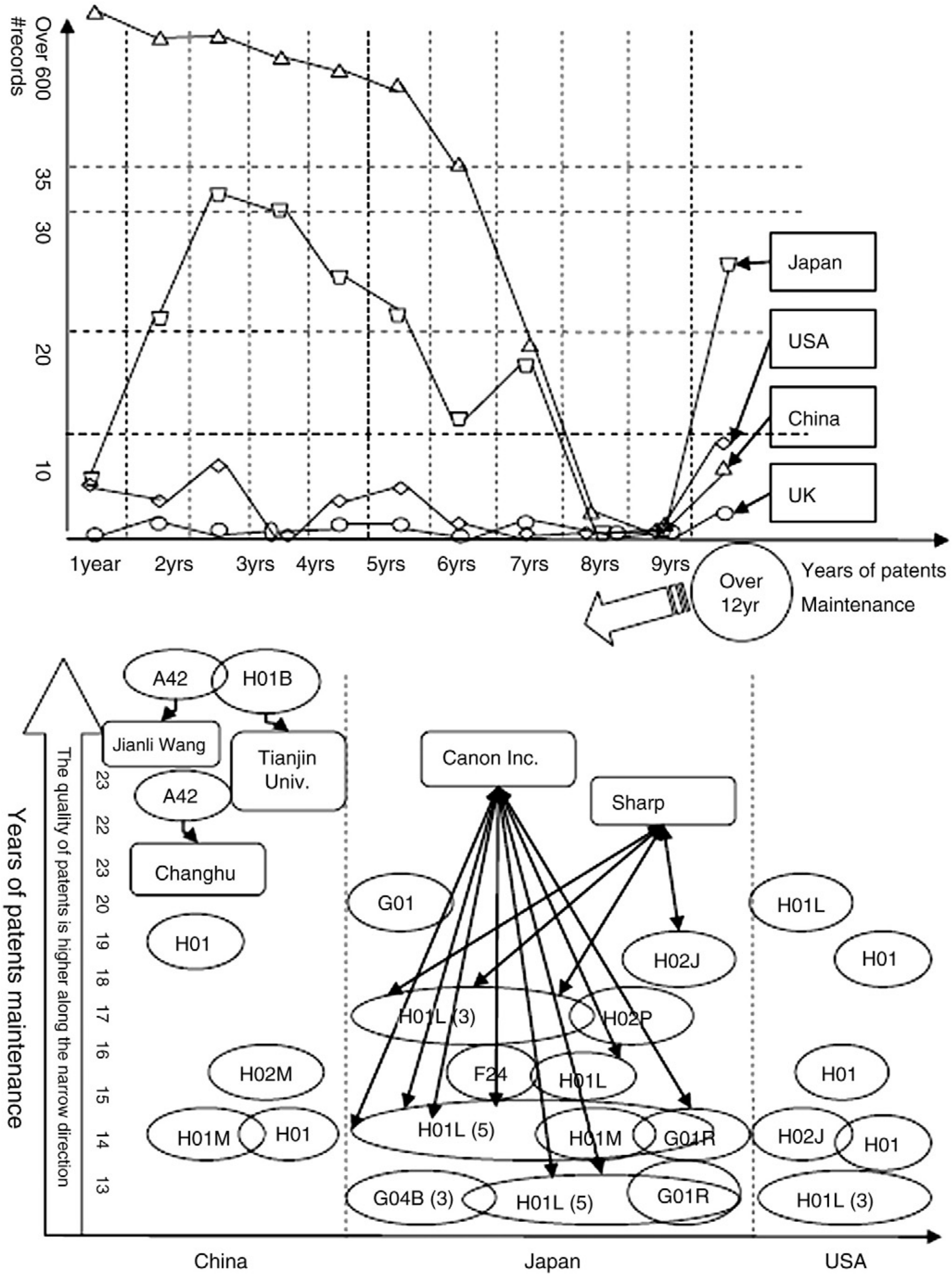

Fig. 4. Technology quality analysis of China's solar cell industry.

maintenance times. We also mark the important IPCs in the chart to indicate which solar technology fields are considered especially significant. These provide useful information for further in-depth analyses of the technology (not presented here).

From this analysis, on the one hand, we could understand the technology emphases and trends for China's solar cell industry, while, on the other hand, we uncover the technology distance between China and advanced solar cell countries. Based on this, the paper will explore the industry structure and pathways to promote the development of China's solar cell industry in the next section.

3.3. Level 3—Industry analysis for China's solar cell industry

This section will explore the key enterprises and institutions in China's solar cell industry. Again drawing on the SIPO patent data, we develop a roadmap for China's solar cell industry from the perspective of "product research," and also a detailed description of China's solar cell industry considering the whole industry chain (Fig. 5).

Fig. 5 shows that, before 2000, China's solar cell industry was in its infancy, with few universities, research institutions, and influential enterprises patenting. At this stage, Japanese solar companies, represented by Sharp and Sanyo, dominated solar cell patenting in China. From a patent perspective, we can say that, before 2000, China did not have a local solar industry, and the research on solar cells was only in a theoretical phase. Patent activity by Chinese inventors and assignees was early stage. After 2000, under the active promotion of national policy, the Chinese Academy of Sciences and a large number of universities and research institutes began actively patenting solar cell technologies. Their R&D results were quickly applied by industry, which promoted the formation and development China's solar cell industry. Based on SIPO patent patterns, after 2005, China's solar cell industry entered a rapid development period; enterprises with great influence both abroad and at home formed, such as Wuxi Suntech and Changzhou Trina. Notable cooperation began with several cooperative enterprise groups emerging; collaboration between enterprise and academia also increased. In Fig. 5, the red and blue circles represent two different cooperative groups.

Fig. 6 concerns the major parts of the solar cell innovation chain. On the innovation chain (upper tier), we mark the current stage and notable problems within China's solar cell industry and propose possible solutions. Currently, China's solar cell industry has two prominent characteristics. First, the two endpoints in the industry chain are subject to foreign restrictions (border marked in dotted line in Fig. 6). China depends greatly on imported silicon, which is an important issue that impedes the development of the solar cell industry. In solar cell applications, export is the main direction, indicating that China's domestic market is still very limited. These two issues largely limit China's solar cell industry.

The problems encountered at all stages can be divided into three categories: dependency on the import of raw materials, weak R&D capability, and a small domestic market (circles in Fig. 6). Thus, R&D capability is an important issue to be mentioned. Extending upon the patent analysis in the last section, we know that, though a number of cooperative efforts between research institutes and enterprises have emerged, R&D and production are still not well-integrated. Few enterprises take part actively in R&D, so research results are not smoothly converted into production.

Integrating these results to inform technology planning, we propose the following:

(1) Policy should encourage thin-film solar cell R&D and production in order to address dependency on the import of silicon raw materials. Although thin-film solar cell technology cannot immediately replace silicon cells, it appears to be an important future direction for the solar cells industry.

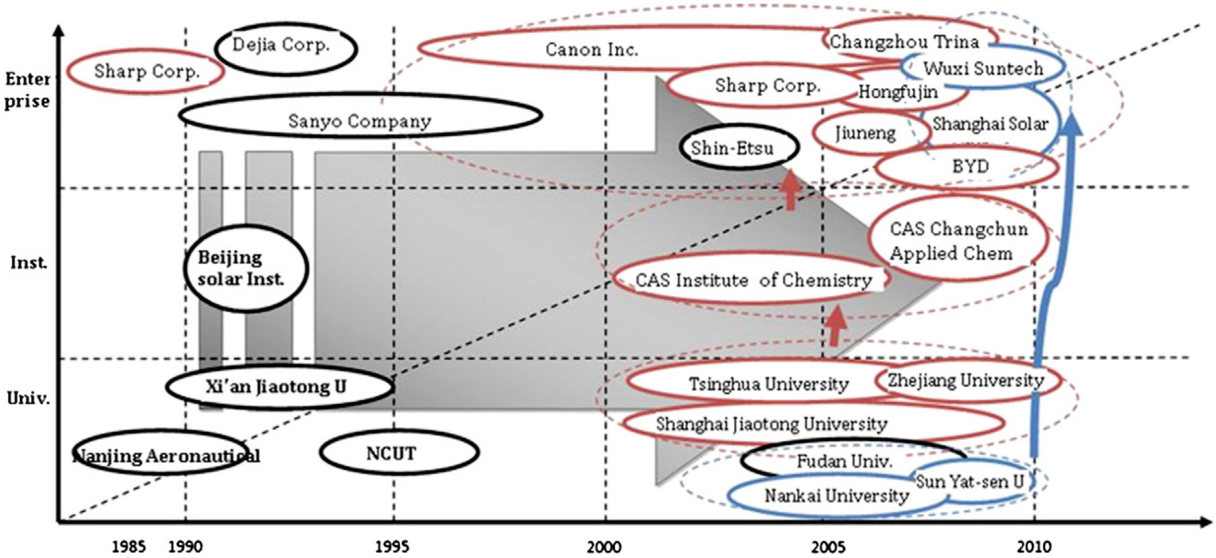

Fig. 5. China's solar cell industry roadmap.

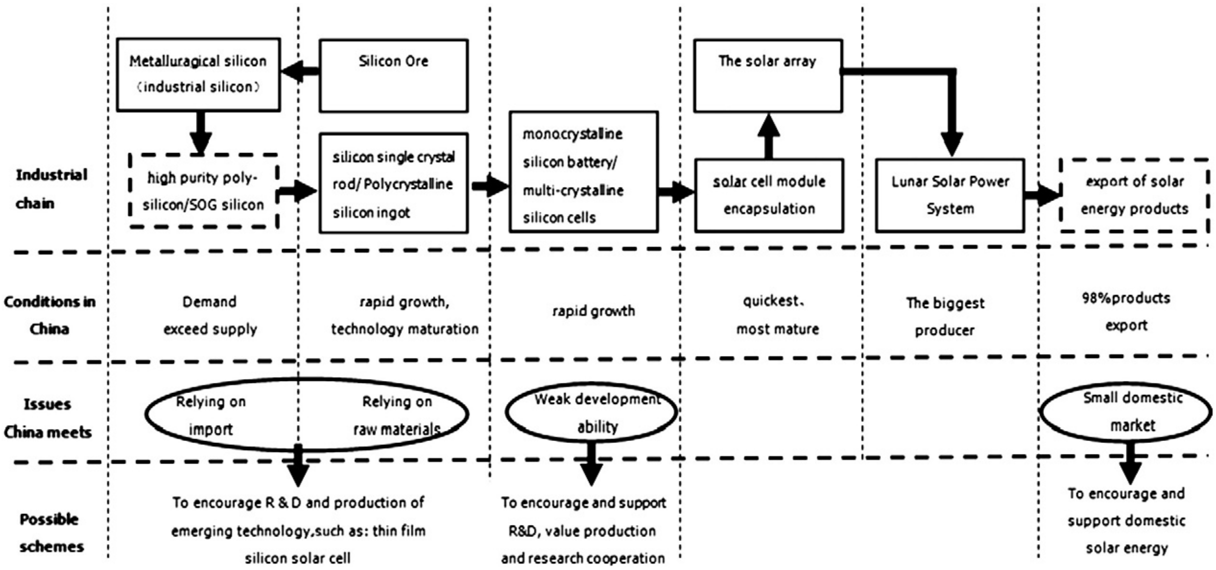

Fig. 6. Innovation chain map of China's solar cell industry.

(2) Policy should expand R&D capacity. R&D capacity is one of the most significant problems for China's enterprises, especially for the emerging technology industry, like solar cells.
(3) To expand the domestic market, China could learn from the experience of advanced countries. Meanwhile, there is still great potential for further promotion of China's solar power in remote areas.

3.4. Level 4—Tentative impact analysis for China's solar cell industry

The solar cell market in China is mainly in communications and industrial applications, especially for rural and remote areas, grid-connected solar power, and other solar cell commodities. Among all of these applications, about 53.8% belong to commercial markets (communications and industrial applications, solar photovoltaic products), while the other 46.2% belong to the market which need government and policy support, including rural electrification and grid-connected solar system. Among the 46.2%, grid-connected solar system represents a small share, which is a quite different pathway situation other advanced solar cell nation.

Solar cells are a promising NEST, but compared with other energy technologies, they are at an early developmental stage. Solar cells have unique advantages, considering "sustainable" and "clean" attributes; however, in other aspects, solar cells compare less favorably with other energy sources. Solar cells' light conversion efficiency and long-term stability presently lag.

In-depth impact assessment remains to be done. This would include checking for potential environmental or health implications of silicon vs. other materials being used in advanced generation solar cells. Economic analyses of the consequences of solar cell production, distribution, and eventual disposal should be considered (both nationally and regionally). What sort of issues appear most significant? In what ways would the risk and regulation landscape need revision? Are the protocols for handling possibly hazardous substances in place (e.g., disposal after useful lifespan—consider life cycle analyses)? The model directs attention to address such issues that could affect solar cells' development and successful applications.

4. Conclusions and discussion

To truly address strategy-relevant intelligence, a systematic framework for capturing and exploring S&T planning for emerging technologies is necessary. As we have outlined, we see an effective approach in the following steps: preparing tools for the smart capture of information, fleshing out the model of the Technology Delivery System, identifying technology opportunities, and then zooming into the industry innovation chain through augmented expert engagement exercises. This paper presents a four dimensional (nation, technology, industry, risks and impacts) S&T planning model for emerging technology that combines qualitative and quantitative methods aiming to answer different MOT questions in different stages. We introduce bibliometric methods to support the planning and decision making of experts.

In addition, an empirical study addresses China's solar cell industry planning from four progressive stages—macro-level national contextual status, meso-level target technology characterization, micro-level industry (to deliver the target technological innovations) features, and the tentative impact analysis. For example, solar cell use promises a tremendous secondary benefit in reducing the use of other energy sources that contribute heavily to global warming. We note the limitations of this case analysis, especially in terms of the desirability of engaging a wider spectrum of stakeholders and conducting a thorough impact analysis. Furthermore, scope of "the industry" should be adjusted to address the policy or managerial needs driving the analysis. As implied by Figs. 2 and 6, in the case of solar cells in China, this could be highly specialized or involve multiple industries. The depth of the various analyses implied by the four levels should also vary as a function of the intelligence needs behind the study.

We believe that the model is applicable to a) other socio-economic-political situations and b) other NESTs. It further could be applied by either a government, academic, industry association, or private business enterprise for different purposes, including patent strategy and/or competitive analysis. A follow-on research project to apply the model to comparative analysis of the China, Japan, EU, and USA solar cell industries, including the costs and benefits of global collaboration and specialization versus competition, could provide a basis for making useful national and/or global generalizations.

Acknowledgments

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