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Nanotechnology and Renewable Energy Development in China and South Africa: Bridging the Gap between Research and Innovation

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Introduction

The funding of nanotechnology research worldwide has increased rapidly since about 2002, due to the expectation that this emerging field will be one of the main drivers of technology-based economic growth in the near future (Shapira and Wang 2009). Another dimension of this push in light of growing concerns about climate change, is the increase in the intensity of the discourse around “green” nanotechnologies that could address the problem of sustainable development, particularly in energy production and use, the provision of water, health, agriculture and other environmentally-sensitive applications (Shapira and Youtie 2012). More than 60 countries have now established national nanotechnology programs, including rapidly industrializing nations like China which is investing heavily, and smaller emerging countries like South Africa, which is also trying to capitalize on the new technological frontier (Shapira and Wang 2010).

However, the major challenge facing both countries is how to convert their efforts in research into commercializable products. Although China now ranks first in scientific publications produced every year since 2010 (See Figure 1), and has increased the scale of its research in terms of the number of researchers (thousands) and the number of institutions (hundreds), there is a significant gap between its scientific research and successful commercialization (Shapira and Wang 2009). Similarly, South Africa, which has the highest research output in Africa, though much lower than China’s, has also shown little evidence of new product development. The problem of how to bridge this gap between R&D and innovation, or between science and industry, thus looms large for these countries in order for them to address their specific developmental and national technological aspirations, which go beyond simply trying to tap into the estimated $2.6 trillion nanotechnology market in 2014[1].

This paper seeks to understand the underlying sources of this “innovation gap”, that is, to clarify the reasons for the weak linkages between science and industry in the specific sector of nanotechnology for renewable energy. I first provide a general overview of the NSI in the two countries, as well as their national nanotechnology policies and renewable energy initiatives. The South African Nanotechnology Initiative (SANI) was started in May 2002 by some of its

[1] For estimated size of the global market, see: Appelbaum, R. P. and R. A. Parker (2008). "China's bid to become a global nanotech leader: advancing nanotechnology through state-led programs and international collaborations." Science and Public Policy **35**(5): 319-334.

university researchers and with the support of the Department of Science and Technology (DST), this effort later led to the adoption of a ten-year plan known as the National Nanotechnology Strategy (Cele, Ray et al. 2009). The strategy has two clusters: an industrial cluster, and a social cluster which includes water provision, health, and affordable and renewable energy (RSA 2011). Chinese scientists have organized tens of national conferences since 1990 covering a wide range fields related to nanotechnology in order to use this technology as a driving force for economic growth (Bai 2001). China's twelfth five-year economic plan includes six green pillars, one of which is climate change, and several emissions reduction targets, such as a 17% reduction in Carbon per unit GDP by 2017 (Shapira and Youtie 2012).

Secondly, I employ a bibliometric database on worldwide nanotechnology publications in the decade from 2002 to 2011 to not only present further evidence of this gap between research organizations and industry, but also to explore their interrelationships within the countries and between countries. In China, for instance, the main indicator is that there are more SCI (Science Citation Index) journal articles by its resident scholars than the number of industry patents, and in nanotechnology, the number of papers disproportionately outnumber its industry patents (Liu and Liu 2011). Similarly, although South Africa is the only semi-industrialized country in sub-Saharan Africa and has the largest number of journal publications and patents in the region (Teitel 2011), its NSI focuses primarily on scientific institutions and R&D, and much less on firms (Kruss and Lorentzen 2011).

Thirdly, I will then enrich the NSI narrative by discussing the role that concepts from the economic sociology of innovation, such as strong and weak ties within inter-firm networks, the degree of embeddedness of economic action in social relations, organizational strategy and routinization, have on the innovation process. For example, contested ideas about whether or not, and under what conditions Foreign Direct Investment (FDI) may produce knowledge spill-overs (Lee, Park et al. 2011), or what the benefits and risks of international collaboration are to national innovation (Liu and Liu 2011), will be addressed using some of the concepts outlined above.

Objectives

The goal of this research paper is to understand the innovation process in nanotechnology for renewable energy by primarily using the National Systems of Innovation (NSI) framework in comparative perspective between China and South Africa. The main research questions I will attempt to answer are as follows:

1. Why are there weak linkages between scientific research and successful commercialization in nanotechnology in the two countries?
2. How can they bridge the innovation gap between science and industry with respect to nanotechnologies for renewable energy development?

Methodology

1. A survey of applications of nanotechnology in energy has already been completed on the basis of a literature review and influential reports such as Lux Research's 2006 "Nanotechnology Report", the Meridian Institute's 2006 report on "Nanotechnology, Water and Development", the Toronto Group's 2004 study on "Nanotechnology and the Developing World", and others.
2. Based on this survey, I have developed a keyword strategy or "thesaurus" that has been used to retrieve nano-energy journal articles from a bibliometric dataset of nanotechnology articles constructed at Georgia Tech. The strategy has been used to categorize the various applications of nanotechnology to energy. It will also use it to retrieve the patents from the PATSTAT dataset we have collected from the EPO (European Patent Office) Worldwide Statistical Database.
3. The next step is to track the evolution of nanotechnology research and development in the general energy sector and its various sub-categories in both China and South Africa, based on the publication and patent datasets, which we have from 1990 to 2011. The analysis will focus on the important decade in the blossoming of nanotechnology from 2001 to 2011.
4. I then attempt to map the distribution of academic, government and corporate actors doing research in renewable nano-energy within each country, their relationship with each other and the relative strengths of these relationships, based on the publication and patent records. In this step, I also map the other countries with which China and South Africa are each collaborating with the most.
5. The bibliometric analysis is then be expanded by drawing from the scholarly literature which describes the particular nature of the networks within each country, including

those concepts from the economic sociology of innovation which will allow me to fill in some additional explanatory narratives into the framework provided by the NSI. Interview data with South African nanotechnologists and scientists collected in 2011 is also used to help enrich this narrative.

6. Finally, some conclusions are drawn from the analysis, and based on these, some policy recommendations are provided on how both China and South Africa can bridge the innovation gap in their respective countries with respect to nanotechnology in general, and with respect to renewable energy in particular.

Systems of Innovation in China and South Africa: With Special reference to Nanotechnology Programs

China:

China's National System of Innovation can be characterized by three main periods, which help to explain how China came to occupy a dominant role in science, technology and innovation. The first period was the "Big Push" under the centrally planned economy from 1949 – 1978, the second period was one of reform and opening up of the economy from 1978 – 2005, and the third is the period of indigenous innovation from 2005 to the present day (Liu and White 2001). While the two main characteristics of the Chinese government during this period of central planning were national self-sufficiency, the role of the institutions and actors changed significantly during the transition era, because Deng Xiaoping and other pragmatic leaders saw that the inefficiencies and lower effectiveness of a centralized economy would not achieve their national economic and developmental goals. The two main institutional changes that define the reform period were the use of economic measures as the dominant criteria for evaluating performance, and the decentralization of decision-making over operational decisions within primary actors, and resource allocation within the economy. As a result, performance has improved both at the organizational level and at the system level, and the government has allowed new primary actors to emerge, including multinationals. However, China leveraged its large market to establish a precondition that foreign companies license sector-specific technologies to its companies in order to invest in the country, and also required that they sell most of their products internationally in order to protect infant Chinese industry (Liu and Lie 2011).

China has an impressive electrification rate of 99.4% and most of its rural villages now have access to electricity, including a particularly successful program in small hydroelectric power that was guided by three principles namely, self-construction, self-management, and self- use (Yao and Barnes 2007). Under the principle of self-construction, local governments and populations were encouraged to use local materials, technology and water resources to build the systems. Self-management allowed investors to own and manage stations, while preserving the enthusiasm of the local communities to develop SHP and reducing excessive administrative interference. Self-use then ensured that the electricity produced by the stations be used locally, and the locally integrated markets were protected by not allowing the conventional grid to compete with them (Yao and Barnes 2007). This step-by-step process can be said to be equivalent to learning by doing, using, and interacting (DUI) mode of science, technology and innovation (STI). China's Renewable Energy Development Program (REDP) provided 402,000 solar home systems (SHS) from 2001 to 2008 (Xinlian and Wei 2008), and its "Golden Sun" program, which was initiated in 2009 and is based on competitive bidding, subsidizes 70% of off-grid systems and 50% of grid-connected ones (Martinot 2010).

While there is an increase in the scale of Chinese nanotechnology research in terms of the number of researchers (thousands) and the number of institutions (hundreds), there is also a significant gap between its laboratory research and successful commercialization (Shapira and Wang 2009). This is because many of the enterprises were set up to make profits from their core technologies in low, commodity-end products in the value chain, and therefore lacked sustained R&D capabilities (Shapira and Wang 2009). More recent bibliometric analysis and science mapping show a rapid development in the number of China-U.S. co-authored nanotechnology papers, with an emphasis on those fields where China has well-established strengths, namely, materials science, physics, chemistry, and engineering, as opposed to the life sciences, which are very strong in the U.S. (Tang and Shapira 2011). One potential area of concern for Chinese policymakers is that since they have weak linkages between science and industry, the outcome of international collaborations may be that the U.S. or other foreign companies may commercialize nanotechnology innovations based on the joint research (Tang and Shapira 2011). An area of innovation in nanotechnology in the energy sector that has emerged is that of thin film solar cells (TFSC), where in addition to being among the top five countries publishing in the area, China is also now heavily involved with the commercialization of photovoltaic systems (Guo, Huang et al. 2010). These TFSCs are more efficient and represent a more cost-effective solution than the expensive manufacturing required for conventional silicon solar cells.

South Africa:

Following the end of apartheid rule, the newly democratic South Africa that officially began in 1994 adopted the National System of Innovation (NSI), and formally made it a government policy in 1996, thereby making it the first non-OECD member country to do so (Maharajh 2011). Its current Ten-Year Innovation Plan, initiated in 2008, is its most recent document on innovation policy, and has the goal of moving the country from a resource-based economy to a knowledge-based one in order to address its "grand challenges", some of which include agriculture, biotechnology, space technology, climate change, and energy security (Rennkamp 2011). However, despite the extensive consultative process that included the wider public in the formulation of the original NSI, South Africa has yet to significantly deliver a better quality of life to all its citizens. Maharajh (2011) has suggested that one reason for this is because the vested interests of capital and academia have absorbed the progressive terminology contained in the NSI, while using its allocated resources to maintain the advantages of their elite groups.

The electrification program of South Africa, as one part of its overall energy policy, has shown remarkable results, going from a rate of access to electricity of less than a third in 1990, to over 80%, including more than five million newly connected households in 2008, by some estimates (Bekker, Eberhard et al. 2008). This occurred through a set of bold institutional and planning arrangements, as well as the development of technological innovations that were aimed at both reducing cost and achieving social goals (Bekker, Eberhard et al. 2008). However, in spite of its shortfall in generation capacity and its overdependence on coal, South Africa is significantly behind its renewable energy target of 10,000 GWh every year by 2013, from sources such as solar (both photovoltaics (PV) and concentrated solar power (CSP)), wind, and imported hydroelectric power (Yelland 2011). An important aspect of addressing these targets is the idea of increasing "local content" in the technologies themselves, and in November, 2011, the first wind turbine rotor blade manufacturing plant in South Africa was launched by a Cape Town-based company by the name of Isivunguvungu, which means "big wind" in the official languages of Xhosa and Zulu (Bretenbach 2011).

The South Africa Nanotechnology Initiative was started in May 2002 as some universities established strong working relations with industrial companies and now has about 100 registered members including 12 universities, 10 industrial companies and 4 science councils. The National Nanotechnology Strategy of South Africa requires that the country derive benefits from global advances in this area. The Strategy prioritizes four areas based on the innovation missions of the National Research and Development Strategy (NRDS), namely: Poverty reduction, key technology platforms such as biotechnology, advanced manufacturing and leveraging resource based industries. It has 6 focus areas with the first 3 focused on social issues: water, energy and health. The other 3 focus on industrial development: chemical and bio-processing, mining and minerals, and advanced materials and manufacturing (RSA 2003). As of 2007, two nanotechnology innovation centers had been established at the Council for Scientific and Industrial research (CSIR) which is called the National Center for Nanostructure Materials and the other at MINTEK (South Africa's national mineral research organization). Both are closely aligned with the Strategy from the Department of Science and Technology and have a focus on human capital development. In addition to other initiatives, the Mintek/DST National Innovation Center (NIC) focuses on water nanotechnology in collaboration with the Water Research Commission and the Universities of Johannesburg, Western Cape and Rhodes, while the CSIR center focuses on energy-relevant initiatives such as solar cells and solid state lighting (RSA 2007).

With respect to innovation, a low-cost thin film solar photovoltaic technology based on Copper Indium Gallium diSelenide was developed by Prof. Vivian Alberts of the University of Johannesburg in 2005 , but was then licensed to the German manufacturer, Aleo Solar (Ottery 2012). This was due to an inadequate institutional and legal framework, insufficient financing, and a lack of specialized solar PV manufacturing capability, which meant that this invention was unable to be produced domestically (Perrot 2012). More generally, though, many researchers do not think that Africa can compete in the already advanced field of silicon-based PV, but organic polymer-based solar cells, which are relatively easy to process, and are inexpensive and flexible, are attracting the attention of African solar scientists in spite of their currently low efficiency (Ottery 2012). Our interviews with South African scientists in 2011 similarly revealed that some of its scientists are also working in the area of nanotechnology-based organic solar cells, based on the same technology policy analysis.

Bibliometric Analysis

The number of energy articles in our nanotechnology dataset is 20,961 out of the total of 653908, which is 3.2% of the dataset that includes the years from 2001 to 2011. The search terms that I used to derive these articles was as follows: biofuels, bio-diesel, bio-ethanol, biofuel cell, energy, efficiency, energy generation, energy production, energy storage, fuel cell, geothermal, solar photovoltaic, solar device, solar panel, solar cell, dye-sensitized solar cell, DSSC, solar energy, solar technology, solar electric, solar thermal energy, solar thermal, solar hot water, thermoelectric, wind energy, wind power, wind generation, wind electricity, wind turbine.

The ten leading countries in terms of publications in the energy applications of nanotechnology in 2011 are shown in Figure 1. Table 1 shows the different classes of energy applications and the relative distribution of their publications in China and South Africa. Figure 2 shows the ten leading countries in patents awarded from 1990 to 2010, while Table 2 shows the distribution of patents in China and South Africa.

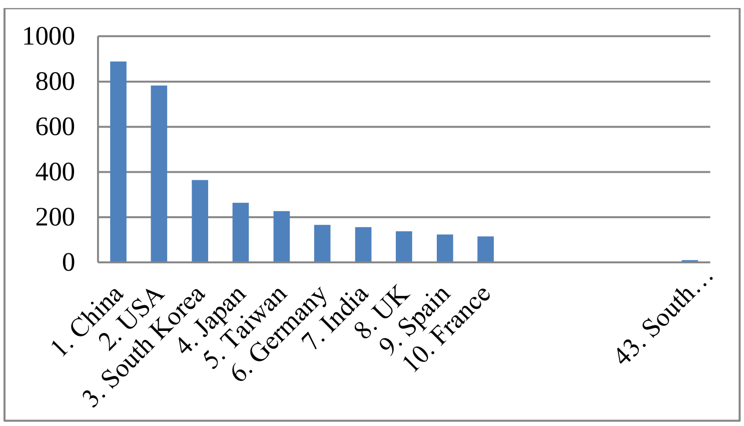

Figure 1. Top 10 Countries in Nanotechnology Energy Publications in 2011

In terms of nano-energy articles, China had 889 articles and the U.S. was in second place with 782 articles, while South Africa had 6 articles as shown in Figure 1. When we include all the nanotechnology articles, China also led the world in 2011 with 15226 total articles surpassing the U.S., which had 13313, while South Africa ranked #41 with 197 articles. It should be noted, however, than the articles for the last few months of 2011 have not yet been added to the dataset, but based on trends from previous years, as well as reports from completed studies, we feel confident that China did in fact surpass the U.S. in nanotechnology articles in 2011.

Table 1. Research Output (Publications) of Main Nano-energy applications in China and South Africa and the U.S. from 2001-2010

Nano Energy Applications	U.S.	China	South Africa
Fuel Cells	2243	2299	37
Solar Photovoltaics	2007	2014	15
Biofuels	253	200	0
Energy Storage	130	80	3
Energy Efficiency	32	19	0
Thermoelectrics	85	14	0
Solar Thermal Energy	8	5	1
Geothermal	14	2	0
Energy generation	8	0	1
Energy production	10	1	0
Wind Energy	7	1	0

China’s publication output is significantly larger than that of South Africa across all the categories as shown in Table 1 above. The U.S. has a total publication output that is only slightly larger than that of China, and both countries match evenly across all technology classes of nano-energy. South Africa’s research strengths, however, lie primarily in fuel cells and solar PV. Figure 2 below shows the historical evolution of nano-energy articles from 2001 to 2010, with China effectively catching up with the U.S. by 2010.

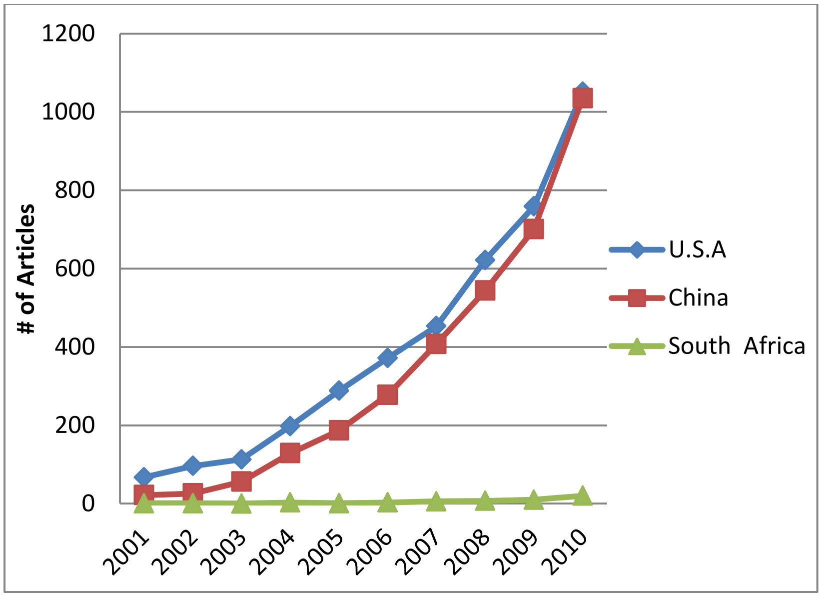

Figure 2. The evolution of nano-energy articles from 2001 to 2010.[2]

Figure 3 below shows that the U.S.A was the global leader in the number of nano-energy patents (based on the PATSTAT database) awarded with 304 patents, China had 295, while South Africa had only one. For comparison, the U.S.A also led the world in total nanotechnology patents during a 21-year period with 23,810 patents, China had 21,009, and South Africa had 51 patents.

[2] 2011 data points have been omitted in this chart because only partial data for that year was available.

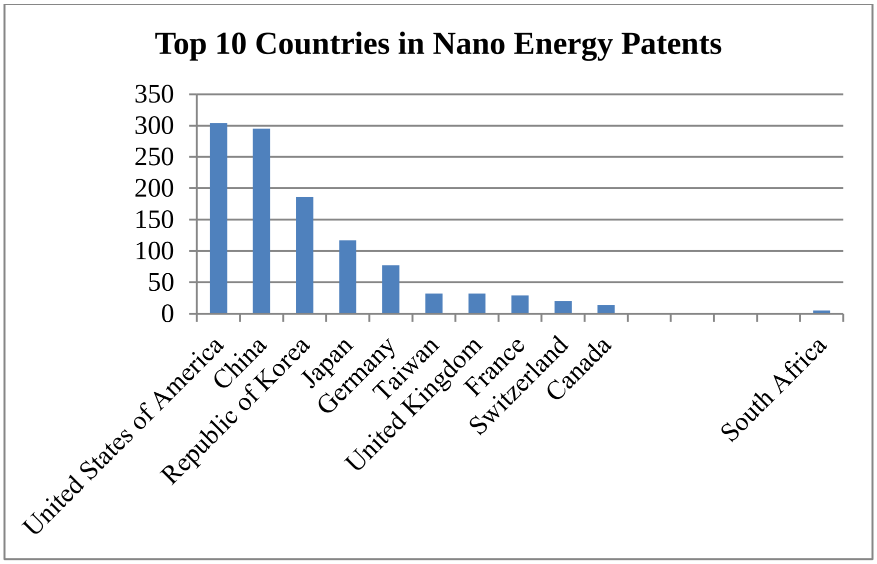

Figure 3. Nanotechnology Energy Patents from 1990 – 2010

Table 2 below shows that there is a significant gap in patenting between the U.S. and China when compared with their publications, where they are about evenly matched. While the number of patents alone is not a sufficient indicator of innovation activity, this disparity suggests that the inventive capacity and intention to protect any future innovations is much stronger in the U.S. than in China.

Table 2. Patents of Main Nano-energy applications in the U.S., China and South Africa (2001-2011)

Nano Energy Applications	U.S.	China	South Africa
Fuel Cells	370	142	0
Solar Photovoltaics	343	124	1
Biofuels	57	17	0
Energy Storage	10	7	0
Energy Efficiency	1	1	0
Thermoelectrics		0	0
Solar Thermal Energy		5	0
Geothermal		5	0
Energy generation		0	0
Energy production		0	0
Wind Energy		4	0

Table 3 below shows, as expected, that the dominant group that is publishing its research in nano-energy are academic institutions in China and South Africa, as well as in the U.S. However, it is also interesting to note that governmental institutions and corporations also publish a sizable number, but their contribution is much stronger in the U.S. than in China, while it is negligible in South Africa.

Table 3. Distribution of publications between sectors:

	U.S.	China	South Africa
Academic	2547	2850	9
Government	569	166	1
Corporate	271	46	1
People	2	1	

Table 4 below shows that the main international collaborator in nano-energy research with China is Taiwan, while the U.S., Singapore, France, South Korea, and Great Britain collaborate with it less.

Table 4. International Research Collaborations with China

# Records	Show Values >= 1 and <= 20948 Cooccurrence # of Records	China	Taiwan	US	Singapore	France	South Korea	Great Britain
20948	China	20948	227	15	13	6	2	1
227	Taiwan	227	227					
15	US	15		15				
13	Singapore	13			13			
6	France	6				6		
2	South Korea	2					2	
1	GB	1						1

Table 5 below shows that South Africa's international collaborators in terms of research publications in nano-energy is low, with only one co-publication with the U.S.

Table 5. International Collaborations with South Africa:

# Records	Show Values >= 1 and <= 43 Cooccurrence # of Records	South Africa	US
43	South Africa	43	1
1	US	1	1

Bridging the Gap between Research and Innovation:

This section seeks to elucidate the character and processes of technological change in general, with a view toward highlighting which of them could promote innovation in the emerging field of nanotechnology. While innovation is a challenging task in general, it is even more difficult in the case of industrializing and non-industrialized countries, which only have a minimal rate of success in achieving it. I attempt to outline briefly how China and South Africa might increase their rates of adoption of the nanotechnologies they need by first explaining the sources of technical change as a key determinant of economic development, and the various network forms of organization with respect to their impact on innovation. Secondly, I explicate the process of transforming research into inventions, and the more crucial one of converting inventions into innovations, as well as the role of tacit or sticky knowledge in innovation. Finally, I discuss the various strategies in patenting and appropriability, and underscore which of them could lead to better innovation in nanotechnology in the two countries.

Characterization of Technological Change:

According to Nelson and Winter (1982), technical change is a key driving force in long-run economic development, but it is highly uncertain, disorderly, and consists of making so many mistakes that the study of the past behavior of firms is more productive than relying on economic analyses that are disconnected from firm decision-making (p. viii). They argue that one of the main constraints associated with understanding technical change is the intellectual constraint imposed by "orthodox" economic theory, which is based on microeconomic theory, and has an over-reliance on strong assumptions of market efficiency, maximization, and equilibrium analysis, as well as the reduction of rational behavior to optimization (pp. 7-8). On the other hand, their evolutionary approach reconciles the realities of decision-making with economic analysis with respect to firm responses to changed market conditions as well as innovation-based competition and growth ((Nelson and Winter 1982),p.3).

The investment rule is a major predictor of a firm's profitability, with the profitable ones growing and the unprofitable ones shrinking or being eliminated. This selection mechanism is analogous to the natural selection of genotypes in biological evolutionary theory, whereby differential net rates of reproduction are similar to a firm's growth rate in the face of adversity or prosperity ((Nelson and Winter 1982),p. 17). The routine-guided, routine-changing processes are modeled as a "search" in the sense that a firm will have certain criteria that help it evaluate proposed changes in routines, which are overwhelmingly based on anticipated profit (p.18). The "search", which is analogous to "mutation" in evolutionary biology, denotes a firm's activities that are aimed at improving on its current technology, and invokes the idea of that firm engaged in exploring its preexisting set of technological possibilities ((Nelson and Winter 1982),p. 210).

Markets represent the major selection environment for green nanotechnology innovation, especially in the China's case and partly so, or inconclusive in the case of South Africa. However, the nature of markets and their origin are the subject of considerable debate and scholarship. Harrison C. White proposes embedding the neoclassical theory of the firm within a sociological view of markets, which are self-reproducing social structures among specific cliques of firms and other actors who evolve roles from observations of each other's behavior (White 1981). Walter Powell (1990) is also sympathetic to the view of economic exchange as being embedded in a particular social structural context, but also believes that certain forms of exchange are less guided by a formal structure of authority, and are more social, being more dependent on relationships, mutual interests and reputation ((Powell 1990)p.300). Powell's view is that the portrayal of economic exchange as lying on a continuum from markets to hierarchies is too mechanical, and blinds the scholar to the roles of reciprocity and collaboration as alternative governance mechanisms (p. 298). The term he prefers to use, which is neither a market transaction nor a hierarchical governance structure, and has a different mode of exchange with its own logic is the "network" (p.301). Network forms of exchange entail indefinite sequential transactions within the context of a general pattern of interaction, and he provides examples from the construction industry (a quasi-firm) to "boutique" publishing (small, non-bureaucratic operations) versus scholarly publishing (dependent on academic fashions), to the socially integrated, decentralized production units of the Emilian model in Italy, and so on (Powell 1990).

With respect to green nanotechnology development, some of the insights about network forms that may be relevant are that in industrial districts, firms choose to locate in an area, not because of the presence of an untapped market, but because of the presence of a dense, overlapping cluster of firms, skilled laborers, and an institutional infrastructure. Also, while joint ventures are increasingly becoming popular as a form of economic organization, international joint ventures are not regarded favorably by multinationals because they prefer foreign investment or export or occasionally, international licensing. Only when political exigencies or protectionist policies prevent them from operating fully owned subsidiaries, do they resort to joint ventures (Powell 1990). The last point that can be made here is that the rationale for the existence of firms is based on the sharing of know-how in terms of specialized knowledge or craft skill, with the demand for speed being based on compelling economic logic and trust. Thus, the type of firm that would best address China's needs (which targets a global market more and requires speed), is likely to be different from the type of firm that could address South Africa's needs (which is more local and oriented toward the poor).

Transforming Research into Inventions and into Innovation:

Many scholars in the past have addressed the need to break from routine, in order to seize new business opportunities, but Schumpeter viewed innovation as being a deviation from routine behavior, and it was his contention that innovation repeatedly upsets equilibrium (Nelson & Winter, 1982, p. 41). Following in this line of thinking, evolutionary economic theory focuses on market processes due to both exogenous changes (such as market conditions) and endogenous change (innovation), rather than on equilibrium conditions.

Stinchcombe (1990) clarified the basic distinction made by Schumpeter in 1942 between invention and innovation. Since the latter was interested in the transformation of the economy by the development of new technology, he was only concerned with those inventions that could produce a continuous effect in the market, and not with those discovered by isolated inventors. Stinchcombe then goes on to argue that building a social system around an innovation is still not routine, even when it is done in large organizations, and that only those organizations that successfully innovate take on monopoly profit positions because not everyone is able to follow their lead. He demonstrates that turning an invention into an innovation, or an ongoing concern that can produce regular benefits for a firm, is actually creating a social system that has to nurture technical ideas, make investments in risky situations, and arrange the division of benefits so that both investors and personnel are motivated to develop the competences that are needed to do all these things, and actually do them (Stinchcombe 1990).

In addition, despite the fact that it is very difficult and risky to routinize innovations, it nevertheless produces profits when well-done and creates investment booms that followers try to catch up to, while inducing creative destruction of outdated social forms during the recession that follows the boom. It therefore follows, Stinchcombe argues, that the profitability of innovations depends on how fast an innovator and his or her potential competitors come down the learning curve, and on how solid the network connections that an innovator builds to his clients are (Stinchcombe 1990). One illustration of this with implications for nano-based devices can be seen from a comparative analysis of the development of resist materials for an Argon Fluoride laser lithography (ArF resist materials) by three major electronics companies, Fujitsu, NEC, and IBM (Kubota, Aoshima et al. 2011). The study showed that Fujitsu, whose development team was closest to the divisional manufacturing environment had the fastest pace of groundbreaking technological development because its researchers tried to solve problems in a way that would fulfill a variety of performance requirements simultaneously (Kubota, Aoshima et al. 2011). On the other hand, IBM, whose corporate-level research sought to clarify principles while solving performance requirements individually, did not make any significant contribution to the immediate practical use of ArF resists, but their technology only came to be used later in conjunction with the development of one of the processes (Kubota, Aoshima et al. 2011).

To Patent or Not to Patent?

Arora and Gambardella (1994) attempt to show that while in the past, trial and error was the main engine of innovation, the use of general and abstract knowledge in innovation opens up the possibility of a division of innovative labor based on new knowledge produced by firms, and the spreading of the locus of innovation across both users and producers. They found that in most industries, other means of appropriating rents such as secrecy or first mover advantage were more important than patents. They also thought that broader patents would increase the rate of technological progress by encouraging innovators that lack size and downstream capabilities (Arora and Gambardella 1994). The strategy of appropriating rents based on first mover advantage is the one that appears to have been chosen by the South African government in the area of hydrogen-based fuel cells (as emphasized in our interviews), because the country has 75% of the world's reserves of Platinum, which is the key catalytic material used in most fuel cells (RSA 2011). To this end, its Department of Science and Technology (DST) has established a National Hydrogen Fuel Cell Technologies Research, Development and Innovation Strategy, known as HySA, with three university-based Centers of Competence (COC) to address systems integration, hydrogen catalysis, and infrastructure (SAASTA 2012).

However, the assertions of Arora and Gambardella (1994) that industrial research and innovation rely more and more on abstract knowledge (particularly with respect to innovation) runs counter to the evidence that shows that the "small worldliness" of networks fosters creativity. In addition, his belief that the ability to represent concrete information in abstract categories allows it to be used in various locations, is questionable, if we look for instance at the ineffectiveness of most joint ventures with reluctant multinationals, which may provide this abstract knowledge, but not transfer the tacit know-how. Because the technical information required to solve a problem is expensive to acquire, transfer and then use in a new place, the abstract information or knowledge and problem-solving capabilities must be brought together to find an innovative solution. This is what Eric Von Hippel calls “sticky information” (Hippel 1994)

Lastly, the patent system may deter or prevent adoption of patented innovations developed by the competitor of a given firm, just like the institutional machinery may block imitation (Nelson &Winter, p. 265). Kash and Kingston (2001) find that an intended result of the changes brought about by the U.S. Patent Act of 1952 (which adjusted patent administration to the reality that invention and innovation result primarily from investment than from individual creativity) was that the present emphasis of the patent system is on large firms in simple technologies, while denying smaller firms in complex technologies the power to operate patent pools. This has forced them to multiply their patents as bargaining chips, which essentially bars entry by newcomers to complex technologies, thereby reducing competition. Thus, small firms in complex technologies like nanotechnology will require more legal protection for their risky investments in innovation ((Kash and Kingston 2001),p.21).

Conclusions:

The bibliometric analysis presented in the first part of the paper confirms that China has a strong publication record in nanotechnology across all renewable energy applications, which is on par with that of the U.S. South Africa also has a good publication record in the areas of fuel cells and solar PV. However, China’s patenting record is much weaker than that of the U.S., while South Africa’s is almost non-existent. The scholarly literature also informs us that the innovative capacity, in terms of new products and process, is weak in China and much weaker even in South Africa. One reason for this, as stated earlier, is that many Chinese firms lack R&D capability (as seen in Table 3) and they were established to derive their profits primarily from commodity-end products that are low in the value chain. Another reason is that weak linkage between science and industry, despite the efforts of the innovation agencies of both countries. Furthermore, a study of China’s innovation system reform based on a survey of 22,000 manufacturing firms found that even though it is important to consistently promote science and industry linkages, it is also necessary to improve the technological level of the domestic companies, so as to improve absorption capacity (Motohashi and Yun 2007). This is also a critical factor for South Africa, if its high-level laboratory research is to have any impact on the country’s impoverished people.

With respect to innovation in nanotechnology for renewable energy, the trajectory of China would more likely face a market selection environment, while the South African case would probably face a significant non-market selection environment, because of the target population of the users and the purpose of the innovation. Because of its emphasis on poverty alleviation, the South African case especially would need to foster close ties, and indeed a “small world” network between the researchers, inventors and producers on the one hand, and the consumers on the other hand, in order to increase the rate of successful innovations. In the case of China, with its larger and more global market base, it can invest more in imitative R&D than in innovative R&D, which may not pay off, while it carries a lower cost burden from imitation. Although in principle, imitative R&D would in principle also be beneficial for South Africa, because it is not currently competitive in fields such as silicon-based solar PV, for instance, it is has a better chance to invest in the more recent technological arena of organic solar cells, which are much cheaper and more applicable in an African context more generally, where cheap off-grid electrification is a necessity.

China’s firms can form patent pools in order to take advantage of the wider legal protection for large firms, and thus lower the barriers to entry for its small firms. This mainly applies to the export market since patents are largely not enforced in China. Furthermore, because of the nature of the nanotechnology-based renewable energy industry (i.e. primarily chemicals and electronics), the literature suggests that both countries should focus on product innovations particularly in devices and electronics, while emphasizing process innovations in chemicals. In fact, during our interviews, we found that there is a company in Johannesburg that manufactures high quality carbon nanotubes cheaply as a material precursor to be used in other research, based on innovation in its manufacturing process. Also, since many of the renewable energy applications of nanotechnology especially solar PV, are in semiconductor firms, both countries’ firms may try to accumulate exclusionary rights to enable them to safeguard their investments in new technologies, while foregoing some of the costs and delays associated with contracting ‘ex ante’ or being fenced in by companies that already own the designs the firms might need (Ziedonis 2004).

In conclusion, this study suggests that incremental, rather than ‘radical’ innovations are the norm, and that therefore modifications or slight innovations to existing products or processes, as well as imitation of existing innovations, are likely to be much more effective than ‘ex nihilo’ creations. However, contextual requirements for a given society and comparative advantage based on locally available resources would justify the selection of niche areas for further development. Some policy recommendations are that fostering a social environment that is favorably suited to particular products is crucial; firms should undertake more in-house R&D while drawing on the efforts and general direction of publicly funded laboratories; and that the users, particularly the target groups in the South African case, should be more actively involved in all aspects of the national system of innovation. Finally, innovation is a very challenging process and to quote Winter (2003), 'there is no general rule for riches'. Therefore, a keen understanding and awareness of the idiosyncratic nature of the process, combined with its more stable features, is fundamental to increasing the chances of achieving successful innovations in nanotechnology for renewable energy.

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