Research Profiling: Nano-enhanced, Thin-film Solar Cells

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Abstract: Nanotechnology-enhanced thin-film solar cells constitute one of the most promising solar energy solutions and an important currently emerging application of nanotechnology. This paper profiles the research patterns via "tech mining" to capture key technological attributes, leading actors, and networks. We compare the leading countries, and key organizations, in terms of R&D quantity, quality, and diversity.

We find that India is a leader in this field, which is a little surprising. India and China show strong trends of relative increase in both the research activity and quality. One German organization appears as especially productive and the central node in Germany's research network, which contrasts with the diffused network of the US. International collaboration patterns also vary, with China particularly showing much lower international cooperation than others. Some countries appear to share common interests, but they don't have much cooperation with each other, like China and Japan.

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 nano-enhanced thin-film solar cells.

Keywords: nanotechnology, thin-film solar cells, bibliometric analysis, tech mining, R&D patterns, technology innovation system

1 Introduction

Solar cells, or photovoltaic ("**PV**") cells, transform incoming solar radiation to electricity. The technology has a large potential as a source of renewable energy since the Earth receives many times more energy from the sun than is currently used in the global energy system. The mainstay at present is the silicon solar cell which accounted for 90% of the market in 2006. However these are costly to manufacture and have limited efficiency (around 14% in most production modules, and up to 25% in the lab -- The Institute of Nanotechnology, 2006).

Thin-film is a more cost-effective solution and uses a cheap support onto which the active component is applied as a coating. Cheaper and impure materials are used and lower cost technologies are utilized (Chopra1, 2004). Also, incorporation of nanotechnology (**"nano"** – taking advantage of molecular scale properties and manipulations) into the films shows special promise to both enhance efficiency and lower total cost (Aydil, 2007; Escolano et al., 2005; Honsberg et al., 2006; Singha et al., 2004). Many nano-structured materials are now being investigated for their potential applications in thin-film photovoltaics. These are widely researched and hold bright market prospects (Shah et al., 1999). Thus, nano-enhanced thin-film solar cells constitute one of the most important current emerging applications of nanotechnology.

To understand the development and diffusion of this emerging application, research profiling is needed. Such information would facilitate policy makers' design of efficient policy instruments, and could also help technology managers optimize photovoltaic R&D investments and speed operational applications. Positioning of countries relative to one another in scientific performance, particularly in emergent fields such as nanotechnology, is an important part of research profiling. Some previous empirical studies are Glanzel et al., (2003), Kostoff et al., (2007), Miyazaki et al., (2007), and Youtie et al., (2008). Research profiling can also inform at the organizational level. There has been much interest in identifying key players and profiling their differential emphases in nano-enhanced thin film solar cells research.

So, the purpose of this paper is to characterize the patterns of nano-enhanced thin film solar cells research. Questions to be answered include:

(1) What are the indications of different national approaches (cross-country comparisons)?
(2) Who is doing this research (R&D actors and their activities)?
(3) How is the research interconnected (research networking)?

The paper is structured as follows: Section 2 presents brief background on solar cells. Section 3 describes the data and methods used. Section 4 offers cross-country comparisons to explore multiple characteristics of the research in this emerging technology – quantity (publication numbers), quality (citations), and diversity (variety of research fields involved) for the leading countries. These provide multiple perspectives on nations' R&D directions. Section 5 attempts to identify key institutes and their activities in this research field, which can also offer insights into the strategic purposes of organizations– vital information for informed technology management and policy formulation. Section 6 analyzes the research knowledge networks (at both national and organizational levels). Conclusions are formulated in Section 7.

2 Background on Solar Cells

It has been estimated that the technical potential of PV is 23 times higher than the present world electricity production (Hoogwijk, 2004; Marigo et al., 2008). On a world-wide scale, solar energy is attracting attention, and the market is increasing, with a yearly growth of 26 to 46 percent during the last decade. Studies suggest three generations for solar cells (Green, 2003; Conibeer, 2007; etc). We summarize their materials, functions, types, and commercialization status in Table 1.

(1) **1st G** -- The First Generation--- "Conventional Solar Cells" are the mainstay at present, accounting for 90% of the market, but these are too expensive for true mass production.
(2) **2nd G** -- The Second Generation is usually called "Thin-film Solar Cells," but it could be divided into two groups: "Silicon Thin-film Solar Cells" and "Compound Semiconductor Thin-film Solar Cells," according to the materials used to absorb light. Nanotechnology could facilitate the latter.
(3) **3rd G** -- Some studies suggest the Third Generation solar cells could be named "New Concepts Solar Cells." People argue about the definition and classification. We provide some examples and try to divide them into two groups. The first group is based on the same solar-to-electricity principle as traditional "Compound Semiconductor Thin-film Solar Cells" and makes use of the same materials, however, it tries to increase the efficiency to surpass the Shockley-Queisser limit[i], mainly by Quantum Dots Nanotechnology. That is to say, this group can also be called "Advanced Compound Semiconductor Thin-film Solar Cells." The second group applies totally different principles, but employs nanotechnology too. One important example we show here is "Dye-sensitized Solar cells."

We focus on nano-enhanced thin-film solar cells (**"NE-TF-SCs"**), illustrated in the big square brackets in Table 1, containing the traditional "Compound Semiconductor Thin-film Solar Cells" and "Advanced Compound Semiconductor Thin-film Solar Cells."

Nano impacts thin-film solar cells on two different levels:
(1) In traditional "Compound Semiconductor Thin-film Solar Cells," nanomaterials provide large surface and interfacial areas per unit volume, a significant advantage for both light absorption and charge separation, two critical steps in solar-to-electric energy conversion (Konenkamp, 2004). Nano helps but such cells are still not very efficient.
(2) In "Advanced Compound Semiconductor Thin-film Solar Cells," nanoparticles provide the ability to tune the optical properties of the solar cell in ways that are not possible with bulk materials. The most exciting advantage that may result from using nanoparticles in solar cells is known as multiple exciton generation ("MEG"), effected by Quantum Dots, which researchers are trying to employ here.

[i] The Shockley-Queisser limit or detailed balance limit refers to the maximum theoretical efficiency of a solar cell using a p-n junction to collect power from the cell.

	Material	Main Research target	Functional objectives	Examples	Commercialization
1st G	• single-crystalline silicon • multi-crystalline silicon	To make use of solar energy	To convert solar energy into current	Conventional Solar Cells	Now, 85–90% solar cells market
2nd G	• amorphous silicon • microcrystalline (mc-Si:H) silicon	To decrease cost	• To take silicon as the thin-film • To use other semiconductor to replace silicon • No vacuum processing • Low temperature fabrication	Silicon Thin-film Solar Cell	Now, 90–100% thin-film solar cells market
2nd G	• cadmium sulfide (CdS) • copper indium diselenide (CIS) • cadmium telluride (CdTe) • ……	To improve efficiency (by nanotechnology)	• Enlarged the effective optical path for absorption • Photon management to shorten the path electrons and holes need to travel	Compound Semiconductor Thin-film Solar Cells	In research, some of them will come to market
3rd G	• cadmium sulfide (CdS) • copper indium diselenide (CIS) • cadmium telluride (CdTe) • ……	To improve efficiency (mainly by Quantum Dots nanotechnology)	• Utilization of materials or cell structures incorporating several band gaps	• Intermediate band gap solar cells	In research, very promising in the future
			• Modification of the photonic energy distribution prior to absorption in a solar cell	• Up/down conversions	
			• Reducing losses due to thermalization	• Hot carrier solar cells • Impact ionization solar cells	
	• TiO2, ZnO…… • Organic materials • ……	Totally new principle (by nanotechnology)	• Enlarged the effective optical path for absorption • Shorten the path electrons and holes need to travel	• Dye-sensitied Solar cell	Is coming to market

Table1: Material-function-commercialization Cross-chart for Solar cell

3 Data and methods

This study applies the "tech mining" approach, proposed by Porter and Cunningham (2005), 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 (Porter et al., 2002). In addition, we use special 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 show results by visualizations, thus opening up new analytical opportunities.

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. 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 Porter et al. (2007)[ii], are then applied. This provides a global dataset of nano publication records (for the period 2001 through mid-2008) downloaded from the Science Citation Index ("**SCI**") of the Web of Science. Then we defined "thin-film and (solar or photovoltaic)" as our search expression to create a sub-dataset. Finally, we acquired the dataset containing 1659 records for the time period from 2001 to mid-2008 in the field of NE-TF-SCs for this paper. We also have nano data from two prominent engineering databases, INSPEC and EI Compendex. SCI focuses more on fundamental research and provides citation information, helpful to study research networks and relationships. In future extensions, we anticipate analyzing the more applied R&D in INSPEC and Compendex, as well as patents from the PatStat database.

4 Cross-country comparisons

To gain a sense of which research fields are engaged in this work, Figure 1 overlays the concentrations of the 1659 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 (Rafols and Meyer, forthcoming; Leydesdorff and Rafols, forthcoming). Those journals are associated with Web of Science "Subject Categories." In Figure 1, these constitute 175 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 the figure. The NE-TF-SCs research concentrations appear as nodes on this map.

What we see is that NE-TF-SCs research is concentrated in the Materials Science and Chemistry macro-disciplines. It engages many specific Subject Categories. So, this is highly multidisciplinary research. We are particularly interested in cross-national differences in research on this technology. With that in mind, we have compared the relative emphases of the leading countries (discussed shortly). We generate such science overlay maps for each country (not reproduced here). What stands out among those is that

[ii] 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 Porter et al. (2007, 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.

all of them show very similar involvement of the key component research fields:

(a) Materials Science, Multidisciplinary

(b) Physics, Condensed Matter

(c) Physics, Applied

(d) Chemistry, Physical

(e) Materials Science, Coatings & Films

But one of the countries, India, shows by far the most research in "energy & fuels." Such concentration differences could be important in distinguishing national (or institutional) emphases. They can also help technology managers identify appealing collaboration opportunities to take advantage of complementary national (or organizational) strengths.

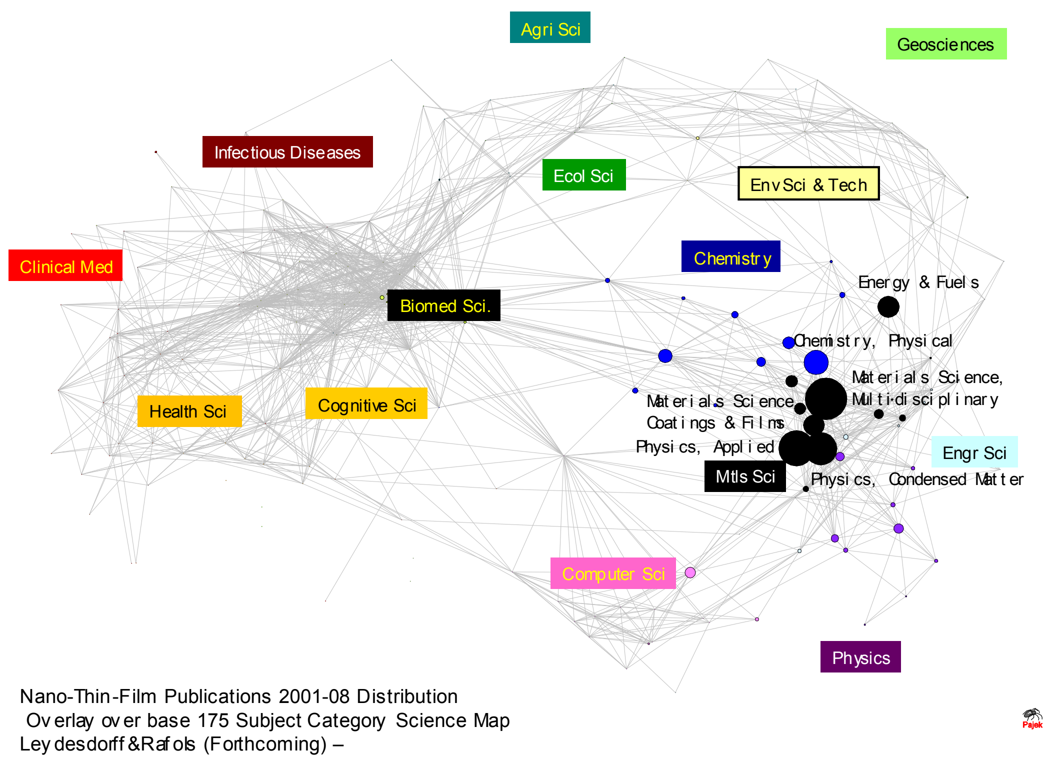

Figure1: NE-TF-SCs Publications by Research Field

Figure 2a shows the number of publications by country based on the location of any author affiliations (not just first authors). We sought to use this comprehensive perspective to capture the widest range of publication activity by author country. Figure 2a shows that, in terms of individual countries, the US is at the top followed by India, Germany, China and Japan. We can see that the top 10 countries are quite widely distributed globally, but Asian countries take three places in the top 5. India (Figure 2a) is notably in the 2nd position, just behind the US. This is especially striking in comparison with India's much lesser prominence in Figure 2b (a broad, global comparison of nano publication – not restricted to solar cells).

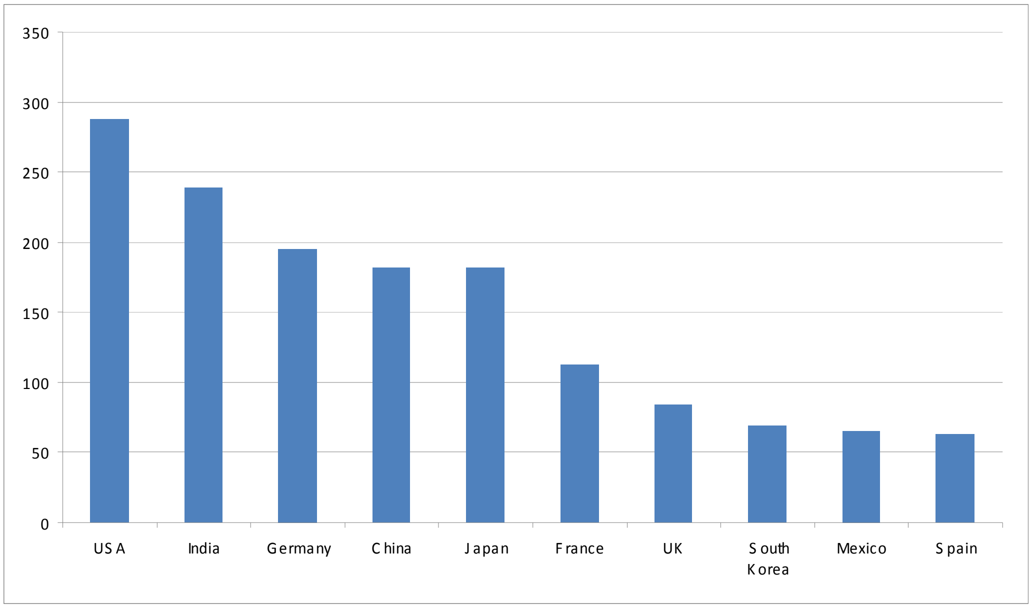

Figure.2a: NE-TF-SCs Publications by Countries [Science Citation Index, 2001-08 (part-year)]

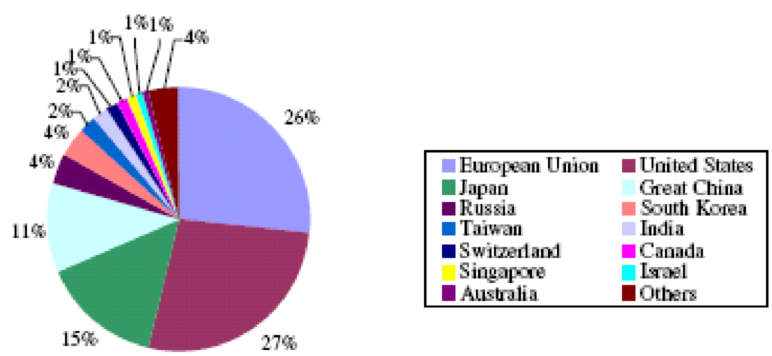

Figure2b: Nanotechnology Publications by Countries (Miyazaki et al., 2007)

To investigate changing national research levels in NE-TF-SCs, we show the percentage publication shares of the top 5 countries for 4 years—2001, 2003, 2005, and 2007—in Figure 3. In 2001, Japan accounted for the highest share of countries in NE-TF-SCs SCI publications at 17.7%. By 2003, the US comprised 22% of publications compared to 15.6% for Germany -- Japan is then in fourth position, following India. By 2005, there is not much difference between the top 5 countries and China accounts for nearly 14%, which is much higher than before and in third position, just behind the US and India. By 2007, China is the only country in these top 5 that is still rising in the percentage of publications; at the same time, Germany and Japan demonstrate an obvious downswing in representation, accounting for less than 10%, respectively. As a whole, China's rise in NE-TF-SCs research stands out boldly, in contrast to Germany and Japan.

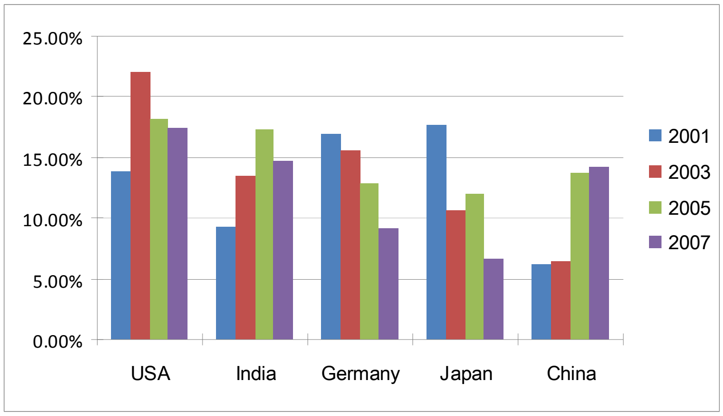

Figure3: Percentage of NE-TF-SCs Publications by Country for Selected Years.

In order to gain a richer perspective on the future of global R&D activity for NE-TF-SCs, we extrapolate the national R&D activity trends for these top five countries. Figure 4 shows results of trend analyses of publications indexed by SCI extrapolated through the year 2012.[iii] Here, we choose a Fisher-pry Model to fit the data with a high "R^2" coefficient of 0.89 for USA, India and China. It suggests that a steep growth could continue for these three countries over the next few years, and China would be likely to surpass India to reach second position. Similarly, trend analyses were done for Germany and Japan, using a Fisher-pry Model with the coefficient of 0.59 (a linear model represents similar results with the same coefficient of 0.59). According to the results of our trend extrapolation, we can estimate that Germany and Japan are gradually losing their leading positions in NE-TF-SCs in the next few years.

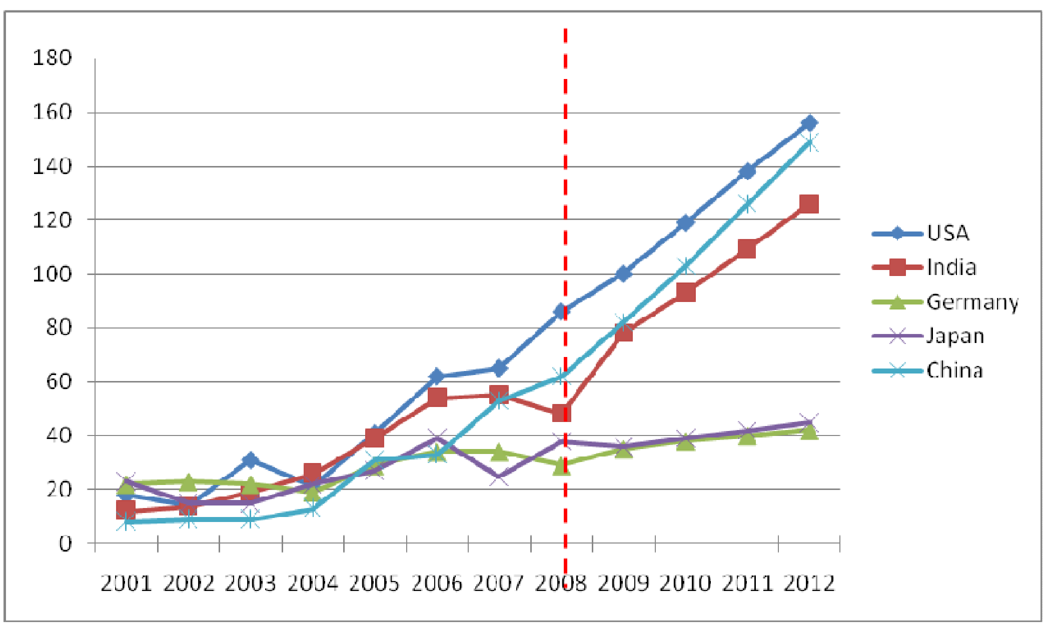

Figure 4: Forecasting the R&D Activities Trends for Top 5 Countries

[iii] We have the data through 2001 to 2008 (half year), so we estimate the whole year data for 2008 using the half year number and forecast the data for 2009,2010,2011 and 2012.

Figure 5 shows the activity and diversity of the top 10 countries in the NE-TF-SCs research for the time period from 2001 to 2008 (half-year). Number of publications is used to measure the research activity of each country and number of SCI Subject Categories shows the diversity of each country's research. It should be noted that we only tally the Subject Categories with two or more publications for each country. Figure 5 shows that, no matter the particular degree of activity or diversity, the top 5 countries stand out from the countries in sixth to tenth position. As expected, the US is the most active country, however, it has the least diversity of the top 5. China is leading in the diversity of research fields represented, followed by Germany. Japan and India show almost the same level of diversity but India is ahead in activity. The UK, South Korea, Spain and Mexico are different in diversity, but maintain about the same level of activity. We think that such analyses of R&D patterns can help technology managers understand differences in approach.

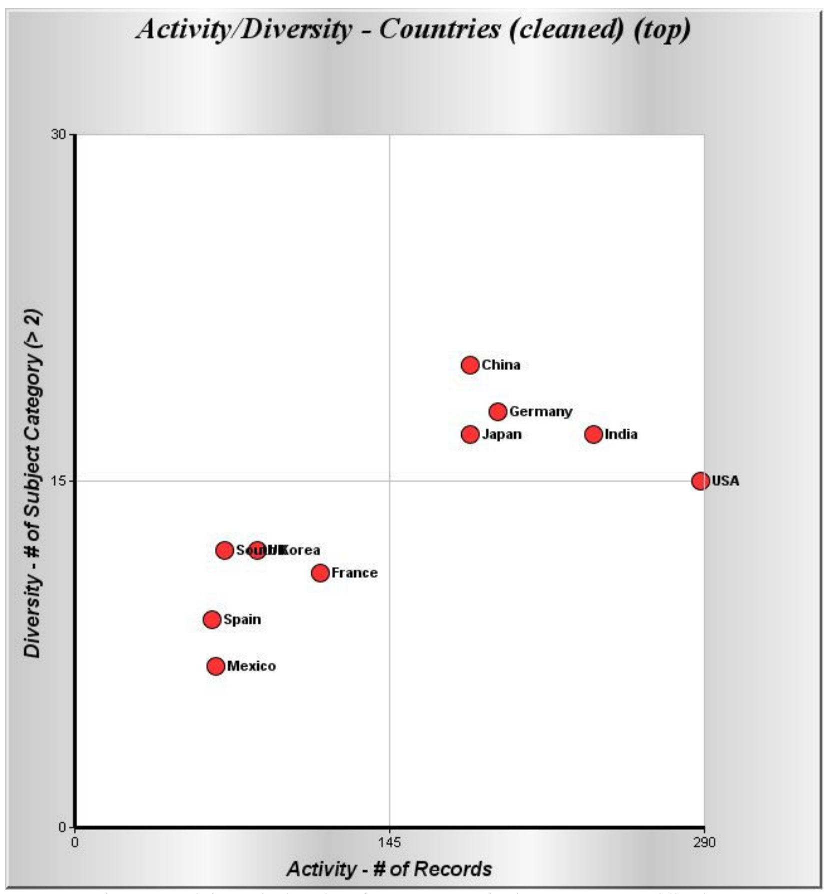

Figure5: Activity and Diversity of Top 10 Countries in NE-TF-SCs Publications

However, quantity (activity) and diversity are not sufficient to describe country position in the NE-TF-SCs research arena. Quality and influence in the field is important to consider in depicting inter-country standing in research efforts (Glanzel et al., 2003). Citations, as measured by the number of times a paper has been referenced by others, are used here to gauge the level of quality of the publications of a country. To probe the quality of each country's R&D further, we show the trend of citations for the top five countries in recent years. In this article we employ an aging practice based on dividing the citations in a given year by the number of years of opportunity to be cited. Figure 6 averages 2001 and 2002 to get the initial points. So the number of citations to articles from this initial period is divided by 6.5. Similarly, the year 2006 and 2007 papers have about 1.5 years to attract citations; hence the citations counts are divided by 1.5.

Figure 6 shows the change over time in publication and citation intensity, with a line connecting the results for the initial period – "2001" (combining 2001 and 2002 publications) and the recent period -- "2006" (combining 2006 and 2007 publications). The steeper the slope of the line connecting these two points, the greater the increase in quality of the country's research on this topic. Taking the aging effect into consideration, the US has the steepest slope, suggesting that its NE-TF-SC research receives the greatest attention by researchers. China and India, although they lag on both quality and quantity in 2001, their trend relative to Germany and Japan also shows a promising rise.

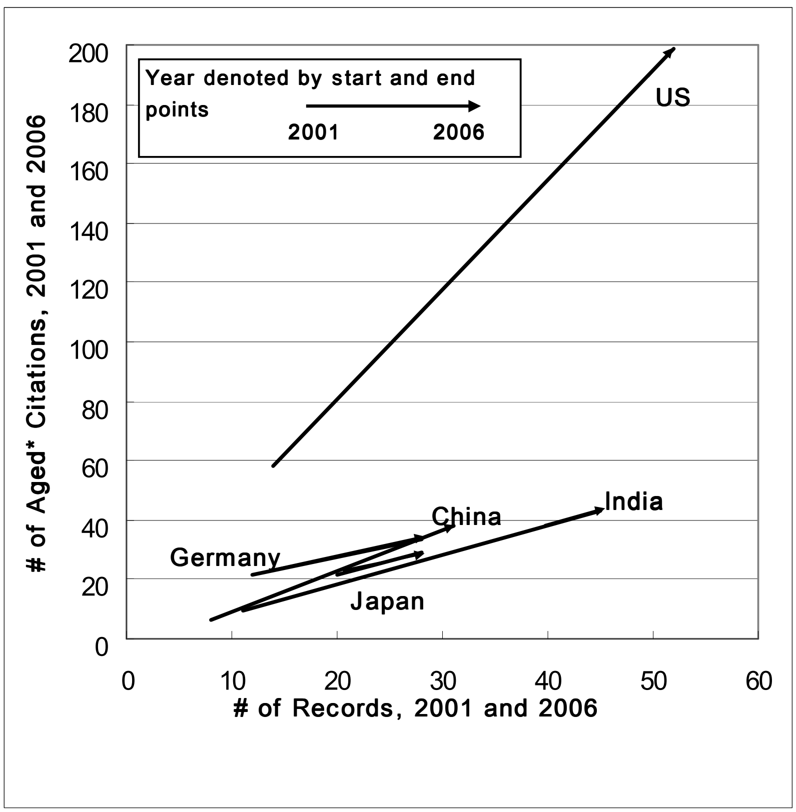

Figure6: Number of aged NE-TF-SC citations in the end of 2001 and the end of 2006 relative to number of articles by first author.
*Aged citations (AC) for a country is calculated as ACi = Cti / (Yn - Yt) where Cti = total number of citations for articles in target year for country i; Yn = most recent year in dataset (2008, mid-year); and Yt = the end of target year. For 2001, Yn - Yt = 6.5; for 2006, Yn - Yt = 1.5. Country is based on an article;s first author's affiliation address.

5 R&D actors and their activities

Table 2 lists the top 15 research organizations worldwide for these research publications. This reveals an important role of Indian affiliations, which take 5 positions in these top 15. Except for India, the other most active countries—US, China, Japan, and Germany—only have one organization respectively in this list. "Hahn Meitner Inst Berlin GmbH" — a German "limited liability company" [quasi-governmental research organization] — leads.

However, we recognize that corporate publication activity can be a leading indicator of commercialization. We examined the top 15 companies (not reproduced here), showing that all have 5 or fewer publications for 2001 to 2008. 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 engage in applied research and development of specific applications. Another explanation would be that the data are from SCI—a fundamental research database, and many companies do not publish such work.

No.	#Records	Affiliation	# Records % since 2006	Country
1	61	Hahn Meitner Inst Berlin GmbH	49% of 61	Germany
2	49	Shivaji Univ	63% of 49	India
3	36	Chinese Acad Sci	58% of 36	Peoples R China
4	32	Bulgarian Acad Sci	25% of 32	Bulgaria
5	31	Natl Renewable Energy Lab	55% of 31	USA
6	28	Indian Inst Technol	39% of 28	India
7	25	CNRS	64% of 25	France
8	22	Alagappa Univ	18% of 22	India
9	22	Osaka Univ	27% of 22	Japan
10	21	CIEMAT	52% of 21	Spain
11	19	Hanyang Univ	74% of 19	South Korea
12	19	Cent Electrochem Res Inst	26% of 19	India
13	18	Indian Assoc Cultivat Sci	39% of 18	India
14	17	IPN	53% of 17	Mexico
15	16	UNAM	25% of 16	Mexico

Table2: Profiling the top 15 organizations in R&D of NE-TF-SC

As the research above reveals, universities and other public research institutes have particularly large shares in NE-TF-SCs research (they account for 91.9% (=(1389+285)/1821) of the SCI research publications worldwide, shown in Table 3). The corporate sector plays a limited role to date (globally 8.1% of publications), but is more prominent in some countries (US, Germany, Japan and UK), demonstrated in Figure 7. If one considers Hahn Meitner Inst Berlin GmbH as a company, Germany holds a strong share (35.3%) in the private sector. Japan is in second position (15.7%), UK (11.3%), and the US (9.9%) follows. Companies in these countries seem to be more actively pursuing R&D.

	USA	India	Germany	Japan	China	France	UK	South Korea	Mexico	Spain	Total
Academia	242	206	140	150	180	93	81	59	50	39	1389
Government/NGO	69	37	12	17	5	40	5	17	20	27	285
Corporate	34	4	83	31	5	3	11	3	1	1	147

Total	345	274	235	198	190	136	97	79	71	67	1821

Table3: Top 10 countries and the shares of different sectors

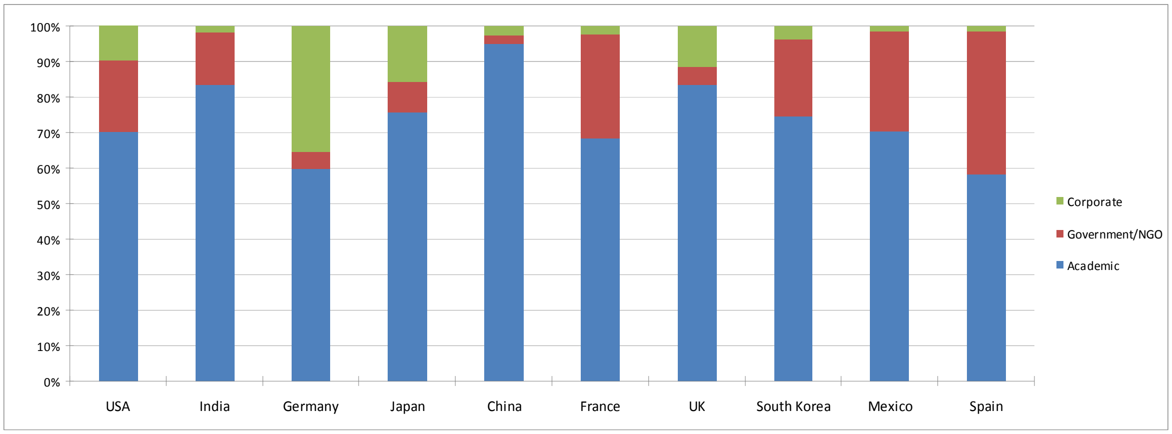

Figure 7: Top 10 countries and the shares for different sectors

In Figure 1, we presented the concentrations of the 1659 articles in this research field on a base map of science. This is a highly multidisciplinary research field. We know that corporate activity is a leading indicator of commercialization, indicating the future of the market. We next compare the difference of research focus among corporate, government, and academic institutes.

We generate a macro-disciplines[iv] matrix for each sector (not reproduced here). We find that there is a big drop-off after the fifth macro-discipline (e.g., for academia, the volume for the fifth one is 48 publications, but the sixth is 14, with just 4 for the seventh macro-discipline), so we create Figure 8 choosing the top 5 Macro-disciplines. What stands out is that all sectors show a similar share of the key component research fields: "Materials Science", "Chemistry", "Engineering" "Physics" and "Computer Science."

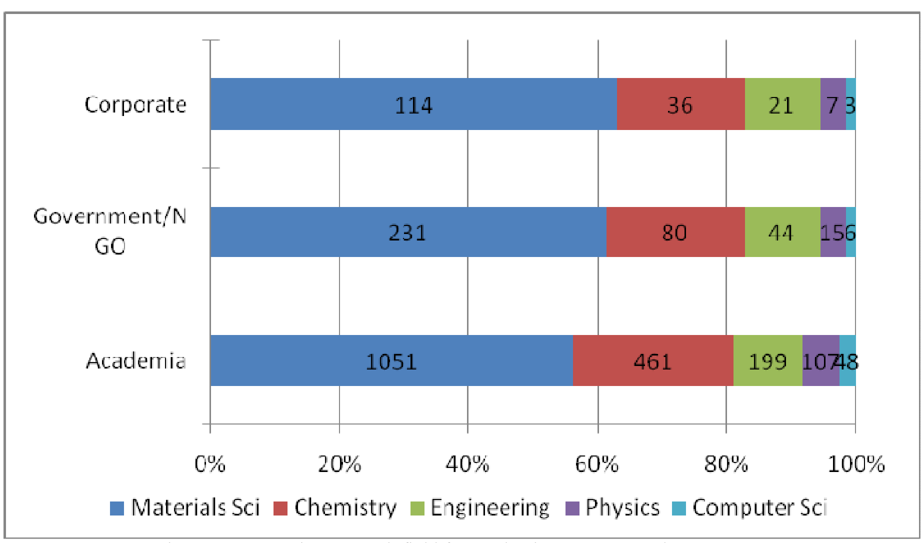

Figure 8: Comparing research field for academia, corporate and government

[iv] See the explanation in the beginning of Part 4.

6 Research networking

Figure 9a uses clustering and cross-correlation techniques to compare the top 10 countries by measuring and visualizing the similarity of their focus. This computer-generated map uses physical distance to symbolize the proximity or divergence of academic focus. In the present study, the measure is based on a computer-supported analysis of 7,892 keywords. Each article was associated with multiple keywords, and VantagePoint identified the relevant keyword clusters, revealing similarities in research interests of specific countries. The size of a circle, symbolizing the respective country, indicates the overall volumes of articles written by the authors with a particular national affiliation. 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 and China; and between the US with the UK, Germany, France, and Spain. If these countries cooperate, it could be particularly fruitful.

Figure 9b and Table 4 illustrate the cluster of knowledge networks of these top 10 countries in this research field. For Figure 9b, the heavier links among nodes represent more co-authoring among countries. Information boxes in Figure 9b show the leading co-author nationalities. From Figure 9b and Table 4 we can clearly see that China lags in cooperation with other countries (publications with international cooperation only constitute 10.4% among all the papers with Chinese authors; it's 20%~40% for other top 10 countries). In contrast, South Korea (52.2%) leads in the share of international cooperation, mainly because of links with India [we find these particularly involve Hanyang University, co-authoring with Shivaji University on 13 of its 19 papers]. The UK and Mexico also collaborate notably on NE-TF-SC.

Comparing Figure 9a and Figure 9b, we can see that some countries have quite similar research orientations, but few have developed correspondingly strong cooperation patterns. This suggests a potential chance for co-operation – e.g., China and Japan have notable common research interests (Figure 9a), but few links among papers (Figure 9b and Table 4). The US might gain from strengthening cooperation with the noted European countries in this field.

	% International Cooperation (among top 10)	**USA**	**India**	**Germany**	**Japan**	**China**	**France**	**UK**	**South Korea**	**Mexico**	**Spain**
USA	20.1%	288	5	16	5	6	5	3	9	8	1
India	26.4%	5	239	4	15		4	5	20	10	
Germany	27.1%	16	4	195	10	2	8	8	1		4
Japan	24.2%	5	15	10	182	4	2	5	2	1	
China	10.4%	6		2	4	182	2	2	1	2	
France	24.8%	5	4	8	2	2	113	4			3
UK	34.5%	3	5	8	5	2	4	84	1		1
South Korea	52.2%	9	20	1	2	1		1	69	2	
Mexico	38.5%	8	10		1	2			2	65	2

Spain	17.5%	1	4		3	1		2	63

Table4: Number of publications of top 10 countries and cooperation among each other

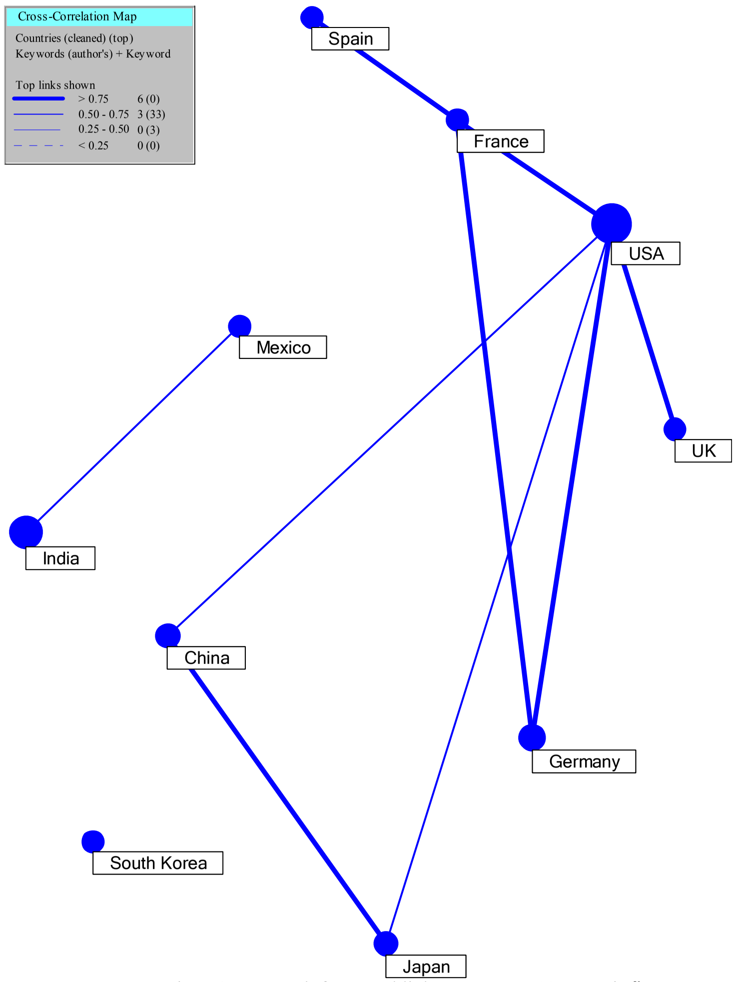

Figure9a: research focus and links among top 10 countries[v]

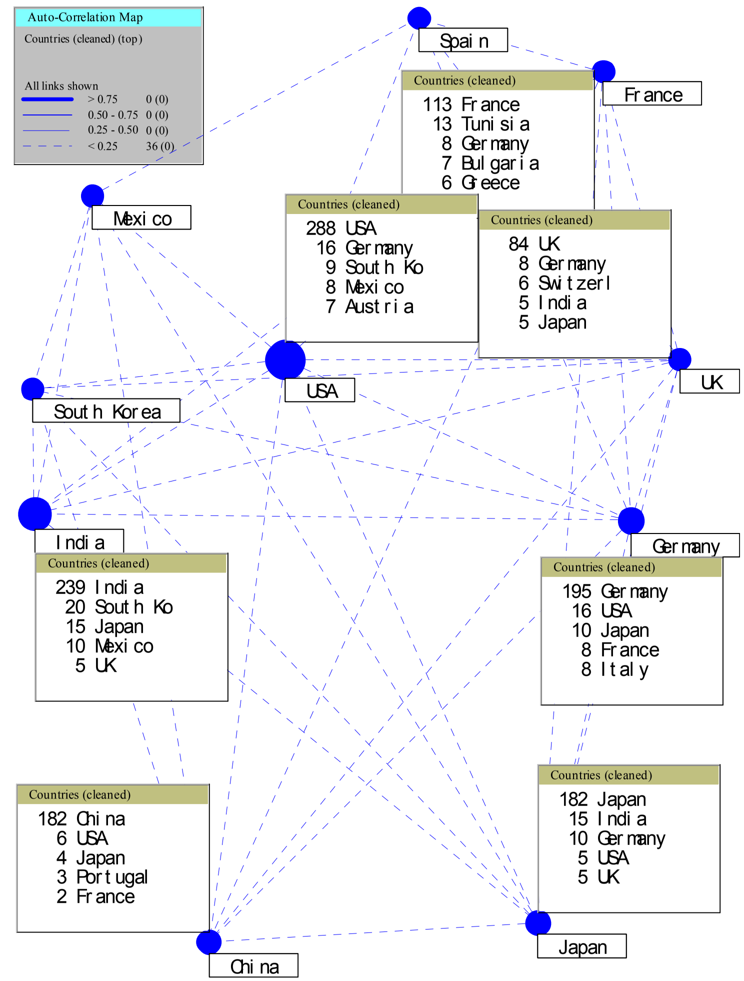

Figure 9b: Cooperation among top 10 countries

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[v] This is a Multi-Dimensional Scaling ("MDS") representation. Location along the axes has no inherent meaning. Proximity reflects degree of association. However, to accurately depict the association among N nodes would, in principle, require an N-1 dimensional representation. So this 2-D visualization is a rough approximation. Accordingly, a Path-Erasing Algorithm is applied to show relative strength of association between pairs of nodes. As per the legend, stronger ties are shown by heavier connecting lines.

We next examine the collaboration pattern within a country by mapping the leading organizational affiliations based on co-authoring relationships. We choose the US and Germany as our cases. We map "Affiliation by Affiliation" for those with 7 or more publications by US authors in the NE-TF-SC area. Similarly, we create such a map for Germany for affiliations with 6 or more publications. Figure 10 shows both. Strong links between affiliations are indicated by heavier lines. Node size represents the relative number of records published by that affiliation. We find that the core researchers and nature of collaboration in the US and Germany are quite different! In the US, the number of publications for each institute differs only slightly, that is to say, no institute is in an absolutely leading position in NE-TF-SC research. At the same time, the cooperation among them is relatively limited and weak. For Germany, Hahn Meitner Inst Berlin GmbH shows its great advantage by its node size, discussed before. All the affiliations are considerably interconnected, most of which are linked to Hahn-Meitner (now Helmholtz Zentrum Berlin). Therefore, Hahn-Meitner stands out as especially important for NE-TF-SC progress in Germany.

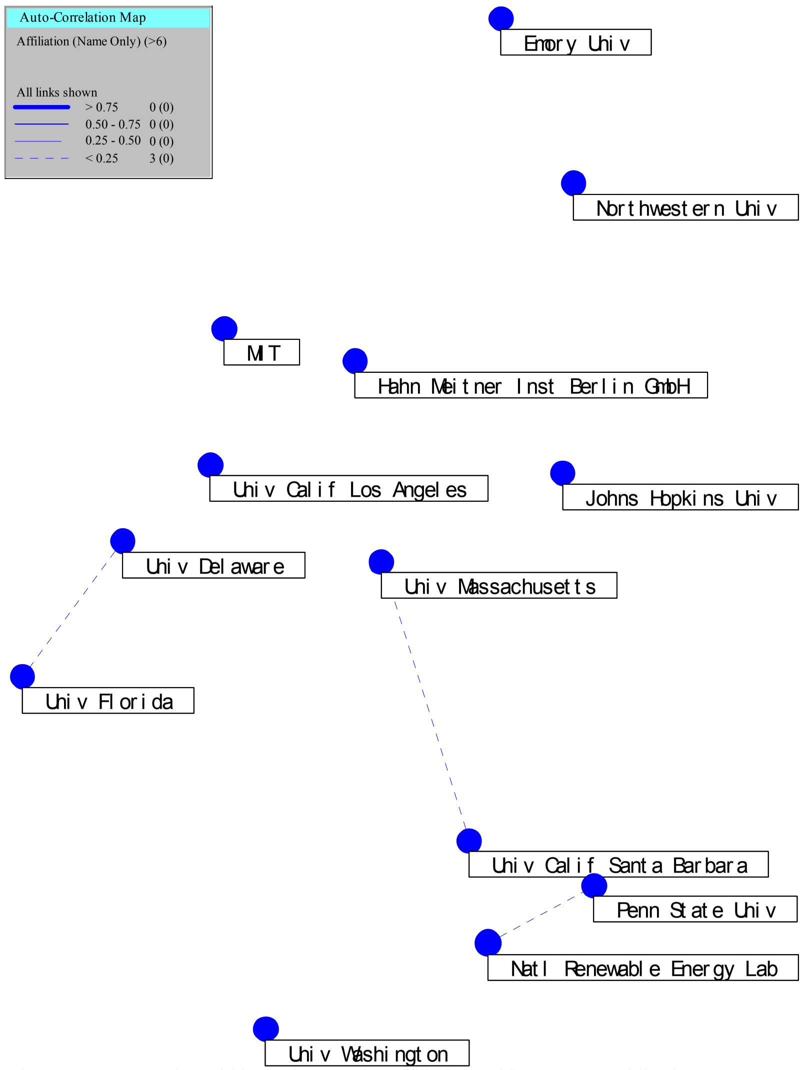

Figure10a: Cooperation within US by mapping affiliations with 7 or more publications

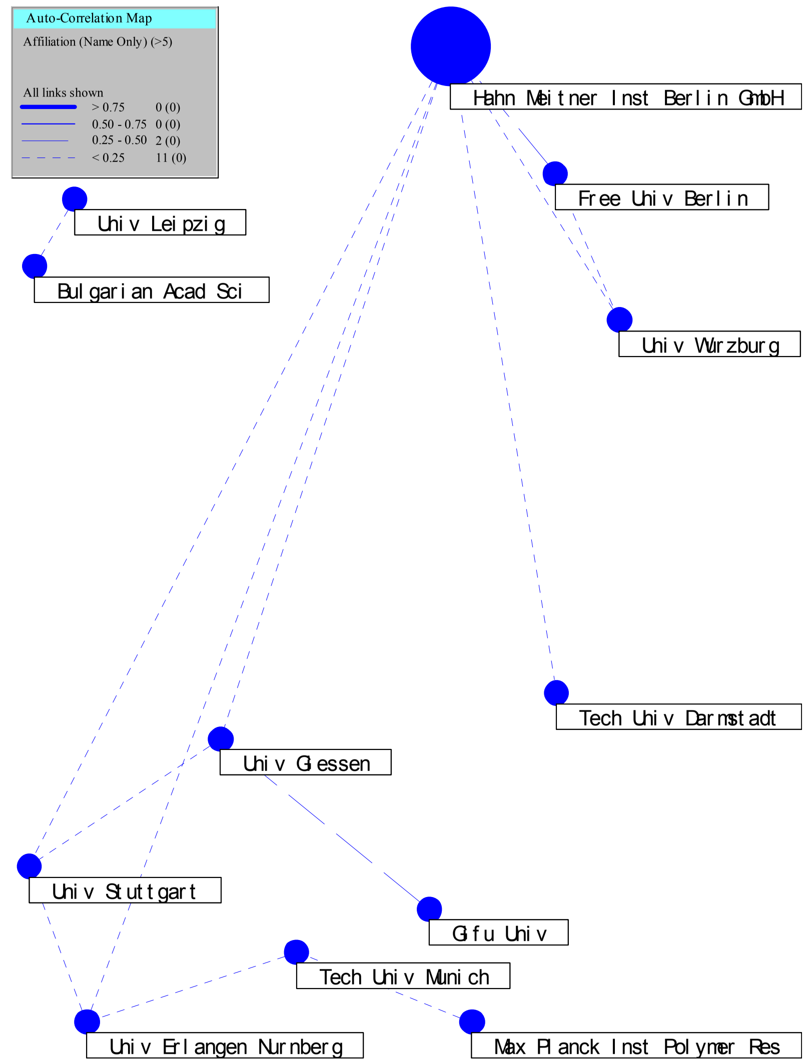

Figure 10b: Cooperation within Germany by mapping affiliation with 6 or more publications

7 Conclusions, policy implications and future prospects

Profiling the extent of nano incorporation into thin-film solar cell research can offer valuable intelligence to facilitate technology management (Porter and Cunningham, 2005). We explore characteristics of the research in this emerging technology – cross-country comparisons, actors and activities, and research networking. These provide multiple perspectives NE-TF-SC research, with several R&D policy implications.

This study shows that the US remains the leader in international research publication concerning NE-TF-SCs as of mid-2008. Comparing the leading countries in research on this emerging technology finds today's "usual suspects" — Japan, Germany, and China. Somewhat surprisingly, India is a leader in this Materials Science/Chemistry field as well. Furthermore, India and China show strong trends of relative increase in both the research activity (publication rates) and quality (citations received). We forecast continuing gains from Asia in R&D on this emerging technology. As "technology watchers," we want to track whether the increasing citation of Indian and Chinese research continues; if so, this could really be a leading indicator that their research is having an impact. Such analyses can be useful for R&D policy makers and managers in establishing national R&D strategy. It may also inform corporate R&D management, in terms of tracking and engaging in such activities more globally.

In Section 5, keying on the organizational level, we point to prominent players to watch and their differential emphases. We also illustrate alternative visualizations to help convey "who is doing what." We find that compared with corporations, academia and government conduct the majority of the NE-TF-SC research. However, corporations in the US, UK, Germany, and Japan represent a notable share in their countries' publications. This points to a probable edge for these four countries toward commercialization.

We also explore patterns of research networking -- both within countries (among organizations) and among countries. We find that some countries appear to share common interests, but they don't have much cooperation with each other [like China and Japan]. R&D managers might gauge relative opportunities for collaborative development, as well as monitoring emerging competitors. For networking among organizations, we only present resulting collaborative maps within the US and Germany in this paper. Those are quite different. For the US, no institution dominates the research publication and inter-institutional networking appears weak. For Germany, we identify strong networking with an apparently key, central organization (Hahn-Meitner Institute). Those interested in competitive technical intelligence would want to obtain expert review to check that this pattern is a good representation of the research networking. They could then pursue the tech mining illustrated here further to probe more deeply into particular organizations' strengths. That would be vital information to use in monitoring competition and possibly developing research and development alliances.

Apart from these policy implications, the study could also enrich understanding of mechanisms that could hinder the diffusion of this emerging application. We plan to carry these analyses "downstream" to investigate the NE-TF-SC Technology Innovation System (**"TIS"**) (c.f., Bergek, 2002; Bergek et al., 2008; Carlsson and Stankiewicz, 1991; Galli and

Teubal, 1997). A TIS proceeds through stages, from basic R&D to commercialization, in a non-linear fashion where constant interactions between different agents contribute in shaping and delivering an eventual commercial innovation or innovations (Lundvall, 1992; Freeman and Soete, 1997). The present analyses mainly help compose the "R&D" components of the TIS. We intend to address manufacturing, market, and environmental analyses pertaining to NE-TF-SC development and applications. We plan to explore more about corporate R&D by examining patent activity, where the corporate presence would likely be prominent. We especially are interested in seeing if patent "prior art" points to particular NE-TF-SC research publications, to explore this avenue of research knowledge transfer. We also want to explore alternative innovation paths for the solar cell arena, to find the more likely development pathways. In particular, we seek to assess the relative prospects for NE-TF-SC options. This might be important for policy makers, technology managers, and entrepreneurs to determine how best to advance this important renewable energy form.

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