

Profiling Research Patterns for a New and Emerging Science and Technology: Dye-Sensitized Solar Cells

Ying Guo^{1,2}, Lu Huang^{1,2}, Alan L. Porter^{2,3}

1 School of Management and Economics, Beijing Institute of Technology, Beijing, 100081, P.R.China

2 School of Public Policy, Georgia Institute of Technology, Atlanta, GA 30332-0345, USA

3 Search Technology, Inc., Norcross, GA, USA 30092

Abstract: This paper explores a framework to profile research patterns for New and Emerging Science and Technology (NES&T), and applies it to Dye-Sensitized Solar Cells (DSSCs), a promising NES&T. Such work is done via “tech mining” to capture key technological attributes, leading actors, and networks. The result shows that DSSC research is an interdisciplinary field, with increasing cooperation among different levels. Japan is notable not only in the number of papers but also for considerable involvement of the corporate sector in research. In contrast, China, as the second country in quantity, shows an obvious imbalance with few industrially associated authors, limited international cooperation, and low citations. Research profiling, as illustrated here, can inform technology strategies, and science and technology policies.

I. INTRODUCTION

New and emerging sciences and technologies (“NES&T”) are characterized by a challenging combination of great uncertainty and (hopefully) great potential. At an early stage it is unclear if and how their potential might be realized. However, researchers and technologists, R&D managers, funding agencies, and policy makers need to understand the development and diffusion of these technologies to identify and guide likely future development paths [1]. This paper provides a framework to profile NES&T research activities, and we apply the framework to Dye-Sensitized Solar Cells, a promising NES&T.

Nowadays, nanotechnology is playing an increasing role in the development of sensors. Solar cells represent an especially exciting opportunity for high-impact applications benefiting from “nano” attributes. “Dye-Sensitized Solar Cells” (“DSSCs”), invented by O’Regan and Grätzel in 1991 [2], constitute perhaps the most promising and, so far, the most efficient of all solar cells that employ nanotechnology [3]. A wide variety of nanomaterials with novel properties have found broad application in DSSCs. Although the commercialization of DSSCs is still in its infancy, many technical papers anticipate fascinating prospects for DSSCs. However, to the best of our knowledge, no one has “profiled” the DSSC literature – i.e., characterized the overall R&D patterns. To do so, we adapt the tech mining approach and

selected technology management methods, along with suitable visualization tools.

The paper starts with the approach and data in Part 2. Parts 3, 4, and 5 illustrate the R&D profile for DSSCs at three levels – respectively, overall, national, and organizational. Part 6 presents our conclusions.

II. APPROACH AND DATA:

A: Contextual framework of the paper:

NES&T have some obvious characteristics. First, plenty of scientists believe in the future of the NES&T, and apply themselves to advance it, so such technologies often show accelerating activity and rapid development. Second, NES&T R&D is often multidisciplinary or interdisciplinary, as is the case for nano science and engineering [4]. Third, because of the first two characteristics, NES&T often calls for cooperative development, which could be among different countries, institutions, or researchers. When we explore the R&D activity for a given NES&T, we will address these three characteristics as indicators.

Profiling R&D activities can be done at different levels. For instance, from the overall level, we could get the whole picture of how interdisciplinary a given NES&T is; from the national level, it’s easy to tell the international collaboration networks; from the organizational level, we could pay attention to who are key players in this NES&T field. Thus, we profile the R&D activities from all three perspectives.

Understanding the characteristics and levels above, we make a matrix, with the three characteristics discussed as the abscissa, and the three levels as the ordinate, shown in Table 1. Some possible research content for profiling the R&D activities for a chosen NES&T is listed in the table.

TABLE 1: RESEARCH FRAMEWORK

	Rapid Development	Interdisciplinarity	Abundant Cooperation
Overall	Overall trends	Science overlay maps	Trends in cooperation
National	Quality and quantity measures	Research content maps	Co-author maps
Organizational	Leading organizations	Research content maps	Co-author maps

In this paper, we apply this framework to DSSCs. Actually, we just list a few research angles we use here. There could be others with respect to each of the characteristics and levels noted.

B: Method and data

This study applies the “tech mining” approach, proposed by Porter and Cunningham [5], combining analyses of relations among actors and technologies within a given research-development-innovation system, based on data extracted from article and/or patent databases [6]. Volume of scientific publications is a commonly accepted indicator of scientific performance in specific technological domains --- research activity helps illustrate the existing status and forecast future developments of a technology, which is important for a NES&T, as discussed.

We use text mining software, VantagePoint [www.theVantagePoint.com], which goes beyond limitations of traditional, paper-based bibliometric research. It helps us statistically and textually analyze articles, cluster thousands of keywords occurring in abstracts, and visualize results, thus opening up new analytical opportunities. In Table 1, the “research content maps” and “co-author maps” are done using VantagePoint. We also use network software, Pajek, which provides extensive functions in testing and visualizing various networks. We employ it here to locate DSSC on our science overlay map.

In this paper, data are first gathered using a multi-stage Boolean search strategy for identifying research publications in the nano domain. Data-cleaning methods, described in Reference [7]¹, are then applied. This provides a global dataset of nano publication records (for the period 1991 through mid-2008) downloaded from the Science Citation Index (“SCI”) of the Web of Science. Then we defined “DSSC or (dye-sensitized) or (dye-sensitised) or (dye sensitized) or (dye sensitised)” as our search expression to create a sub-dataset. We thus acquired 1349 records for the time period from 1991 to mid-2008 in the field of DSSCs. We also have DSSC data from a prominent engineering database, El Compendex. SCI focuses more on fundamental research and provides citation information, and this is particularly helpful to study research networks and relationships.

III.RESULT 1: OVERALL LEVEL DSSCs RESEARCH PATTERNS

A: Overall trends

¹ To operationalize the definition of nanotechnology, we use a two-stage modularized Boolean approach. The first stage of the search process involved application of eight search strings. These are detailed in Reference [7], Table 2a. The second stage involves exclusion of articles that fell outside the nanotechnology domain and those only referencing measurement (e.g., nanometer) without another substantive combination of nano-related terms.

We begin by showing trends based on the annual number of publications from SCI and Compendex in Figure 1. We sought to use this more comprehensive perspective to capture the range of publication activity. Although Compendex is a prominent engineering database, and SCI focuses more on fundamental research, it should be noted that there are overlaps between these two databases, as one paper could be indexed by both.

It is clear that the publications from both databases keep ascending. Before 2006, the number of SCI publications kept ahead, which suggests that fundamental research held the more important status in the DSSC research. However, in recent years, the number of Compendex publications climbs up quickly and exceeded SCI publications in 2006 and 2007.² This suggests possible maturation of DSSC technology, which could imply impending commercialization.

[We use SCI data for most analyses in the following parts as their format includes some especially helpful information on citations and subject categories.]

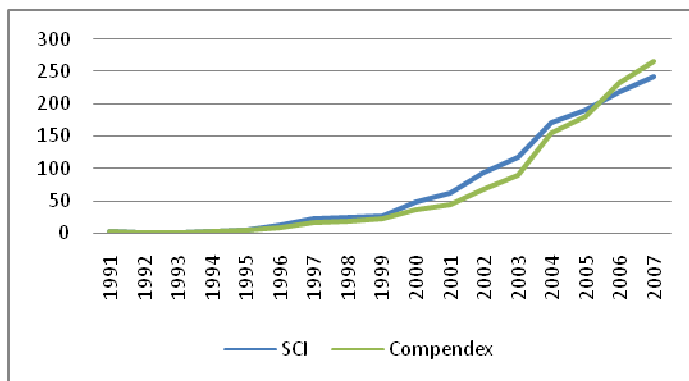


Figure 1: Dye-Sensitized Solar Cell research publication trends

We compare the different shares of the academic, government/NGO (Non-Governmental Organizations), and corporate sectors, by publication year, in Figure 2. The academic sector has a particularly large share of the DSSC research in SCI and keeps a steady increase (incomplete data for 2008). The corporate sector plays a limited role to date. This is not surprising because emerging technologies are often developed through initial strong involvement of publicly-funded research institutions, which gradually encourages commercial companies to pursue further applied research and development.

² We checked whether the recent gains for DSSC research in Compendex might be due to an increase in database record counts; they are not. DSSC activity as percentage of total records shows a similar pattern to Figure 1.

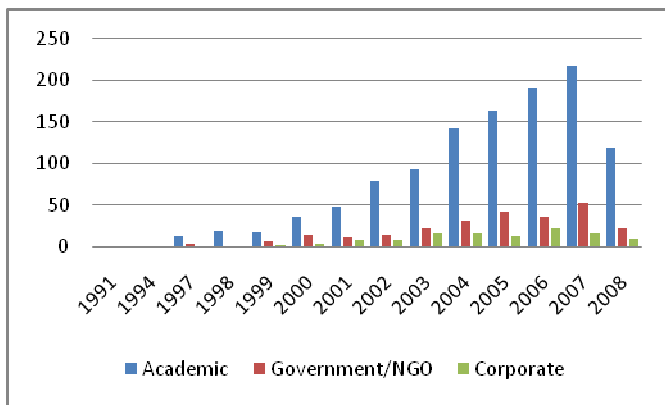


Figure 2: DSSC research in SCI by sector

B: Cooperation trends

The increasing number of authors and research institutions per article reveals increasing collaboration in DSSC research (Figures 3 and 4). For instance, while in 1998 about 60 percent of research articles were authored by single institutions (Figure 4), by 2008 only about 30 percent were the output of single institutions. Meanwhile, in the same period, the percentage of articles co-authored by three different research institutions increased from 0 percent to 18 percent. The increasing number of authors per article also implies increasing collaboration (Figure 4), although this is an increase that may take place within the same research institution.

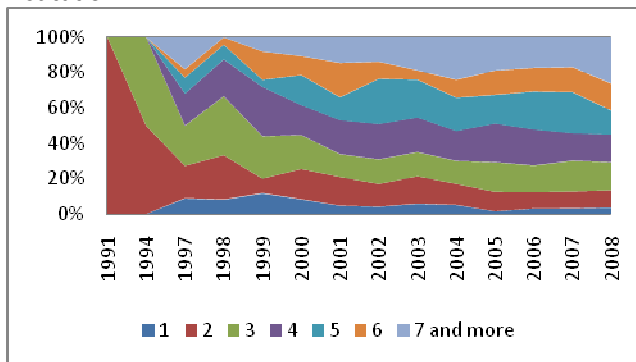


Figure 3: Number of authors per DSSCs paper (SCI)

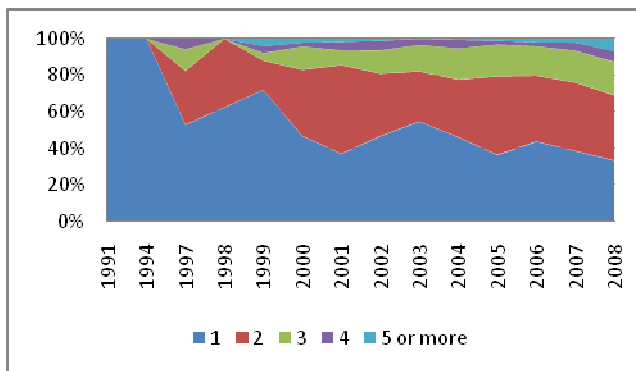


Figure 4: Number of affiliations per DSSCs paper (SCI)

C: Science map

To test if this research area is interdisciplinary and gain a sense of which fields are engaged in this work, Figure 5 overlays the concentrations of the 1349 DSSC articles on a base map of science. This mapping process categorizes articles indexed in Web of Science according to the journals in which they appear [8,9,10]. Those journals are associated with Web of Science "Subject Categories." In Figure 5, these constitute 221 nodes (research fields) reflected by the background intersecting arcs among them. The Subject Categories are then grouped into "macro-disciplines" using a form of factor analysis (Principal Components Analysis) based on degree of association. Those macro-disciplines become the labels in Figure 5. The DSSC research concentrations appear as nodes on this map.

What we see is that DSSC research concentrates in the Materials Science and Chemistry macro-disciplines, accompanied by Biomedical Science, Engineering, Physics and Computer Science. It engages many specific Subject Categories. So, this is highly multidisciplinary research. The key component research fields (specific Subject Categories) are:

- Materials Science, Multidisciplinary
- Chemistry, Physical
- Chemistry, Multidisciplinary
- Energy & Fuels
- Physics, Applied

Locating research on a given NES&T in this way can help identify key contributing disciplines. That information, in turn, can point R&D program managers or others toward requisite skills. For instance, if one's organization lacks strength in a critical component domain, collaboration could be advantageous.

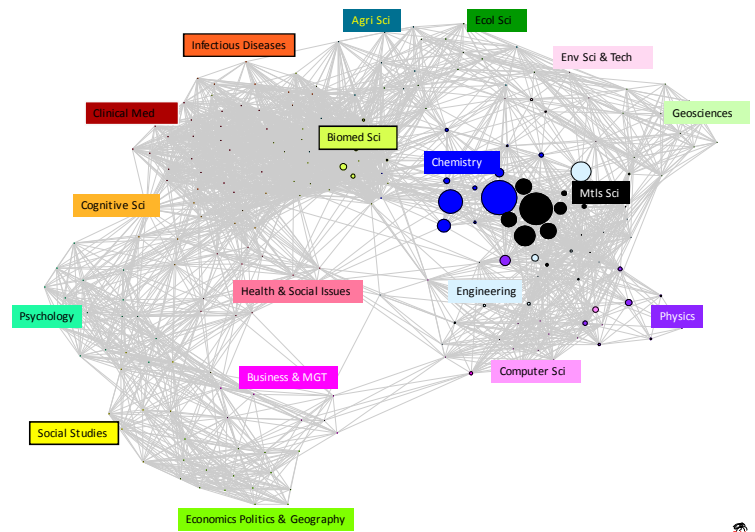


Figure 5: DSSC research areas superimposed over a base map of science

IV.RESULT 2: NATIONAL LEVEL DSSC RESEARCH COMPARISONS

Figure 6 shows the number of publications by country based on the location of any author affiliations (not just first authors). In terms of individual countries, Japan is at the top followed by China, USA, Switzerland, and South Korea. We can see Asian countries take three places in the top 5. We were told by experts that until now, Japan is the leader not only in academe, but also in advancing the DSSC industry. Switzerland is particularly strong in DSSC research because of Prof. Gratzel and his team, who created this kind of solar cell and are continuing development. Srilanka is a little surprising in top 10 countries; we note that Srilanka co-authors with Japan on 18 of its 41 publications.

Figure 6 also shows the percentage of each country's publications appearing in 2006 or later. China and South Korea are notable. Most of these leading DSSC countries show about 40% of their SCI publications recently. China and South Korea published more than 60% of their DSSC papers since 2006, which reveals the rapid development of this field by both countries in recent years and suggests likely strong activity in the future. In contrast, Srilanka shows lower activity (17%) recently.

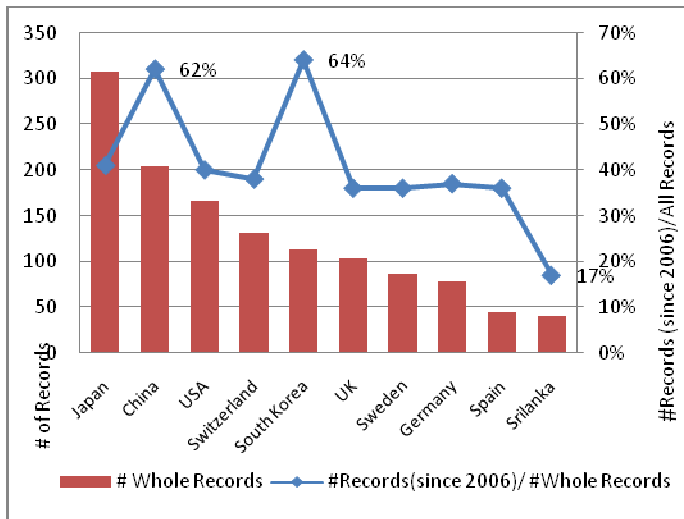


Figure 6: Top 10 countries – DSSC publications in SCI

Citations, as measured by the number of times a paper has been referenced by other SCI-indexed publications, are used here to gauge the level of quality of the publications of a country. Citation counts are related to publication counts, in that the greater the number of publications, the higher the probability of larger citation counts. Thus, we make a scattergram to see both publication and citation counts (Figure 7). This kind of Fig helps assess research quality relative to activity.

Nodes above the diagonal suggest relatively higher quality, and Switzerland is outstanding. That is because the first paper about DSSC, composed by Oregon and Gratzel, has

been cited 2544 times until 2008 May (when data were downloaded). The USA, England, Sweden, and Srilanka are around the diagonal, showing relatively higher quality than the other leading DSSC publishing countries. In contrast, Japan and China, the top 2 active countries, lag behind the others.

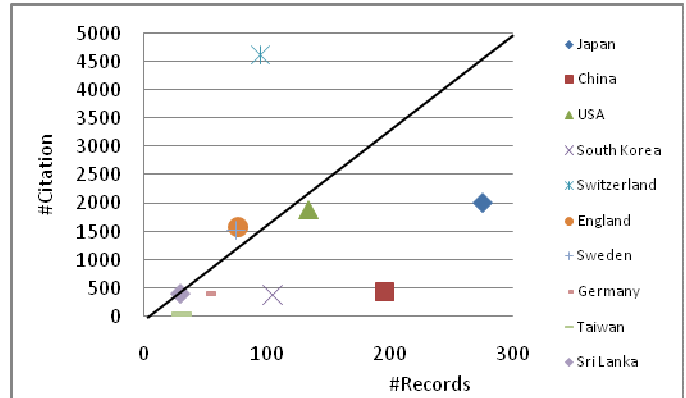


Figure 7: Quality and quantity of DSSC publications (SCI) for top 10 countries

Universities and other public research institutes have particularly large shares of the DSSC SCI research publications worldwide. The corporate sector plays a limited role to date, but is more prominent in some countries (Germany, Japan), as demonstrated in Figure 8. Germany holds a strong share in the corporate sector. Japan is in second position. The USA and South Korea, (>10 corporate-author publications), are ahead of the others. China shows particular imbalance with 202 papers having one or more university-based authors, but only 4 with an industrial author affiliation.

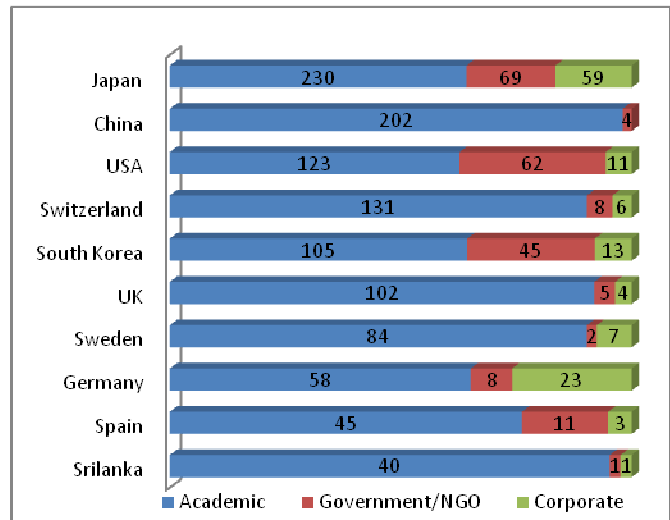


Figure 8: Different sectors authoring DSSC papers for leading countries (SCI)

Figure 9a uses clustering and cross-correlation techniques to compare the top 10 DSSC publishing countries (in SCI) by measuring and visualizing the similarity of their focus. This computer-generated map uses physical distance to indicate

the similarity of national foci. Each article was associated with multiple keywords, and VantagePoint identified the relevant keyword clusters, revealing degree of similarity of the research interests of these countries. The size of a circle indicates overall volume of articles. Lines linking specific countries symbolize statistical relations between the analyzed objects (degrees of similarity). On this map, one can identify strong links between interest areas in Japan, China, the US, and South Korea. Collaboration could be particularly fruitful.

Figure 9b shows the co-authoring networks among these top 10 countries. The heavier links among nodes represent more co-authoring among countries. We can see that there are no particularly dominant links among these countries. However, compared with the other top 5 countries, China lags in international collaboration.

Comparing Figure 9a and 9b, we see that some countries have quite similar research orientations, but few have developed correspondingly strong cooperation. This suggests a potential opportunity for enhancing collaboration – e.g., China and South Korea have notable common research interests (Figure 9a), but lack co-authoring links (Figure 9b).

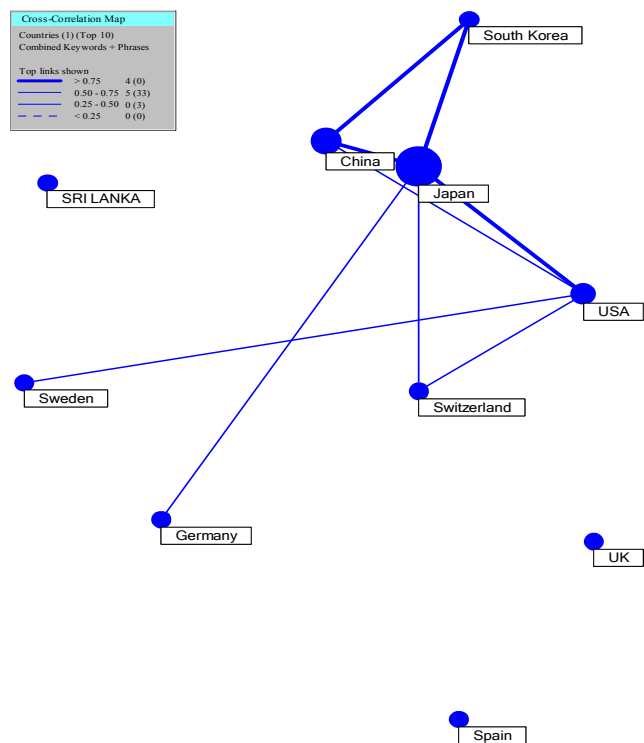


Figure 9a: Top 10 DSSC countries reflecting topical similarities

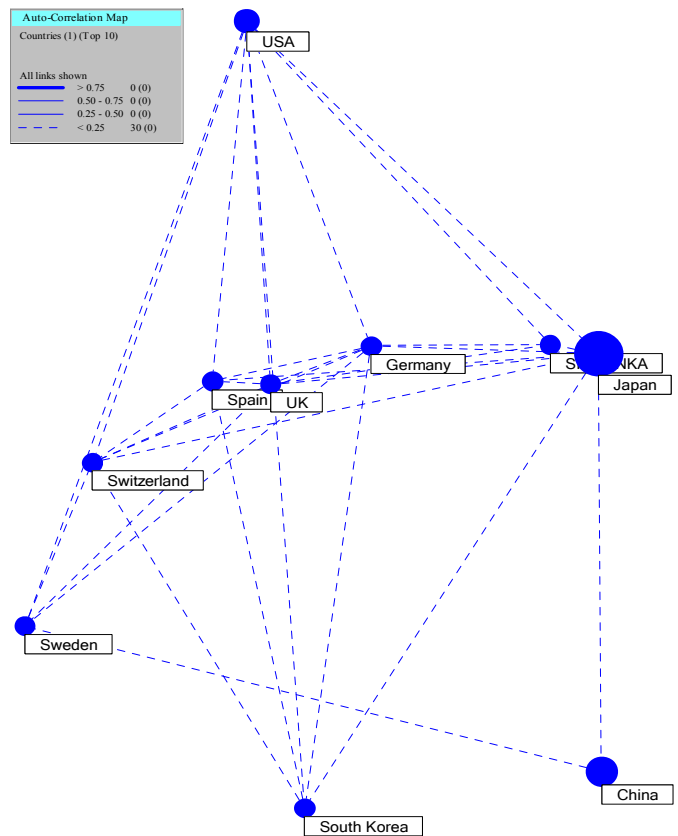


Figure 9b: Top 10 DSSC countries degree of co-authoring

V. RESULT 3: ORGANIZATIONAL LEVEL DSSC COMPARISONS

At the organizational level, we start with the list of the top 10 affiliations (Table 2). Identifying "new" emphases within the DSSC research of these leaders might be of interest widely as an indicator of potential research fronts. Table 2 breaks out other details for the set of papers by each of the Top 10 DSSC research organizations. "Countries" reflects their degree of international collaboration (i.e., tabulating any co-author affiliations' nationalities). "Authors" helps spot the degree of concentration (e.g., Gratzel's prominence in Switzerland). "% since 2006" is an indicator of how recent this organization's DSSC research is.

The Chinese Academy of Science (CAS) is outstanding as the most active affiliation from all over the world. CAS is very important for DSSC R&D in China, as it has 88 publications of about 200 for China. However, several points should be noted. First, among the 88 publications, only 6 reflect international cooperation (with Japan). This again notes China's lack of international collaboration. Second, compared with other leading affiliations, no CAS author is in an absolutely leading position. We created an "auto-correlation map for authors of CAS" (not shown here) and found three CAS institutes are notably active in DSSC research. These three institutes publish pretty much the same volume but evidence little collaboration. Third, CAS publishes 52% of its

88 papers since 2006, which implies strong future DSSC research inclinations.

As for Switzerland, Gratzel is the leading author for both the “SWISS FED INST TECHNOL” and “ECOLE POLYTECH FED LAUSANNE.” However, what is interesting is, he is affiliated to these two organizations separately, which means, his 60 publications in “SWISS FED INST TECHNOL” don’t overlay his 48 publications in “ECOLE POLYTECH FED LAUSANNE”. We can also see he is more active in latter in recent years. Gratzel is an author (not just 1st author) of 114 papers, among Switzerland’s 135 papers.

Compared with other countries, DSSC research in Japan is more dispersed. Three organizations of Japan are listed in the top 10. We created auto-correlation and cross-correlation maps of top 10 authors of Japan (not shown here). We found that in both maps, authors cluster in three groups (different position, but similar connection among those authors in the two maps), which means the ones who have similar interests co-author. Especially, these three groups are “Natl Inst Adv Ind Sci & Technol”, “Osaka Univ,” and “Gifu Univ.”

TABLE 2: TOP 10 DSSC RESEARCH AFFILIATIONS

Affiliation	Countries	Authors	Publication Year
Top 10	Top 3	Top 3	% since 2006
Chinese Acad Sci	China [88] Japan [6]	Wang, K J [20] Lin, Y [18] Dai, S Y [18]	52% of 88
SWISS FED INST TECHNOL	Switzerland [66] UK [11] Italy [6]	Gratzel, M [60] Nazeeruddin, M K [26] Zakeeruddin, S M [22]	24% of 66
ECOLE POLYTECH FED LAUSANNE	Switzerland [54] UK [9] Netherlands [4] USA [4]	Gratzel, M [48] Zakeeruddin, S M [16] Moser, J E [13]	54% of 54
Univ London Imperial Coll Sci Technol & Med	UK [48] Spain [12] Switzerland [11]	Durrant, J R [39] Haque, S A [21] Palomares, E [16]	31% of 48
Natl Inst Adv Ind Sci & Technol	Japan [47]	Arakawa, H [24] Hara, K [21] Sugihara, H [16]	28% of 47
NATL RENEWABLE ENERGY LAB	USA [42] South Korea [3] Switzerland [2] Israel [2]	Frank, A J [22] van de Lagemaat, J [16] Gregg, B A [15]	14% of 42
Osaka Univ	Japan [40] SRI LANKA [4]	Yanagida, S [36] Wada, Y [23] Kitamura, T [22]	28% of 40
Inst Fundamental Studies	SRI LANKA [38] Japan [18] USA [2]	Tennakone, K [29] Konno, A [13] Perera, V P S [10]	18% of 38
Univ Uppsala	Sweden [32] Switzerland [3]	Hagfeldt, A [25] Lindquist, S E [8] Boschloo, G [7] Siegbahn, H [7]	3% of 32
Kyoto Univ	Japan [32] China [4] Thailand [4]	Yoshikawa, S [15] Adachi, M [11]	56% of 32

“Inst Fundamental Studies” is a Srilanka organization, which conducted nearly all of the DSSC research of that country (38 of 48 papers), many in cooperation with Japanese colleagues.

As discussed, the corporate sector is really limited in DSSC research indexed by SCI. However, we are interested in the cooperation between corporate sector and public sector. We made a new dataset of companies with two or more DSSC records, and created the auto-correlation map (Figure 10) for affiliations with three or more records in the new dataset to show the pattern of collaboration.

What is not surprising, but still interesting, is that all the corporations shown here cooperate with public research organizations. For instance, Bridgestone Corp. and Keio University; Hahn Meitner Inst Berlin GmbH and Hanyang University; Samsung SDI Co. Ltd. and Korea Univeristy. Even in the biggest cluster (containing Fujikura Ltd., Sharp Co. Ltd., Sumitomo Osaka Cement Co. Ltd., and Hayashibara Biochem Labs Inc.), companies are not connected directly. It implies that at the early stage of NES&T, those who are actively pursuing R&D rely on academe.

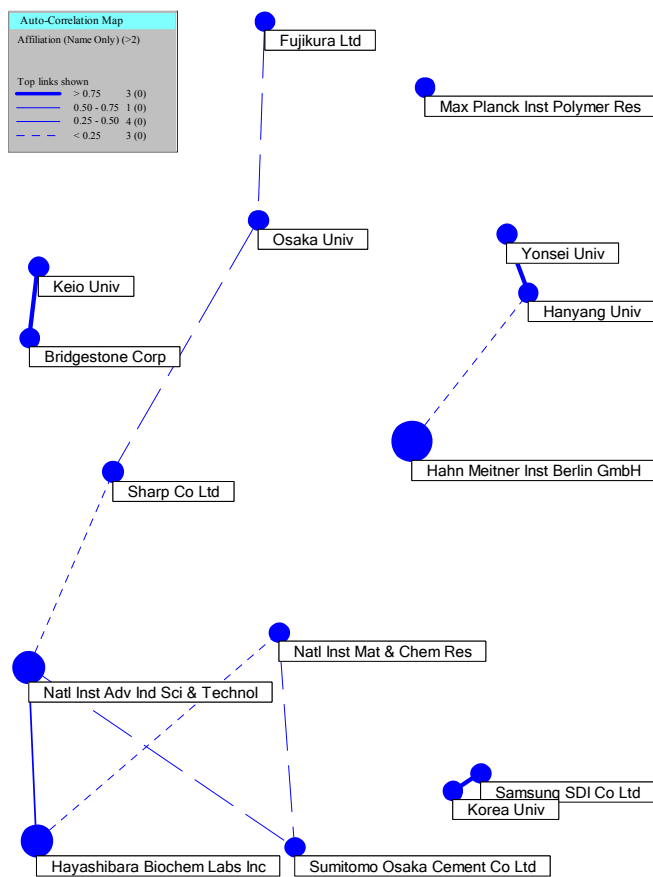


Figure 10: DSSC research Collaboration pattern between corporate sector and public sector

Looking at the four clusters in Figure 10, two of them are from Japan, containing five corporations. Different from the

others, the companies of Japan usually cooperate with more than one public organization. Japan is a leader, not only in academe, but also in DSSC industry participation. "Hahn Meitner Inst Berlin GmbH", a German "limited liability company," is notably active in DSSC, but it is a quasi-governmental research organization.

VI CONCLUSION

Considering the characteristics of New and Emerging Science and Technology (NES&T) and different research levels, this paper first offers a contextual framework for research pattern profiling. Then, using the "tech mining" approach, along with visualization tools, we analyze DSSCs to represent the comprehensive research patterns of this NES&T.

We see that DSSC research is a multidisciplinary field, with increasing cooperation at individual, organizational, and international levels. However, the corporate sector plays a limited role in fundamental research to date. This is not surprising because emerging technologies are often developed through initial strong involvement of publicly-funded research institutions, which gradually encourages commercial companies to pursue further applied research and development. Compared to other leading countries, the corporate sector holds a stronger share in Germany and Japan, which implies that these countries may be well-positioned to pursue commercial activities.

Switzerland is notable in both quality and quantity of DSSC research, mainly due to Gratzel and his research team. In contrast, China and South Korea show increasing publications in the recent three years, but continue to lag in citations. Moreover, China shows particular imbalance with only 4 of 202 papers with an industrial author affiliation and limited international collaboration.

Research profiling, as illustrated here, can inform technology strategies, and science and technology policies, by revealing emerging topical emphases and key players' interests. It also helps understand the strengths and weaknesses of the research, development & innovation

system for emerging technologies, such as dye-sensitized solar cells. All this would be vital information to use in monitoring competition and possibly developing research and/or development alliances.

ACKNOWLEDGMENT

This research was undertaken at Georgia Tech drawing on support from the National Science Foundation (NSF) through the Center for Nanotechnology in Society (Arizona State University; Award No. 0531194); and the Science of Science Policy Program -- "Measuring and Tracking Research Knowledge Integration" (Georgia Tech; Award #0830207). The findings and observations contained in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

- [1] T. Propp, A. Rip. "Assessment tools for the management of new and emerging science and technology: state-of-the-art and research gaps," unpublished.
- [2] B. Oregan, and M. Gratzel. "A low-cost, high-efficiency solar-cell based on dye-sensitized colloidal TiO₂ films," *Nature*, vol.353, no. 6346, pp.737-740, October 1991.
- [3] E.S. Aydil, "Nanomaterials for Solar Cells," *Nanotechnology Law & Business*, vol.4, no.3, pp. 275-291.
- [4] A.L. Porter, and J. Youtie. "How Interdisciplinary is Nanotechnology?" *Journal of Nanoparticle Research*, vol. 11, no. 5, pp, 1023-1041, 2009.
- [5] A.L. Porter, and S.W. Cunningham, *Tech Mining: Exploiting New Technologies for Competitive Advantage*. Wiley, New York, 2005.
- [6] A.L. Porter, A. Kongthon, J. Lu, "Research profiling: Improving the literature review," *Scientometrics*, vol.53, no.3, pp.351-370, 2002.
- [7] A.L. Porter, J. Youtie, P. Shapira, D. Schoeneck, "Refining search terms for nanotechnology," *Journal of Nanoparticle Research*, vol. 10, no. 5, pp. 715-728, 2007.
- [8] L. Leydesdorff, and I. Rafols, "A Global Map of Science Based on the ISI Subject Categories". *Journal of the American Society for Information Science and Technology*, vol. 60, no.2, pp. 348-362, 2009.
- [9] I. Rafols, and M. Meyer, "Diversity and Network Coherence as indicators of interdisciplinarity: case studies in bionanoscience," *Scientometrics*, in press.
- [10] A.L. Porter, and I. Rafols, I. "Is science becoming more interdisciplinary? Measuring and mapping six research fields over time," *Scientometrics*, in press.