UNIVERSITY OF QUEBEC AT MONTREAL

THE EVOLUTION OF A SECTORAL SYSTEM OF INNOVATION: A STUDY OF THE SOLAR PHOTOVOLTAIC SECTOR

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L'ÉVOLUTION D'UN SYSTÈME SECTORIEL D'INNOVATION: UNE ÉTUDE DU SECTEUR SOLAIRE PHOTOVOLTAÏQUE

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RÉSUMÉ

L'étude est utilisée pour comprendre le secteur photovoltaïque solaire avec les théories et les méthodologies du système sectoriel d'innovation. Les questions, y compris les raisons pour lesquelles le secteur a évolué si vite, les différences parmi les pays et les régions, les rôles des scientifiques et des petites entreprises dans l'innovation technologique et la façon dont la Chine peut se développer si rapidement, même sans les fortes capacités technologiques et le soutien industriel gouvernemental, sont explorées.

En intégrant l'analyse quantitative en employant le brevet USPTO et les données de publication SCOPUS, et une étude qualitative avec des études de cas et la collecte de données secondaires, les caractéristiques distinguées du secteur photovoltaïque solaire, y compris la variation intensive et innovation cascade, les clusteurs déséquilibrés, les limitées d'entrepreneuriat des scientifiques étoiles et le soutien gouvernement limité lié aux militaires pour les petits innovateurs américains, sont détectés. Totalement, il y a neuf chapitres dans la dissertation, dont quatre articles ont été soumis aux journaux.

Les contributions théoriques et empiriques indiquent que l'étude donne plus de détails au concept de cascade d'innovation, que les clusteurs plus diversifiés pourraient être plus résistants, que l'esprit d'entreprise et l'innovation des petites entreprises sont spécifiés par l'industrie.

Mots-clés: solaire photovoltaïque, système sectoriel d'innovation, évolution sectorielle, clusteur, scientifique étoile, entrepreneuriat, petites entreprises

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ABSTRACT

The study is employed to understand the solar photovoltaic (PV) sector with the theories and the methodologies of sectoral system of innovation, to answer the questions including why the sector developed so fast, what the country and regional differences are, what are the roles of star scientists and the small firms in the technological innovation, and how China can developed so quickly even without the strong technological capabilities and governmental industrial support.

By integrating quantitative analysis by employing the USPTO patent and SCOPUS publication data, and qualitative study with case studies and secondary data collection, the distinguished characteristics of the solar PV sector including being variation intensive and innovation cascade, the imbalanced clusters, the limited entrepreneurship of the star scientists and the limited military-related governmental support for the small American innovators are detected. Totally, there are nine chapters in the dissertation, out of which four papers have been submitted to the journals.

Theoretical and empirical contributions include that the study gives more fleshes to the concept of innovation cascade, more diverse clusters could be more resilient, the academic entrepreneurship and the innovation of small businesses are industry-specified.

Key words: solar photovoltaic, sectoral system of innovation, sectoral evolution, cluster, star scientist, entrepreneurship, small firms

CHAPTER I

INTRODUCTION

1.1. The origin of the study

In the process to review the sectors that Chinese companies caught up fast in the previous 20 years, the solar photovoltaic sector is distinguished from the other sectors. It is the only sector in which that Chinese companies without the strong technological capabilities or strong industrial government support in the early development stage of the sector can get the best market shares throughout the world. How it was realized? What are the factors leading to the success of the Chinese solar PV companies?

With the extensive study of the Chinese solar PV sector itself, it is found that only the domestics factors cannot draw the conclusion on their success if the sector is not studied in the systematic way and in the worldwide.

So the ideas to study the sector comprehensively with the theories of sectoral system of innovation is formulated. The following questions are focused:

- How the sector evolves in both the technological and economical perspectives? Does the evolution helps the global diffusion of the technologies? How the technological diffusion promote the development of the sectors in the developing countries like China?

- What are the functions of innovation-active components in the sectoral system of innovation including scientists and small businesses? What are their innovation performance and contributions to the development of the sector?

Is there the developmental imbalance in the different regions of the world? What are the factors leading to the imbalances?

All the above questions are to be explored in the theoretical framework of sectoral system of innovation.

1.2. Starting point

In order to explore the novelty and maintain the academic value of the study, several aspects have been reviewed. It was found that the solar PV sector is less studied:

- From the standpoint of "Sectoral System of Innovation": when searching the key words "sectoral system of innovation" and "solar photovoltaic", there are just four publications in Scopus. Only one of them is really on reviewing the solar photovoltaic sector with the theories and methodologies of the sectoral system of innovation, in which the case study is about just three countries. When the key words of "sectoral system of innovation" and "solar photovoltaic" are used to search Google Scholar, there is no other paper on the same subject. No paper has been written on the global development of the sector in the world so far.

- From the standpoint of "clusters": when searching the keywords "clusters" and "solar photovoltaic", there are 19 publications in Scopus and just four papers are directly related. One is about California, one is about Norway, one is about China, and the last one is about Taiwan. There is no complete study of the clusters of solar PV sector in the world.

- From the standpoint of "Star Scientist": nothing can be found when searching for the words "star scientist" and "solar photovoltaic " in the Scopus database. When the combination of two phrases is searched in Google Scholar, there are no papers about the same subject.

After the complete literature review was done, it was found that these important aspects of the industries have not been studied yet. The virgin sector is waiting to be explored to formulate the novel ideas for the similar high-tech industries.

1.3.Theoretical framework

1.3.1. The sectoral system of innovation

In order to formulate an integrated view of what the main dimensions of sectors are and what may account for the differences across sectors, the sectoral system of innovation concept is useful (SSI). It was put forward by Franco Malerba (1999,2002,2004) according to whom "A sectoral system is a set of products and a set of agents carrying out market and non market interactions for the creation, production and sale of those products." (Malerba, 2002: 247). SSI highlights a different set of points: knowledge and its structure as a key element; the role of non-firm organizations such as universities, financial institutions, government, local authorities and of institutions and rules of the games such as standards, regulations, labour markets; the dynamics and transformation of sectoral systems is also emphasized.

According to Niosi (2011), the SSI approach emerging from the work of Malerba is as potentially fertile as the previous components of the innovation system perspective. The SSI addition sheds new light on the complexity of the innovation process and helps to understand the trajectories such as how sectoral systems interact with national and regional ones, how sectoral policies are to be understood in the light of national ones and why some countries pull ahead or fall behind.

The sectoral system of innovation includes the following components:

- Different agents: large firms, small firms, public research organizations, universities, and governments.

- Technologies and innovations: the categories of innovations, the process of the innovation produced, the interaction of the organization and technology evolutions

- The institutions: factors including standards, regulations, labour markets all influence the whole system.

These components will be integrated first by exploring the evolution of the sector, the outstanding results about the different components in the evolution are explored further in the different consecutive chapters(see Figure 1.1)

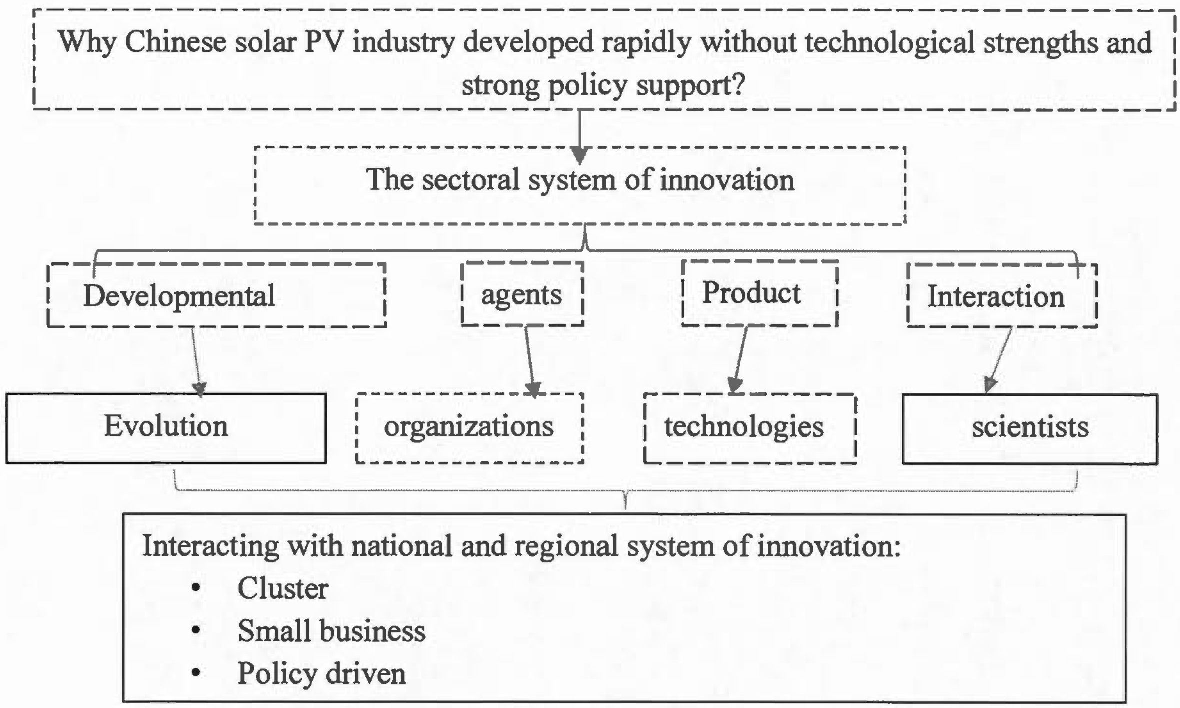


Figure 1.1The study reasoning route

1.3.2. The evolution of the sectors

According to the comprehensive literature review by Malerba (2007), there are two basic models to study sector evolution: sector life cycle models (ILC), based on the product life cycle (PLC) and history-friendly models. Since the late 1970s, several studies using the PLC-ILC model have pointed to the fact that a large number of industries follow a life cycle in which a radical innovation and the related entry of small new producers that introduce new products is followed by demand growth, a greater emphasis on process innovations and a selection process which ultimately leads to a concentrated market structure, and the decline of innovation (Abernathy and Utterback, 1978; Utterback, 1994). But it has been convincingly indicated that that the dynamic sequences are different from one sector to another (Klepper, 1997; Geroski, 2003, Malerba, 2007). Thus, individual-sector case studies are necessary to see the real industrial dynamics, particularly in high-technology sectors such as biotechnology, information technologies, nanotechnology and solar photovoltaic; these sectors became noticeable after the PLC had adopted its canonical form in the 1960s and 1970s. In the meantime, some cases studies have been developed, using history friendly models, for example the computer sector (Malerba et al., 1999, 2001), the pharmaceutical sector (Malerba and Orsenigo, 2002), as well as for other industries such as software and chemicals.

In the study, the quantitative analysis and the case studied will be integrated to explore the evolution paths of the solar PV sector.

1.3.3. Star scientists

When any high tech sector is studied, the contributions of the scientists need to be explored.

Since Edith Penrose (1959) wrote the first scholarly work suggesting that the growth of firms depended on their human resources, highly qualified managers are in short supply and in addition, existing companies are usually employing them. Those companies that can hire and keep this qualified human capital will have a sustained advantage over those who do not.

On the basis of Penrose's work, several successive lines of theoretical thought and empirical work appeared in the human resources and strategy fields, linking competences of the firm to its performance. The resource-based theory of the firm developed to argue that highly performing firms based their advantage on a series of internal resources, among which human capital played a prominent role (Barney, 1991). Sustained competitive advantage and the related sustained performance come from resources that "a firm controls that are valuable, rare, imperfectly imitable and not substitutable" (Barney et al, 2001, p. 625). These resources are composed of managerial, but also organizational and informational elements.

A second line of thought came with the competence view of the firm. For these authors, resources are valuable only if they translate into competences: the capacity to successfully combine those resources, incorporate new technical and scientific knowledge, to attract venture and intellectual human capital, be it administrative, scientific or other. Resources are important if and only if they can be organized in such a way that they deliver performance (Hamel and Heene, 1994). Following this approach, Colombo and Grilli (2005, 2010) argued that the competencies of the founders are key in new-technology-based firms. When they refer to competencies, they are pointing at technical work experience; yet, they found that new technology-based firms have superior performance when the team of founders includes people with both economic-managerial and scientific and technical education. In addition, skilled human capital is able to search for new knowledge and new competencies.

In sum, many empirical works have confirmed the link between managerial talent, including scientific and technical, and the long-term performance of the firm, particularly the high-technology-based firm (Colombo and Grilli, 2005; Hitt et al, 2001). Also, advanced human capital is linked to innovation, attraction of venture capital and growth in a positive feedback loop.

As the founders with the strong background in science and technology became more and more important in the high-tech firms development, the scientists with the spirit of entrepreneurship have drawn the attention of researchers. Who will contribute more to the development of firms and sectors? How do we recognize these scientists? What are their ways to connect the academic research and the business entrepreneurship? What is the performance of their academic entrepreneurship? All the above questions need to be answered.

But not all scientists can contribute to the development of the sector. Lynn Zucker and her colleagues at the University of California Los Angeles (UCLA) launched a small but influential addition to this line of thought. They argued that the biotechnology revolution was the fact of star scientists, those biochemists, biologists, medical doctors and other scientists who had published a large number of articles and appeared as the inventors of several influential patents (Zucker et al, 1994; Zucker et al, 1996). These stars were often the founders and advisors of biotech companies.

In terms of the ways that star scientists can contribute to the development of the firms, it is necessary to see what is the role of the star scientist in the technology transfer from universities and institutes to the industries. Some of these roles include licensing their patents, establishing the university spin-offs (USO), getting listed in the board of directors of start-ups, acting as chief scientists, etc. As to the factors explaining the growth of these spin-offs, using a database of 149 university spin-off companies, Walter et al (2006) argued that network capabilities and entrepreneurial orientation are key variables explaining the performance of these USOs. Other authors have found that spin-offs from different US universities have very different performance. More entrepreneurial universities have a much better score as licensors of technology to academic spin-offs. Using a very large sample of US academic spin-offs, Powers and McDougall (2005) found that universities with experienced (older) technology transfer offices (TTO) do incubate more successful spin-offs. More productive faculty (in terms of articles and citations) are also involved in more successful spin-offs. Early collaboration with the sector is also linked to spin-off growth.

Some studies show that a large percentage of academic spin-offs is related to biotechnology and health sciences. Mowery et al (2001) calculate that some 75% of the patenting and licensing in three of the most research-active universities in the United

States (California, Columbia and Stanford) occurred in biomedical research, particularly in biotechnology. The second most important sector they indicate is computer software. Similarly, in the annual survey of intellectual property generated in Canadian universities (Statistics Canada, annual), health sciences appear as number one, although not so prominent as in the USA. None of the studies mentioned the academic entrepreneurship of solar PV sector. So we will focus on the star scientists and their academic entrepreneurships in our specific sector.

1.3.4. Entrepreneurship and small business

Schumpeter (1916) emphasized the role of entrepreneurs in economic dynamics, but for more than fifty years his insights were lost, as mainstream economics turned to equilibrium, perfect rationality and costless diffusion of knowledge. Under these conditions there could not be entrepreneurs discovering hidden opportunities, technological, market or otherwise.

Yet, since the 1980s, entrepreneurship is a fast-growing field of research. Its rapid growth in the last decades accompanies a change in focus from the individual (psychological) characteristics of the entrepreneur to more environmental variables (Landström et al., 2012). The industrial context was introduced later on (Klepper, 1996; Low and Abrahamson, 1997). The creation of new firms was found to be easier at the beginnings of the sector life cycle, and more difficult when industries are mature. Later on, institutions were linked to entrepreneurship. Scholars underlined the birth of many new firms using academic research results (Wright et al., 2004). However, corporate spin-offs were found to be more successful than university spin-offs (Klepper and Thompson, 2007).

Small and medium enterprises (SMEs) significantly reinforce the performance of innovation-focused economies by creating technical and organizational novelty, employment and economic growth (Robson and Bennett, 2000; Jutla et al., 2002; Foreman-Peck et al., 2006). More precisely, it is argued that knowledge spillovers from universities and public laboratories allow entrepreneurs in the innovation-driven high-tech firms to identify and exploit new opportunities (Carlsson and Eliasson 2003; Acs et al., 2008). Thus, the revolutionary breakthroughs continue to come predominantly from small entrepreneurial enterprises, and by bringing vigorous competition, particularly in high-tech industries, entrepreneurial enterprises force incumbent firms to innovate in order to survive (Baumol, 2004).

Government support for entrepreneurial firms has been analyzed under several conditions in different countries. Lerner (2009) represents the less optimistic point of view when it comes to public efforts to boost entrepreneurship and venture capital. In his analysis, a few cases of successful support may be opposed to many more cases of failed efforts. Another sceptical view was that of Sternberg (2014), who found that in Germany regional factors were much more important than government support of new firms.

While the difficulties involved in creating government support for venture capital firms has been stressed time and again, several cases of undisputed success have also been studied. One is the case of Taiwan's Industrial Technology Research Institute, which has incubated numerous extremely productive semiconductor firms, including in the area of solar technology (Mathews et al, 2011: Mazzoleni and Nelson, 2007).

Among the direct subsidy incentives directed to small and medium sized enterprises in OECD countries, the US Small Business Innovation Research program (SBIR) appears among the most successful (Chu et al., 2006; Allen et al, 2012). Yet it has also been proven that the level of further venture capital success of SBIR subsidies depends on the sector in which new firms are founded (Lerner, 1999; Toole and Czarnitzki, 2006).

The study of how the entrepreneurial and small firms are supported and developed is one indispensable part for the sectoral system of innovation.

1.3.5. Regional system of innovation: Cluster

'Clusters' were defined by Michael Porter as 'geographic concentrations of interconnected companies, specialized suppliers, service providers, firms in related industries, and associated institutions (for example, universities, standards agencies and trade associations) in particular fields that compete but also cooperate' (Porter, 1998: 197–8). A clear condition for the existence of a cluster was the presence of linkages between companies and institutions. Niosi (2011) concluded that external economies, regional knowledge spillovers, cluster absorptive capacity and the existence of anchor tenants are among the reasons why the clusters are established. When some clusters are falling down while other clusters are developing are well studied, the resilience of some clusters is understood. We will use the theories on the high-tech clusters for studying the solar PV sector.

It seems that solar PV sector also has the phenomenon of geographic agglomerations. Vidican, Woon and Madnick (2009) found that the solar photovoltaic sector in the U.S. has been concentrated in these two states, with California hosting the largest share of companies over the years. Mathews, Hu and Wu (2011) found in Taiwan, the Fast-Follower Strategy (FFs) on solar PV sector, which aims at spanning as many steps in the value chain as possible and as quickly as possible, is adopted to promote the solar PV sector by capturing agglomeration and cluster effects for solar PV technology.

The development of solar PV sector shows its financial imbalance in the recent years. With the withdrawal of the governmental subsiding policies, several big European companies including Siemens, closed their operations in 2013. According to Greentech Media, 112 solar energy companies in the United States and the European Union have declared bankruptcy, closed their doors or been acquired by competitors under suboptimal conditions since 2009[1]. But at the same time, the solar PV sector grew well

[1]http://dailycaller.com/2014/12/08/112-solar-companies-have-closed-their-doors-in-5-years/

in China and Japan. In the year 2014, China and Japan were the top two countries with the biggest added capacities (Table 1.1).

In order to see the clusters distribution in the world and to explore the imbalance of the different clusters, the theories on cluster innovations are employed.

Table 1.1Top 10 PV countries in 2014(MW)

Top 10 PV countries in 2014 (MW)

Total capacity			Added capacity		
1.	Germany	38,200	1.	China	10,560
2.	China	28,199	2.	Japan	9,700
3.	Japan	23,300	3.	United States	6,201
4.	Italy	18,460	4.	UK	2,273
5.	United States	18,280	5.	Germany	1,900
6.	France	5,660	6.	France	927
7.	Spain	5,358	7.	Australia	910
8.	UK	5,104	8.	South Korea	909
9.	Australia	4,136	9.	South Africa	800
10.	Belgium	3,074	10.	India	616

Data: IEA-PVPS *Snapshot of Global PV 1992–2014* report, March 2015[3]:15
Also see section Deployment by country for a complete and continuously updated list

1.4. Methodology

1.4.1. Research routes

After selecting the solar PV sector, the secondary information of the sector was explored and the research questions were defined. After searching the academic databases and reviewing the related literatures, our hypotheses were set up. The methodology and the databases were selected to explore the findings, and then the conclusions were put forward. By extending the findings to the related areas, policy implications were made. The research route is see in Figure 1.2.

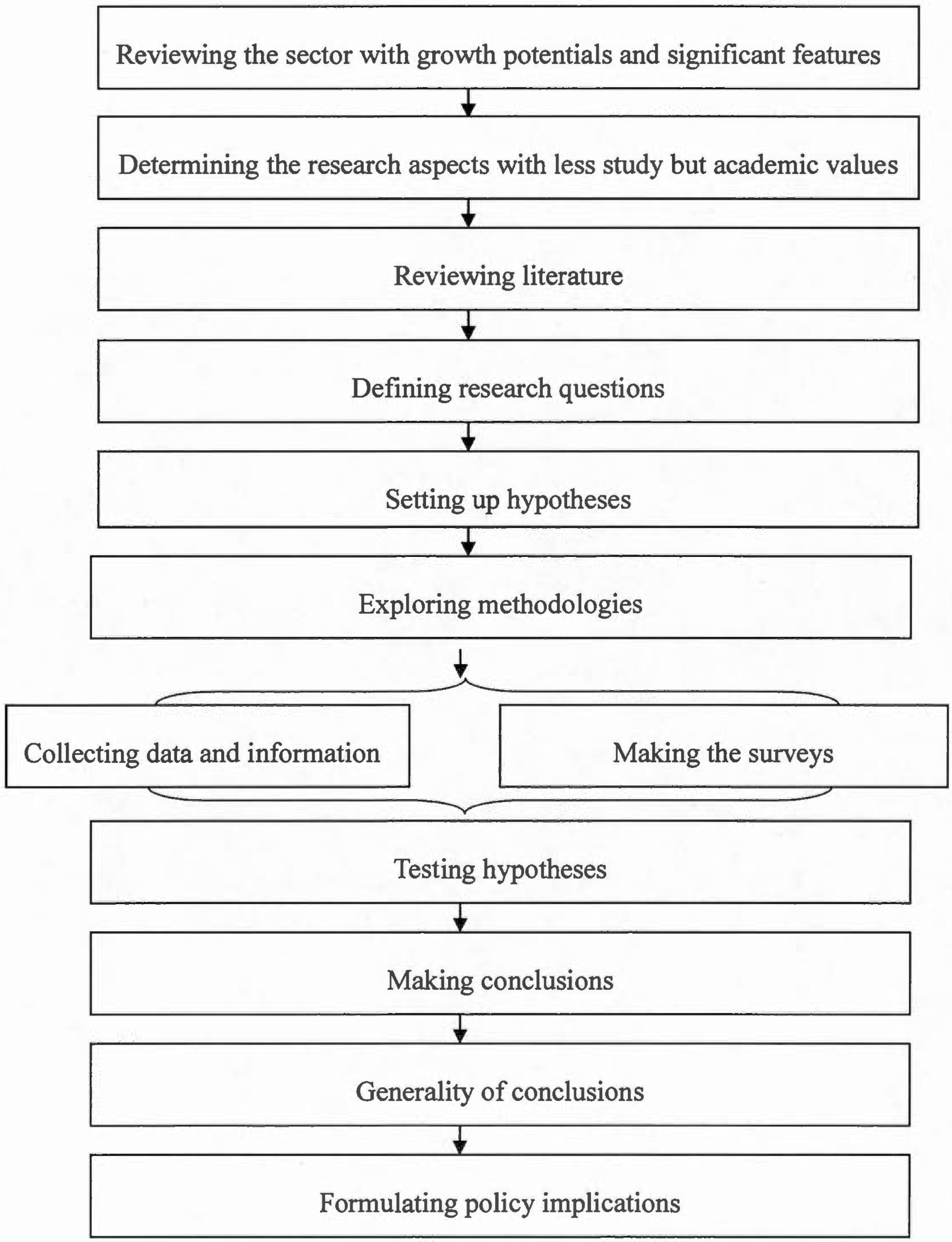


Figure 1.2 Research route of the study

1.4.2. Data collection

In order to get the complete analysis of the solar PV innovation all over the world, both data on patents and publications were employed. Besides, in order to see the reasons for the significant findings, case study and secondary data collection were used for the analysis at the different levels.

1.4.2.1. Patents

Patent is the good indicator for assessing the technological capability. Patents can be analysed by in the patent number or patent citation. Business literature argues that the number of patents is an appropriate indicator for comparing the innovation performances of companies in terms of new technologies, processes, and products (Cassiman et al., 2008; Gittelman, 2008). Even the strongest critics of the general use of patents as performance indicators (Arundel and Kabla, 1998; Mansfield, 1986) admit that patents could represent appropriate indicators in many high-technology sectors. Consequently, the identification of the inventors listed in patents provides key information on the history of R&D processes related to a technical invention and thus, a means for retracing knowledge flow through innovation systems or regional clusters of firms. Yet, a growing number of researchers use patent citations as indicators of the R&D output of firms, or as determinants of innovation performance that could impact on their growth. Unlike a simple counting of patents, which is purely quantitative, patent citations also include a measurement of patent quality because there appears to be a positive relation between a patent's importance and the number of times that it is cited. Patent citations can be very useful as indicators of a patent quality in economic studies of biotechnology-firm innovation and performance (Jaffe and Trajtenberg, 2002).

Hu and Jaffe (2003) initiated a new line of work examining patterns of knowledge diffusion from advanced countries to latecomer catch-up countries with their study of USPTO patents taken out by Korea and Taiwan over the 22-year period from 1977 to 1999. Four stylized facts emerged from their work which have formed a benchmark for subsequent studies of knowledge diffusion, or what be called knowledge leverage by latecomers.

Since then further work has been devoted to taking the analysis to the industry level. Starting with the DRAM industry, Lee and Yoon (2010) investigated patterns of catch-up by Taiwan and Korea, and Lee and Wang (2010) then extended the net to include China. Analysing the patents taken out at the USPTO by Korean and Taiwan over the period 1985–1999, Lee and Yoon (2010) argued that they had found evidence that with regard to relative citation propensity, the order of patent citation follows the order of national entry into the industry, namely that Japanese firms tended to cite US patents; Korean firms tended to cite Japanese patents; and Taiwanese firms tended to cite Korean patents. Lee and Wang(2010) then extended these results to China, arguing that

Chinese firms tended to cite Taiwan patents, and that as the latecomer, China exhibited the lowest level of intra-national knowledge flows (reflecting low absorptive capacity).

The next industry so studied was FPD(flat panel displays (FPD)); Hu (2008) used US patents registered by top five Taiwanese FPD manufacturers to trace their knowledge sources of FPD technologies. The finding suggests that the knowledge source in latecomers, such as Taiwan, is mostly secured from Japan on specific core technologies, rather than fromthe US. Jang et al. (2009) further assessed the innovative capability and international knowledge flows amongst technological forerunners (US and Japan) and latecomers (Taiwan and Korea) in the FPD sector, and confirmed that significant knowledge flows are leveraged by the latecomers (Korea and Taiwan) from the technological leaders (US and Japan). But in contrast with earlier studies, Jang et al. found that Japan dominates knowledge flows for Korean firms in FPD industry (Japan accounting for 56% of total citations by Korean firms at the USPTO between 1976 and 2005, compared with only 20% for the US); likewise Taiwan firms' patenting favored. Japan has been over the US as a knowledge source, but with less divergence (39% for Japan vs. 34% for the US). This too presents a very interesting finding that calls for further examination in emerging industries such as solar PV.

Lee and Jin (2010) then turned their attention to the mobile telephone industry, covering patents taken out at the USPTO by Korean, Taiwan and Chinese firms over the period 1976–2008, and found again that in terms of relative citation propensity, the order of patent citation follows the order of entry into the industry, with Japan following the US, Korea following Japan, Taiwan following Korea, and China following Taiwan.

In the study, the patent numbers are counted as the proof of the innovation capabilities. It is only acted as the preliminary research to get the full picture of the solar PV sector, the patent citation will be employed in the continuous studies to explore the detailed process and product innovations.

As the focus is for the solar PV sector, the key words selected are the "solar cell", "solar cells", "photovoltaic cell" and " photovoltaic cells". After studying the patent data in United States Patent and Trademark Office (USPTO) and in the European Patent Office (EPO), we found that the data in USPTO is more applicable that EPO's due to the following reasons:

1. There are many more patents in EPO and Chinese Patent Bureau database than in USPTO, but the above keywords in EPO and Chinese Patent Bureau database do not produce results as exact as in USPTO, which means by reviewing the patents randomly selected from EPO database, some with the key words in the abstract are not in the domain. And when the patents issued in USPTO in the databank of EPO are compared with the patents directly from USPTO, there is a big difference. So we have to choose the USPTO database for the patent analysis.

2. The list of issues within each individual patent in USPTO is more comprehensive than that in EPO. For example, only the data in USPTO have the inventor locations,

but not the data in EPO.

3. As the biggest inventing country, the United States assignees own nearly 50% of the solar PV patents. Also, competitors in Japan, Germany, Taiwan or the Popular Republic of China also patent their inventions in the United States in order to protect them from potential infringers.

So the patents data in USPTO have been selected as the base for patent analysis. Except three chapters including introduction, characteristics of the sector and conclusion, the different issues in the individual patents are taken as samples in the other six chapters (Table 1.2).

Table 1.2 The dimensions of patents employed in the different chapters

Issues	Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Abstract	*	*		*	*	*
Year issued	*	*		*		
Assignee's name		*		*	*	*
Assignee's state				*	*	*
Assignee country		*	*	*	*	*
Inventor's name				*	*	
Inventor's city		*		*	*	
Inventor's affliation		*	*	*	*	
Inventor's state		*		*	*	
Inventor's country		*	*	*	*	

1.4.2.2. Publications

After reviewing several publication databases, we selected Scopus for analyzing the the solar PV sector due to its quality in terms of journal selection and better taxonomy for academic research papers. All the papers in the databases were searched with the key words of "solar cell", "solar cells", "photovoltaic cell" and "photovoltaic cells", and then all the publications obtained by these key words were taken as the new database for analysis. As it was found that nearly all the authors have the publications in the other domains, their publications in the other domains were also searched and analyzed to explore their academic behaviours, and knowledge transfer.

In order to see the relationship between the academic behaviour and their entrepreneurship for the star scientists, both the patents and publications for the star scientists were studied to see the interrelationship.

1.4.2.3. Case study

In order to explore the reasons and the differences in the world for the solar PV sector, such as how the SSI evolved, the differences among the clusters and why the performance of universities in terms of academic entrepreneurship, case studies with the interviews of some key persons were employed.

1.4.2.4. Secondary data collection

For some important case studies where there is no response for the request of the survey, the secondary data collections are conducted for getting the relevant information. Secondary data were found in the annual report, statistical report, news published in the companies' websites and data in the government departments' websites. For example, in order to seek the influence of the venture capital in the academic entrepreneurship, annual studies from the venture capital association were employed.

1.5. Structure of the thesis

There are ten chapters in the thesis and they are organized in the following way:

Chapter 1 is the "Introduction", which begins with the research questions raised after reviewing the solar PV sector. After highlighting the starting points, the theoretical frameworks and the methodology are introduced. Then the complete research route is described and the structure of the thesis is included.

Chapter 2 is the introduction of the several key points of the solar PV sectors in terms of industrial performance, technologies and regulations. This chapter is employed as the foundation for understanding further specific studies.

Chapter 3 is about the evolutionary path of the sector. It verified that the variation intensive is the distinctive characteristics of the sector within its evolution. It acts as an independent academic paper that has been submitted to the journal for revision and publication. In the thesis, it was kept as originally submitted. It is composed of an introduction, a review of the sector, the methodology, results, conclusion and policy implications.

Chapter 4 is about the innovation cascade of the sector. It acts as an independent academic paper that has been submitted to the journal for revision and publication. In the thesis, it was kept as originally submitted. It is composed of an introduction, a review of the sector, the methodology, results, conclusion and policy implications.

Chapter 5 is the analysis of how China can realize the catch-up in the solar PV sector. The new techno-economic paradigm, the government support, human resource context, and integrative production capabilities are studied to formulate the answers.

Chapter 6 is about the geographic agglomeration of the innovations, the clusters of the solar PV sector are defined in the world and the resilience of the clusters are explored. It acts as an independent academic paper that was submitted to the journal for revision and publication. In the thesis, it was kept as originally submitted. It is composed of an introduction, a review of the sector, the methodology, results, conclusion and policy implications.

Chapter 7 is about the star scientists and their academic entrepreneurship in the solar PV sector. The criteria for defining the star scientist in the world are recalled, and their academic entrepreneurship is explored. It acts as an independent academic paper that was submitted to the journal for revision and publication. In the thesis, it was kept as originally submitted. It is composed of an introduction, a review of the sector, the methodology, results, conclusion and policy implications.

Chapter 8 is about the small innovators in the sector in US. It is found that the military-related government agencies including by Department of Defense (DOD) or National Aeronautics and Space Administration (NASA) through the Small Business Innovation Research Program (SBIR) and Small Business Technology Transfer Research Program (STTR) support most of the small innovators. The small innovators positioned in the niche military market can get more awards. It acts as an independent academic paper that was submitted to the journal for revision and publication. In the thesis, it was kept as originally submitted. It is composed of an introduction, the data and methodology, results, discussion and conclusion.

Chapter 9 is about the features of the solar PV sector. After studying the evolution of the sector, its geographic agglomeration and the behaviours of the star scientists, some divergence in terms of innovation from the other high-tech industries are detected. By comparing with the semiconductor sector, it is found that the solar PV sector is one whose innovation is mostly driven by demand, but not pushed by science and technology progress. Three abnormal aspects are put forward, and whether its distinctiveness is significant enough to be a sub-category of the high-tech sector should be studied further.

Chapter 10 is the conclusion. The contributions of the studies are highlighted, the policy implications are made, and the limits of this enquiry and the further research directions are suggested.

The theme, the research question, theories, methodologies, theoretical or empirical contribution of each chapter are see in Table 1.3.

Table 1.3 Description for each chapter

Chapters	themes	research questions	theories	methodologies	theoretical and empirical contributions
1	Introduction				
2	Key points of the sector				
3	Evolution and innovation cascade	1. what is the evolution of the solar PV sector? 2. what is the characteristics of the technological trajectory?	Sectoral system of innovation, Product life cycle and Industrial life cycle	Quantitative & case studies	Redefinition of term " innovation cascade", the debate of PLC-ILC theories
4	China Catch-up	How the Chinese solar PV sector can realize the catch-up?	Catch-up theories	Case studies and secondary data	Horizontal technological policies, the key entrepreneurs and the integrative production capabilities are the important factors.
5	Cluster	1.Does the solar PV has the innovation clusters? 2.Where do the clusters locate? 3. What are the difference among different clusters?	Cluster	quantitative analysis & case studies	There are 23 clusters in the world, there is the imbalances in the cluster development in Europe, North America and Asia.

6	Star scientist	1.What are the definition of the star scientists for the solar photovoltaic sector? 2. Is there a lot of the academic entrepreneurships in the solar PV sector? 3.What are the roles of ventural capital, universities and tehnology transfer offices?	Star scientists	quantitative analyisis & case studies & secondary data	The definition of the star scientists;the academic entrepreneurhsip and the ventural capitals are limited; famous university and their technology offices do not play the important role in the academic entrepreurship
7	Small business	what factors influence the innovation of the small business?	small business preformance evaluation	quantitative analyisis	The innovation of the small businesses involved in the solar PV innovation has been restricted for the military internal use.
8	Demand-driven	What is the characteristics of the solar PV sector?	evoultion of the sector	comparison study	The solar PV sector is a demand-driven sector
9	Conclusion				

CHAPTER II

SOME KEY POINTS OF SOLAR PHOTOVOLTAIC SECTOR

2.1. Significance of the sector

Today, about 80% of the world's energy production comes from fossil fuel, and to date, coal is the major source of electricity with a share of 42% of electricity and will continue to be the prime source of electricity in many countries in the coming few decades. But after a few years, it will be impossible to generate electricity from fossil fuels like coal and the others. Different organizations such as the US Energy Information Administration (EIA), International Atomic Energy Agency (IAEA), International Energy Agency (IEA), World Energy Council (WEC) have published their projections of future energy demands for 2020, 2030 and 2050,which shows that only the clean energy systems have the capacity to neutralize the environmental impacts.

Clean energy is renewable energy that could have the capability of meeting the energy demands as well as mitigating global warming. In the past few years, it has been observed that renewable energy technology is steadily maturing and its share of energy production has been going up. Altogether, wind, solar, biomass and waste-to-power, geothermal, small hydro and marine power are estimated to have contributed 9.1% of world electricity generation in 2014, compared to 8.5% in 2013. This would be equivalent to a saving of 1.3 giga-tons of CO_2 taking place as a result of the installed capacity of those renewable sources (Figure 2.1).

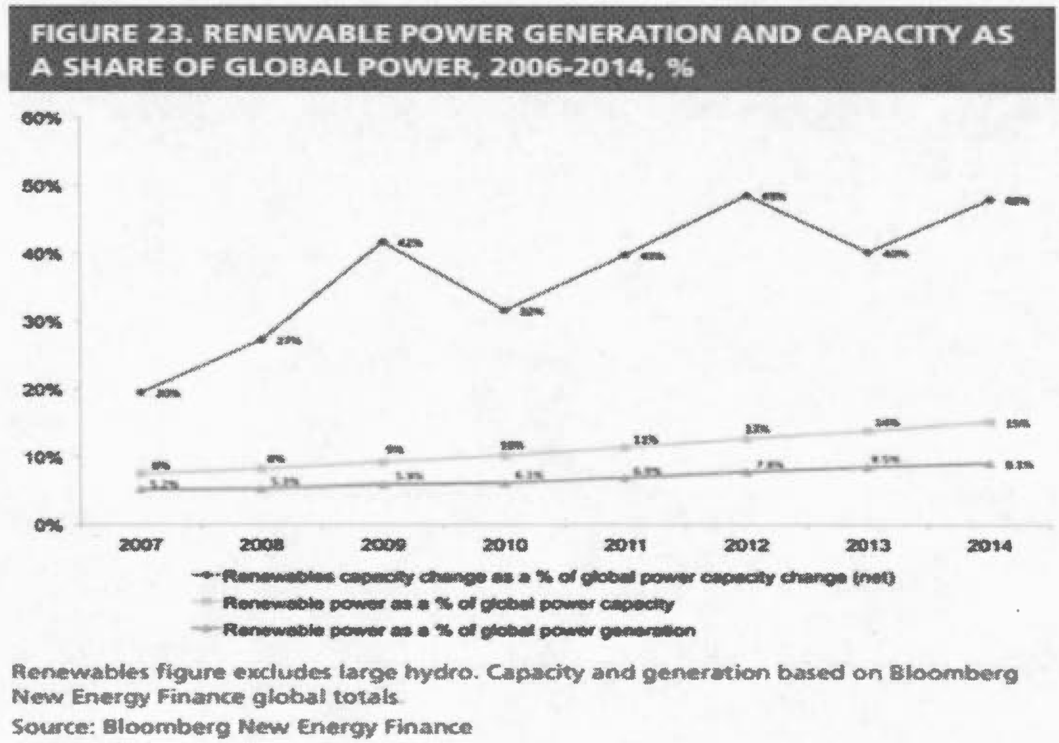
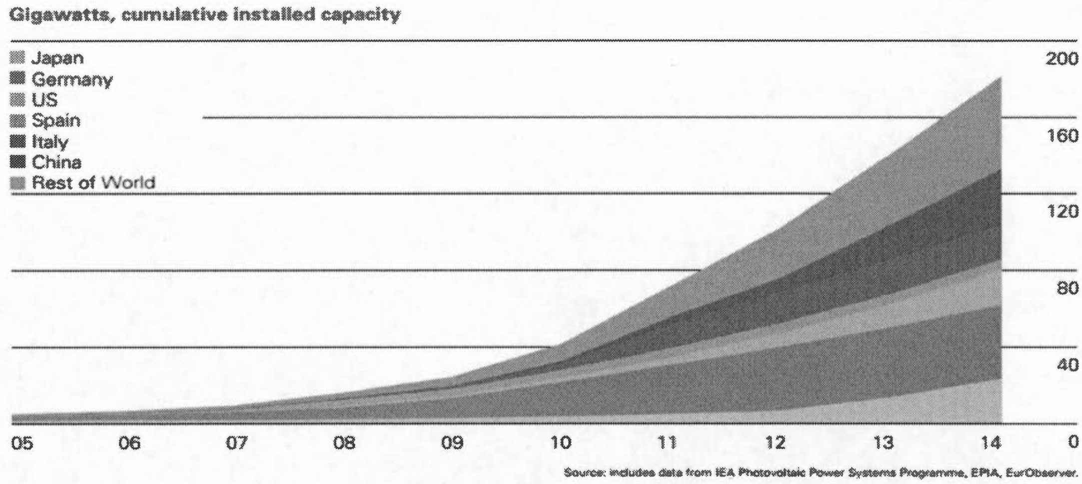


Figure 2.1 Renewable power generation and capacity as a share of global power, 2006-2014,%

Among the renewable energies, solar energy has its own distinctive advantages: it cannot be monopolized by a handful of countries, as is the case with fossil fuels. It has neither excessive maintenance and management costs nor conversion mechanisms producing troublesome emissions, and it can easily be integrated into both public and private buildings without external environmental impacts, such as those incurred by wind turbines. According to the International Energy Agency (IEA), solar energy could be the largest source of electricity by 2050.

According to Pew Charitable Trusts, in 2013, for the first time, solar outpaced all other clean energy technologies in terms of new generating capacity installed with an increase of 29% compared with 2012. From then on, the solar PV generation capacity keeps on growing (Figure 2.2). This is due in part to ongoing price reductions, including significant cuts in manufacturing costs, but also as a result of investment shifting from small-scale projects to less expensive large-scale ones. Added to this is the fact that electricity prices have increased in general. This has led to a situation where grid parity (the moment when electricity from solar panels costs as much or is even cheaper than electricity purchased from the grid) is within reach. China was the top global market in 2013 with 11.8 GW. Germany topped the European market with 3.3 GW, while the UK was runner-up with 1.5 GW. Europe's role as the PV market leader has come to an end, but various markets within Europe still have almost untapped potential.



Source: BP Statistical Review of World Energy (June 2015)

Figure 2.2 Solar PV generation capacity

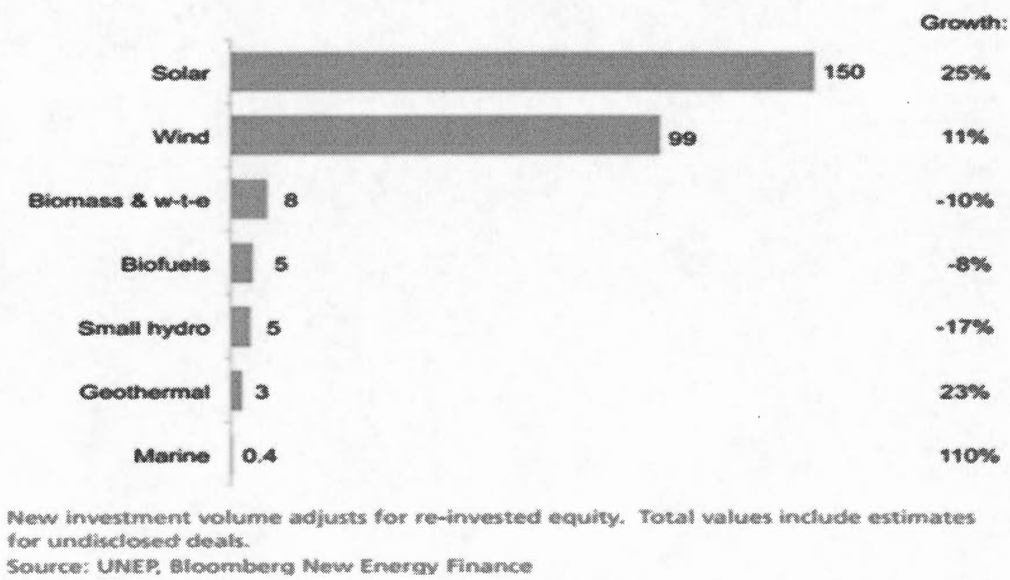


Figure 2.3 Global new investment in renewable energy by sector, 2014, and growth on 2013, $BN

Figure 2.3 shows that solar PV is the renewable energy sector with the highest global new investment and with the highest growth rate in 2014. Although wind was the largest sector in terms of utility-scale asset finance in 2014, the growth of solar is outstanding. Figure 2.4 shows that asset finance of wind farms increased 10% to $92.4 billion, while that for solar parks advanced 15% to $62.8 billion.

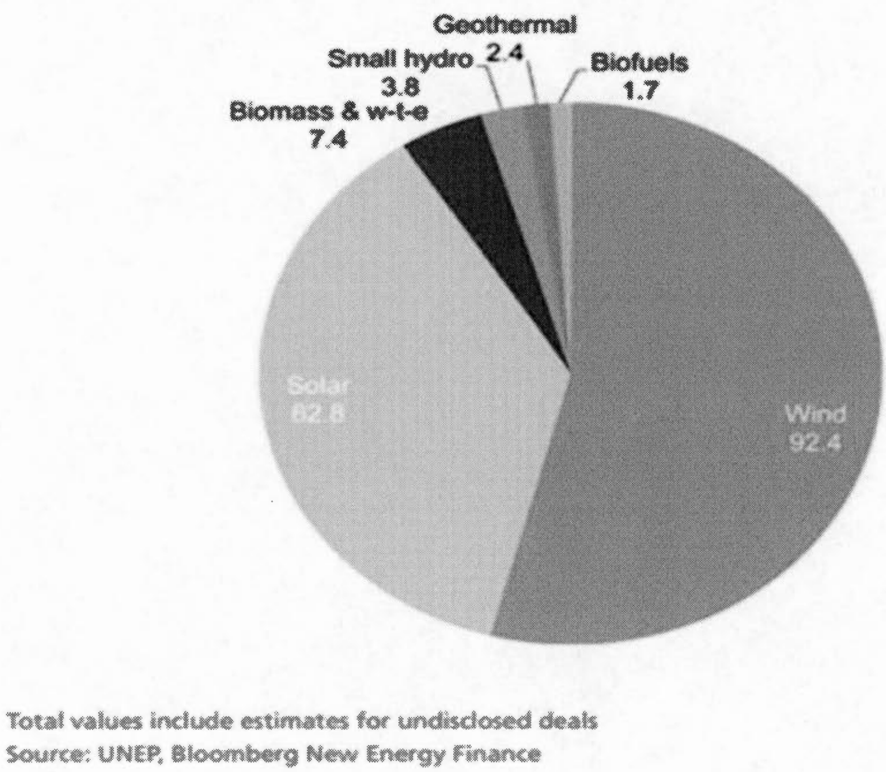
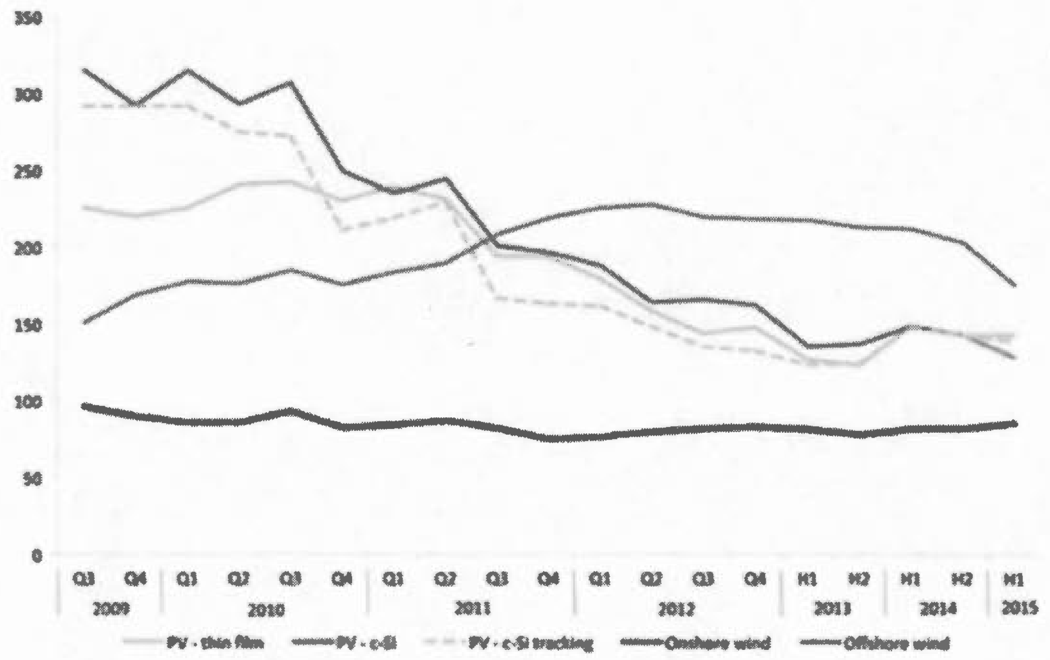


Figure 2.4 Asset finance of renewable energy assets by sector, 2014, $BN

The costs of solar generation are meanwhile continuing to fall. Figure 2.5 shows that the global average levelled costs was $315 per MWh for crystalline silicon PV projects in the third quarter of 2009, but this had fallen to $129 per MWh in the first half of 2015, a reduction of 59% in just five and a half years. All of which shows that the age of solar energy is coming.



PV-c-Si stands for crystalline silicon photovoltaics
Source: Bloomberg New Energy Finance

Figure 2.5 Global average levelled cost of electricity for wind and PV, Q3 2009 to H1 2015, $ Per Month

2.2. Technological innovations

2.2.1. Technology categories

The sun provides 10,000 times the amount of energy actually used by humans every day. Using the totally renewable and sustainable source from the sun, solar technologies have two main types of applications: heat and electricity (Figure 2.6, Source: Zhang et al. 2012).

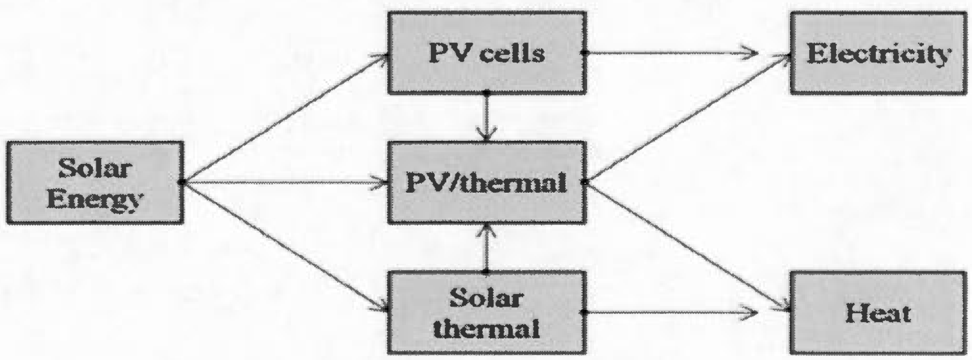


Figure 2.6 Solar energy and its applications

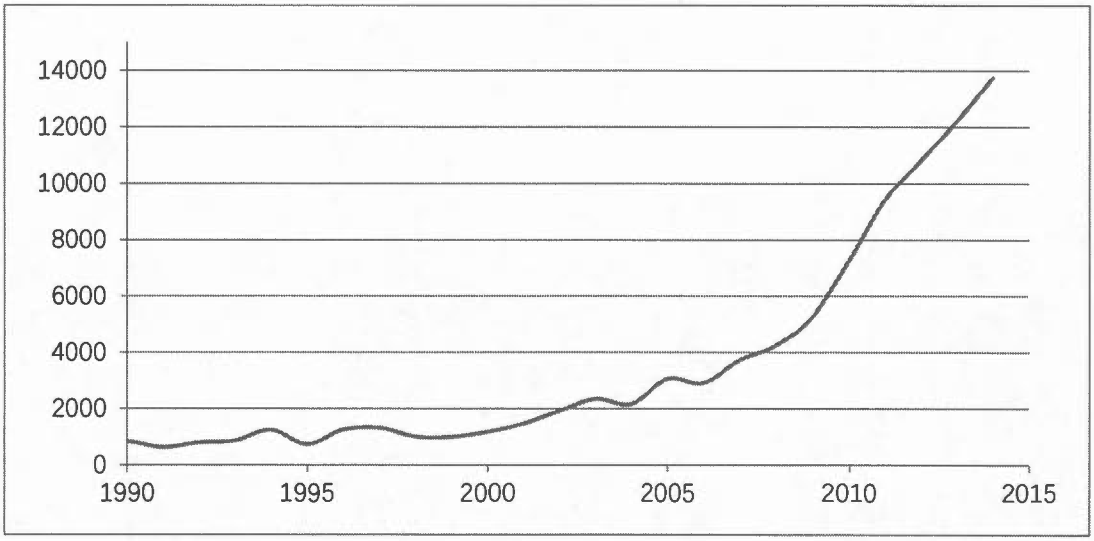
The two applications are embodied into three categories: 1) photovoltaic (PV), which directly convert light to electricity with the solar cells; 2) concentrating solar power (CSP), which uses heat from the sun (thermal energy) to drive utility-scale electric turbines; 3) heating and cooling systems, which collect thermal energy to provide hot water and air conditioning. In this research, only the solar PV sector, the most promising, is studied.

Solar PV cells are at the core of solar energy technologies. Solar cells made of silicon have rapidly become the key component of solar modules (Parida et al, 2011). These cells are specialised semiconductors that convert solar light into electrical energy, with different levels of efficiency. Other elements are less important, but are gaining a more central role in the efficiency of solar equipment. Solar glass is among them. Initially, conventional glass was used to protect solar panels from damage caused by hail or any falling object. New advanced glass increases the efficiency of solar PV systems.

This science-based set of technologies has enormously evolved in its 50-year development[2], but just around 2008, innovation began to boom (8 & 9). The development of the sector is quite slow, particularly when compared with biotechnology and information technology (the evolution of solar cell technology is seen in the Appendix). The reason is partly that solar energy has always had strong competition from other sources of energy (coal, gas, oil, hydro and nuclear, as well as wind among renewable energy sources). The technological development of solar PV sector began to boom since the beginning of the 21st century due to the strong policy support began since 1990s from the different central governments in several countries.

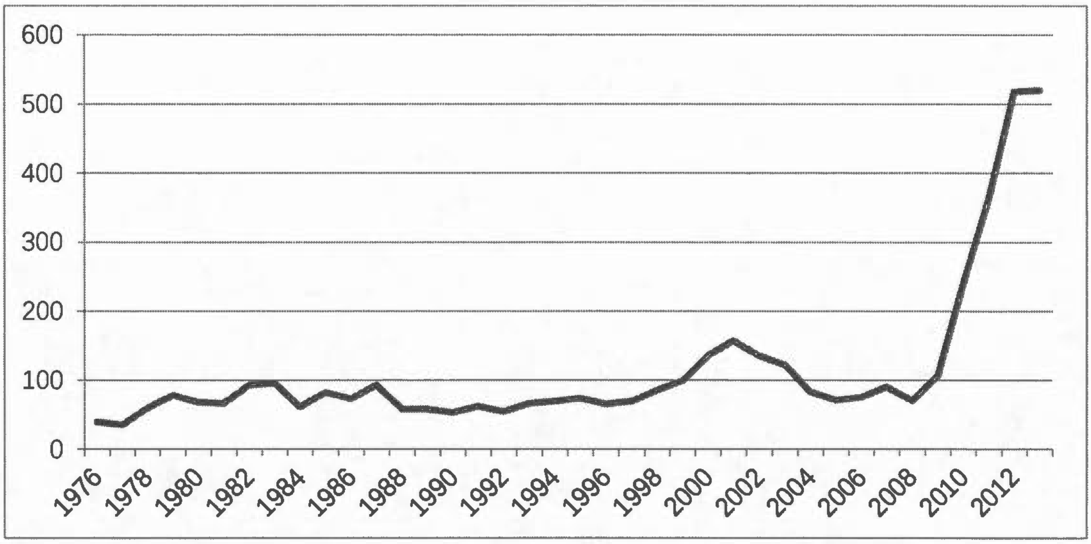
[2]Although some people associate solar panels with new-age technology, scientists have actually been working with solar cells for nearly 200 years. The evolution of solar panels has been a slow but worthwhile undertaking.

(see Figure 2.7 & 2.8).



Source: Scopus

Figure 2.7 Solar cell publications in Scopus(1990-2015)



Source: USPTO

Figure 2.8 Solar cell US patents granted by year (1976-2013)

It is deemed that the science and technological innovation boom from 2000s are due to the strong support of the government. (see Table 2.1)

Table 2.1 Timetable for solar energy policies in the representative countries

Year	Germany	Japan	USA
1991	1,000 PV Rooftop program		
1992			Energy Federal Policy Act
1994		Official launch of New Sunlight Plan	
1998	100,000 PV rooftop program		1,000,000 PV Rooftop program
2000	Renewable Energy Sources Act	Green Procurement Law	
2002		Law on new energy for power generation	
2004	Revised Act on Renewable Energy Law		
2005			Revised Energy Law
2008	Newly Revised Act on Renewable Energy Law	PV industry Subsidy policy restarted	
2010			10,000,000 PV rooftop Program
2011	Decreased Feed-in Tariff for 3 times	Renewable energy Law	
2012		FIT introduced	

Currently, there are three generations of technologies in the solar PV sector:

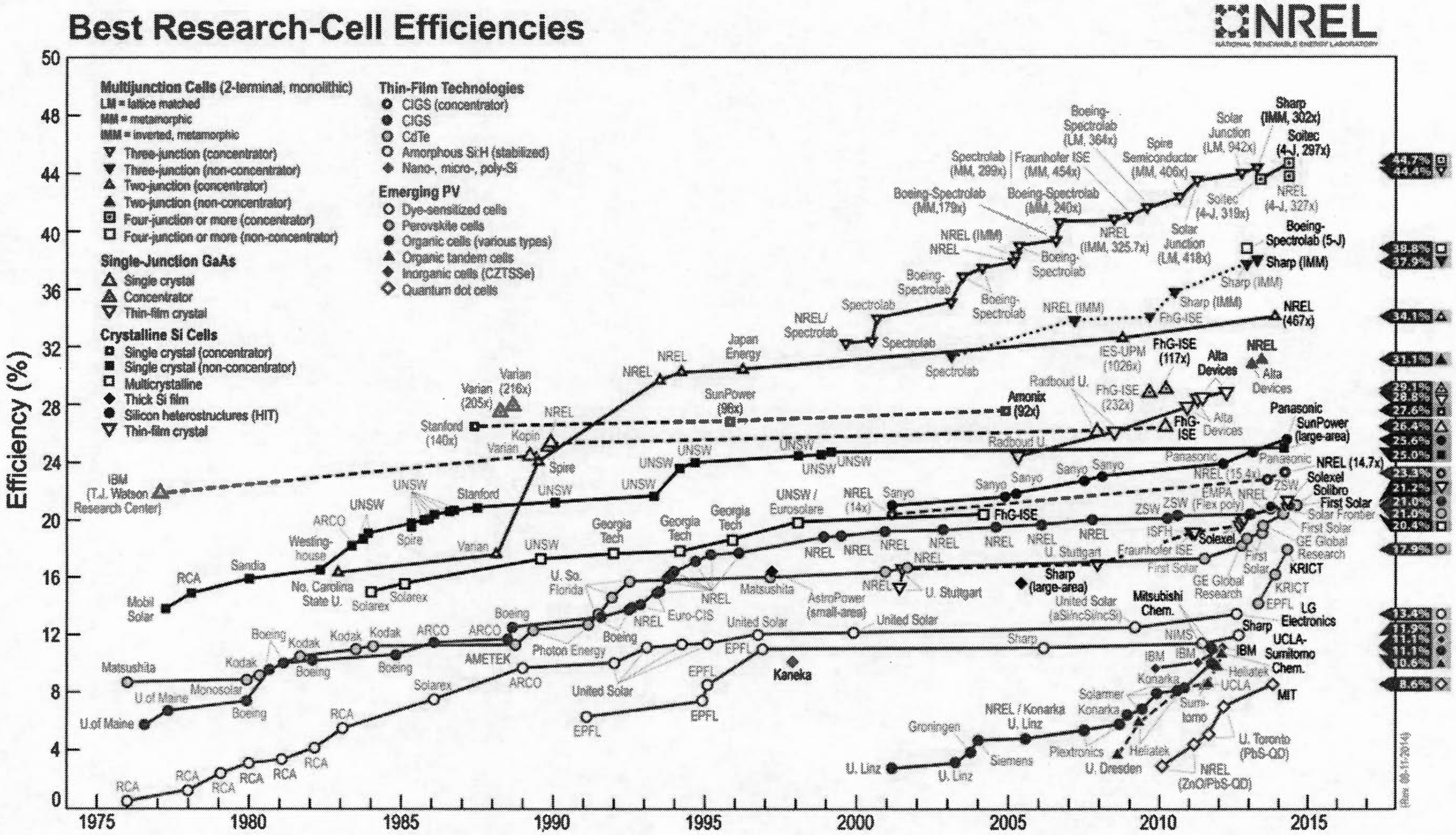
- First generation solar PV cells are made in crystalline silicon. The cells are cut from a silicon ingot, casting, or grown ribbon. So far, this generation dominates the market because of its high conversion efficiency, defined as the percentage of sunlight that is converted into electrical energy, as well as its extensive manufacturing base. Mono-crystalline PV cells today have an efficiency of 16 to almost 20 percent, while the cheaper-to-produce multi-crystalline PV cells achieve a slightly lower 14 to 15 percent efficiency. Crystalline solar PV cells are usually interconnected and encapsulated between a transparent front (typically glass) and insulating back cover material to form a solar PV module, which is usually mounted in an aluminum frame.

- Second generation solar PV cells are referred to as thin film because thin layers of PV materials are deposited on low-cost substrates like glass, stainless steel, or plastic. Their advantage is that they are significantly cheaper to produce, but they have much lower efficiency levels. The oldest and most prevalent thin-film cell technology is "amorphous silicon" with a conversion efficiency of just6 to 7 percent, while hybrid "amorphous/micro-silicon technologies" achieve about 8 percent. Other thin-film technologies, using compound semiconductors, such as germanium (an amorphous silicon thin-film), cadmium telluride (CdTe) or copper iridium di-selenide (CIS), have achieved commercial conversion efficiencies of up to 11 to 12 percent (Barclays Capital 2009 and IEA PVPS 2009a). These improvements in thin-film efficiencies have led to a very rapid expansion of this segment of solar PV technologies in recent years; their market share has risen from less than 5 percent in 2004 to over 22 percent by 2008.

- The third generation of solar PV technologies is not yet being deployed on a large scale. Work to date suggests there is scope for improving solar cell performance by exploring approaches capable of giving efficiencies closer to thermodynamic limits. Low-dimensional structures seem to show some promise due to the small dimensions and new features offered. Common third-generation systems include multi-layer ("tandem") cells made of amorphous silicon or gallium arsenide, while more theoretical developments include frequency conversion, hot-carrier effects and other multiple-carrier ejection techniques. Emerging photovoltaic include: Copper zinc tin sulfide solar cell (CZTS), and derivatives CZTSe and CZTSSe ; Dye-sensitized solar cell, also known as "Grätzel cell" ; Organic solar cell ; Perovskite solar cell ; Polymer solar cell ; and quantum dot solar cell.

2.2.2. Measurement of the solar cell efficiency

Energy conversion efficiency is taken as the most important indicator to measure the technology progress. According to Green (2009), over the last two decades, terrestrial cell measurements have evolved to the stage where independent laboratories measure the same result for standard silicon cells within 1–2%. As a result of early initiatives by SERI (the US Solar Energy Research Institute, now National Renewable Energy Laboratory, NREL) that encouraged the development of high efficient silicon cells, several key silicon cell results were measured at NREL in the early 1980s,the beginning of what will be referred to as the 'modern phase' of silicon cell development. So the calibration of NREL is here employed to show the progress of different categories of solar PV technologies (See Figure 2.9).



Source: National Renewable Energy Laboratory (NREL)

Figure 2.9 The evolution of research solar cell efficiency (1975-2014)

2.3. Regulations of the sector

Government subsidies have played a prominent role in the growth of solar power. According to Sahu (2015), the top ten solar PV power producing countries including US, Japan, Germany, France, Italy, Spain, China, Australia, Belgium and the Czech Republic, mainly depend upon their policies as instruments like Feed-in-Tariff (FIT), net metering, quotas with green certificates, low interest bank loans, renewable portfolio standards (RPSs), country's national renewable energy targets, Investment Tax Credit (ITC), market premiums, and reverse auctions for the development of solar energy. Without such policies, the high cost of generating solar power would prevent it from competing with electricity from traditional fossil-fuel sources in most regions.

But the sector's economics are changing. Over the last two decades, the cost of manufacturing and installing a photovoltaic solar-power system has decreased by about 20 percent with every doubling of installed capacity by the enhancing cell efficiency and the cost of the solar cell panels. The cost of generating electricity from conventional sources, by contrast, has been rising along with the price of natural gas, which heavily influences electricity prices in regions that have large numbers of gas-fired power plants. As a result, solar power has been creeping toward cost competitiveness in some areas. According to Lorenz et al (2008) in the McKinsey Quarterly, during the next three to seven years, solar energy's unsubsidized cost to end customers should equal the cost of conventional electricity in parts of the United States (California and the Southwest).

With the cost reduction facilitated by the technology development, the sector becomes more and more challenging to be regulated. Instead of gradually withdrawing the subsidy policies, Mahalingam & Reiner (2016) concluded that, based on a scenario analysis, if the current levels of carbon price were to exist post-2020, both Italy and Spain would find it rather difficult to increase the penetration of renewables in their electricity mix. A high subsidy world, on the other hand, would result in the most favorable outcome, particularly for Spain, although it may incur additional costs in comparison to a high carbon price world.

CHAPTER III

SECTOR EVOLUTION UNDER INNOVATION CASCADE

There are two basic models to study industry evolution: the time-honoured industry life cycle models (ILC), based on the product life cycle (PLC) approach, and the more recent and fairly incipient history-friendly models (Malerba (2007). Since the late 1970s, several studies using the PLC, and then the ILC models, have pointed out the fact that a large number of industries follow a life cycle in which a radical innovation and the related entry of new producers that introduce new designs is followed by demand growth, a greater emphasis on process innovations and a selection process which ultimately leads to a concentrated market structure, the mergence of a dominant design, and the decline of innovation (Abernathy and Utterback, 1978; Utterback, 1994). But it has been convincingly indicated that that the dynamic sequences are different from one industry to another (Klepper, 1997; Geroski, 2003, Malerba, 2007). Thus, individual-industry case studies are necessary to see the real industrial dynamics, and the differences from one sector to the next, particularly after the PLC had adopted its canonical form in the 1960s and 1970s. In the meantime, some cases studies have been developed, using history friendly models, for example the computer industry (Malerba et al., 1999, 2001), the pharmaceutical industry (Malerba and Orsenigo, 2002), as well as for other industries such as software and chemicals.

Also, the development of high-tech industries in the last forty years shows anything but a decline of innovation. Instead what we observe is a rapid succession of radical innovations, what we will call and innovation cascade. The concept will be here defined, measures will be proposed to give it its empirical contours, and the appropriate theoretical conclusions will be made.

Also, this chapter explores the contours of the solar photovoltaic sector, a high-tech one that, like other science-based industries, shows uninterrupted innovation from its modest start in the 1950s to the present day. Like aerospace, biotechnology, ICT, and nanotechnology the solar PV sector does not see innovation stagnate and decline, as argued by the PLC-ILC approaches, but on the contrary, it shows continuous novelty and its branching into new paths and the creation of new products for new markets. The institutional environment, and multiple positive feedback processes, can explain the “anomaly”. The institutional milieu and the positive feedback effects of the innovation cascades are absent in the PLC-ILC perspective, but is a central element in the innovation systems approach.

3.1.The evolution of industries from life cycles to innovation cascades

3.1.1. PLC and ILC

In these models, new products trigger innovation. Later on product innovation declines and process innovation takes the relay. After a certain number of years, both product and process innovation decline, the industry concentrates and it often moves to countries where the labour force is cheaper. This is the story of textiles, garment, furniture and bicycles in the past, and automobile, electrical equipment and other industries today. In the PLC-ILC theories, innovation is the result of the search activity of a one or a small group of firms, who are manufacturers based in the richest country, often the United States. Companies produce novelty to integrate it in their product lines. Over time, the market of the innovating country becomes saturated and the innovators start exporting to other affluent markets. Then competitors appear in this second cohort of countries, and the original innovators invest in this second tier of markets in an effort to crush the new competitors or at least slow their progression. Yet, in spite of these efforts the industry becomes more competitive, technology more standardized, and foreign direct investment heads towards third world countries. During this progression, innovation declines, first in products and then in processes.

The industry life cycle approach puts more emphasis in the structure of the industry than in the evolution of the product itself. Like in the PLC approach, entry is concentrated in the initial phases of the cycle. The ILC includes an rapid shake out in the maturity phase during which the number of firms declines, and the less efficient competitors are eliminated. The emergence of dominant designs makes economies of scale, not innovation, the crucial competitive factor (Agarwal et al, 2002). Similarly, according to other observers, in the mature stages of the life cycle, entry is more related to filling niches than to conducting radical innovation (Agarwal and Audretsch, 2001).

In addition, some authors have added nuances to the PLC-ILC models. Some of them have noticed that innovation does not necessarily decline in mature industries, when measured by patent activity (McGahan and Silverman, 2001). Those who – in agreement with the PLC-ILC approach – see the number of patents most often falling over the life cycle, oppose this point of view (Haupt et al, 2007). Yet other authors, using a variety of indicators, namely patents and scientific publications, found a variety of situations between invention and innovation. In the science-based industries, the study of the evolution of publication may be extremely useful, as publication either precede or accompany the evolution of patents (Järvenpää et al, 2011). Also, Lee and Veloso (2008) found that architectural knowledge dominates innovation during the early phases while component innovation becomes more frequent at the later phases of the life cycle.

A few authors have criticized the PLC-ILC models on their ambiguities about the length and time of the phases, and the probable coming of dominant designs. The validity of these models in the high-tech industries has been questioned (Grantham, 1997). What exactly declines over time: families of products (i.e. airplanes)? Or specific designs such as turboprop airplanes?(Cao and Folan, 2012).

In their review of the literatures, Cao and Folan (2012) added other criticisms: some products have known second lives, particularly under the product renewal and marketing efforts of original innovators. Also, they pointed out that networks of innovators and other inter-company relationships are absent from the PLC-ILC models. Lambkin and Day (1989) had already underlined the fact that the PLC approach had ignored the differences between large and small pioneers, those that enter by in-house innovation and those that arrive by acquisition, licensing and joint venture. Also, the approach makes no difference of "strategic windows of opportunity" for entrants of different size and competitive position. Also, the models do not predict when the shakeout will occur. Yet the sceptics about these approaches have been few in numbers and have not been widely cited or followed. In some areas of management, such as marketing, their popularity has not decreased for half a century.

Among the few papers that have tried to devise a role for governments in the product life cycle, Tassey (1991) had argued that governments should adapt their technological infrastructure to the technology life cycles of their main industries. Robertson and Langlois (1995) added that governments should act as facilitators, letting firms adapt to their particular environments. Yet, Klepper, the father of the

ILC theory, made it very clear:

"In summary, apart from an occasional influence of the government/military, the evolution of the six products through their formative eras largely conforms with the PLC." (Klepper, 1997)

Thus, in this family of models, governments have an occasional role in the sequence but usually they keep their hands off the product and industry life cycles.

3.1.2. System dynamics, complexity and history friendly models

More recently the sectoral innovation system approach that Malerba, Orsenigo and others have pioneered, is more attentive to the specific contours of each set of industries or sectors, where particular cost structures, competitive advantages natural or built, particular policy incentives or market sizes and structures, can affect the evolution of the sector. This type of models allows for different sequences in the role of innovators, different types of demand structures and knowledge flows, and different institutional settings. Without obliterating the PLC-ILC approach, these perspectives allow for a variety of sequences and industrial dynamics. These models argue that technological regimes and demand structure have major roles in industry evolution (Garavaglia et al, 2012; Malerba and Orsenigo, 2015).

The relative importance of these currents is easy to grasp: when searched in the SCOPUS database, the keywords "history friendly models" find 18 articles in refereed journals; "product life cycle" gets 3100 articles.

The general argument that we put forward here is that science-based industries and sectors (SBIS) show a fairly different set of evolutionary patterns compared to more traditional industries. In SBIS, product variation is overwhelming, the branching out of new industries and the rise of new market segments if widespread. Thus, SBIS are more prone to innovation cascades than low and medium-tech industries (Niosi, 2015). In addition, science-based industries are very much supported by governments.

This paper argues – as Lundvall (1992) Malerba (2004), Nelson (2005), Niosi (2010) and others have done in the past – that institutions play a key role in the development of high-tech industries. This role has specifically been studied in biotechnology (McMillan et al, 2000, Whitley, 2003), in computers and software industries (Mowery, 1996), and nanotechnology (Roco and Bainbridge, 2005; Niosi & Reid, 2007). Governments subsidize these industries in order to improve human health, industrial competitiveness, and aiming at other societal benefits. They do it through public laboratories (think at the National Institutes of Health or the New Renewable Energy Laboratory in the United States), through academic subsidies to R&D, and through multiple incentives to private-sector innovation, including reimbursable and non-reimbursable subsidies, tax credits for R&D, and subsidized tariffs.

In addition, increasing variation is a characteristic of several industries, an evolution that Schumpeter Mark I and Schumpeter Mark II sectors, as well as PLC-ILC industries has not captured. The following insert summarizes the argument that appears as a development based on the Mark I – Mark II dichotomy. (See Table 3.1)

Table 3.1 Four stylized cases of industry evolution

		Initial conditions	
		Concentrated	Dispersed
Long-term trend	Increased or sustained concentration	Cases: satellites and space launchers manufacturing (Schumpeter Mark II industries, following Malerba and Orsenigo, 1996)	Cases: pharmaceutical drugs, computer software services (Kaldor-David-Arthur increasing returns industries)
	Increased or sustained dispersion	Cases: Semiconductors, computer and telecommunications equipment manufacturing (variation-intensive industries following Niosi 2000 and Saviotti, 1996)	Cases: biotechnology R&D services, professional equipment manufacturing, solar PV equipment (Schumpeter Mark I industries, following Malerba and Orsenigo, (1996)

Based on Niosi, 2000

3.1.3. The patterns of innovation

Innovation is the engine of economic growth. It is thus critical to understand how it proceeds. For several decades, evolutionary theories using the biological model were applied to innovation (Basalla, 1988; Petroski, 1994; McKelvey, 1998): innovation was supposed to proceed in a leisurely way, over the centuries if not the millennia, one step at a time, in an incremental process. Similarly, organisations and institutions evolved clearly from one form to the next (Nelson and Winter, 1982; Tushman and Romanelli, 2008). Several evolutionary models, as we have seen, have been advanced to explain this change (Malerba, 2006). For most authors, including the authors of this paper, evolutionary technological change is the most frequent. Arthur (2009) calls 'standard engineering' this evolutionary technical change. Bessant et al (1994) underlined the fact that continuous innovation is sometimes difficult. Yet the vast majority of authors find evolutionary innovation is ubiquitous. Companies and governments alike abhor disruptive technological change that may devalue their assets and sunk costs, and cannibalize their products (Christensen, 1997).

3.1.3.1. Radical innovation

Radical innovation (already identified by Schumpeter in his 1939 book Business Cycles) appeared and, it was deemed analogous to biological change, where saltation (Gould, 1977) and short periods of rapid structural change interrupted long periods of stasis and incremental change. Both in biology and management, radical innovation and saltation were difficult to accept. In biology, the neo-Darwinian synthesis wiped out most ideas about saltation. They came back slowly since the 1950s and 1960s through the work of B. McClintock (Nobel Prize in physiology 1983). The idea was developed and popularized by S.J. Gould and N. Eldridge. How the markets accept these complex modifications of product and/or process? In the postwar period, radical innovation appeared in Britain in the works of Gibbons and Littler (1979), Rothwell (1980) and others. A few years later, several authors were discussing the multifarious dynamics between radical innovation, organizations and industry structure (Souder, 1983; Achilladelis et al, 1990; Christensen and Bower, 1996) as well as the importance of the necessary infrastructure for radical innovation to be adopted (McIntyre, 1988).

The notion of radical innovation is also labelled discontinuous or disruptive innovation. Radical innovation, when successful, has a much larger effect on firm's profitability, market share, and entire industries (Sainio et al, 2012). Key dimensions of radical innovation include technology novelty (clear advances in frontier technology, as in the

I-Pad), and market novelty (products that address themselves to new markets, or to markets that were served by other products, such as MABs). Even if it often the special activity of entrepreneurial firms, it also occurs in large established companies (O'Connor and McDermott, 2004).

Much more recently, innovation seems to be accelerating; new scientific disciplines appear. Thus, it cannot be properly depicted as a smooth path, punctuated by occasional changes in direction. It looks much more like a river where fast-moving water evolves from rapids to waterfalls, splits into several diverging flows that sometimes merge with other flows to form new estuaries. The concept of innovation cascades circumscribes evolutionary change (Antonelli, 2008, 2009; Berkers & Gees, 2011; Delapierre & Mytelka, 2003; Lane, 2009, 2012). Rothwell and Wissema (1986) had suggested that radical innovations arrive in clusters, much in line with the Schumpeterian view of business cycles. This paper argues that innovation cascades are becoming much more frequent today for several reasons: because of the rise of science-based industries (Pavitt, 1984), the increasing number of research universities in a growing number of emerging countries, more linkages between these loci of knowledge creation, and faster technology diffusion. Fastest imitation also increases the probability of new combinations between different strands of knowledge. Cascades have a definite Schumpeterian flavour.

3.1.4.2. Incremental innovation

Evolutionary or incremental innovation (small, continuous improvements in technology and organisation) is the most abundant type of innovation. Its predominance over other forms of innovation is easy to accept. Companies and individuals thinker on what they know best. Such behaviour reduces the risk associated with big jumps.

Evolutionary product and process and organizational innovation is less expensive, because it requires minor adaption of marketing, and operations strategy and infrastructures. Markets recognize, and sometimes even trigger such slow changes. Many organizations almost continuously produce such small adaptations to environmental changes of their output and/or their structure. Large changes, both in biology and economics would produce monsters, which the environment often rejects as such, and do not survive. The organisation produces variety (at the level of technology, product, process, strategy and structure) in a bounded rational way, and the environment selects. Such slow process drives the organisation and its technologies to local optima. "Artifacts, like plant and animal life forms, can be arranged in continuous, chronological sequences./…/ Butler, Pitt-Rivers, Gilfillan, Ogburn and Usher all stressed the accumulation over time of small variations that finally yielded novel artifacts." (Basalla, 1988, p. 24) Yet, the author recognizes that short periods of rapid change may exist between long periods of slow change and stasis. However, the vast majority of authors on technology have adhered to an evolutionary perspective.

In economics, Nelson and Winter (1982) have identified the sources of slow change: the firm's routines, which are the genes of organizations. Over time, organisations have developed ways of solving their search, production and marketing problems; such a learning process has been long and costly, and has been reinforced by the building of complementary infrastructures and practices. Maureen McKelvey (1996) has presented the basic principles of evolutionary innovation in biotechnology. They include variation (generation of novelty); selection; transmission and retention of certain traits over time; and non-optimization but adaptation to local environments. Like Basalla (1988), McKelvey argues that biological evolution cannot be deemed identical to economic evolution. Nelson (2006) has also adopted this perspective: biological evolution and human culture share a few major unifying themes, such as variation, selection and retention, but are split apart by major differences, including the speed of change and the goal-oriented action of humans in cultural evolution. Also, within cultural dynamics there are large differences between fields, such as linguistic and policy evolution.

A lively debate among evolutionary economists and management theorists is linked to the amount of inertia that organizations carry. At one extreme one finds the organisational ecology perspective, with such authors as Michael Hannan, John Freeman, and Glenn Carroll, for which organisational inertia is predominant, and firm level adaptation is limit. Populations of firms change by the birth and death of organizations; those that survive have usually from the start, the right genes. Organizational ecology is more Darwinian, while Nelson and Winter (1982) are more Lamarckian. The more the evolutionary approaches put the emphasis on the importance of strategy, including Nelson and Winter, the farther they are away from the organizational ecology perspective. Whatever the case, it is clear that most companies live and die with their original routines, technologies and strategies. These are the traditional small and medium-sized firms that Bhidé (2000) has shown to be the vast majority of firms. A few of them usually medium-sized and large ones, tend to change from time to time their range of technologies, strategies and structures. This paper adopts a mixed perspective: studies on firm mortality in all OECD countries show that the vast majority of firms disappear a few years after they were founded. A few of them manage to change and adapt to the environment. Even among those that adapt and change, many sometimes err in their choice of new routines, technologies and markets, and also disappear. The roads of industrial change of the latest years are littered with the remains of such companies as Blackberry and Nokia.

In this world of evolutionary innovation, technological trajectories abound, and technological discontinuities are amenable to modelling (Dosi, 1982). New technological paradigms (discontinuities) are linked to the emergence of

Schumpeterian companies and the process of innovation stabilises. The process is fairly structured:

> "...a technological paradigm (or research programme) embodies strong prescriptions on the directions of technical change to pursue and those to neglect."(Dosi, 1982: 152).

Also, evolutionary innovation is the world of path dependency. Institutions, routines, technologies persist over time, even when they have outlived the social matrix in which they were born.

3.1.4. Innovation cascades

The idea of innovation cascades is already present in Schumpeter:

> "First, that innovations do not remain isolated events, and are not evenly distributed in time, but that on the contrary they tend to cluster, to come about in bunches, simply because first some, and then most, firms follow in the wake of successful innovation; second, that innovations are not at any time distributed over the whole economic system at random, but tend to concentrate in certain sectors and their surroundings."(Schumpeter, 1939, p. 98)

More recently, a few authors have explored the subject without arriving to a complete explanation of the dynamics of its development. Delapierre and Mytelka (2003) link innovation cascades to the oligopolistic behaviour of large firms. Competition among large diversified corporations generates the exploration of new technological domains, and the creation of new technologies and new industrial sectors. They do not make any link between their work and Schumpeter's, in spite of the obvious similarities. Antonelli (2008 and 2009) explains innovation cascades by the interplay of Marshall and Jacob externalities within clusters. Cascades appear in regional innovation systems, not necessarily in concentrated industries, as in Delapierre and Mytelka (2003). Lane (2009) explains innovation cascades by a phenomenon called "exaptive bootstrapping". In biology, exaptation is the use of structure or feature for a function other than that for which it was developed originally through natural selection. "Exaption is a change in the function of a trait during evolution. "Bootstrapping," means to help oneself by one's own means and efforts. Thus, in the two previous explanations, the conscious efforts of economic agents launch a cascade; in Lane's approach, some agents would launch a cascade without even noticing it, just trying to solve a local specific problem. His example is Gutenberg's invention of printing by the movable metal type around 1452-54. Such innovation launched a cascade where new organizational forms (printing companies), new technical novelties (new ink, paper), new markets (for printed books), and new functionalities emerge, and imitation from other economic agents increases both the market and the innovative activities, in a positive feedback dynamics that may extend over decades. Once it is launched, the self-reinforcing dynamics is difficult to control or predict, even for those that actively involved in the process (Lane and Maxfield, 1996). Under such conditions, optimization and strategy making become difficult, if not impossible. And predicting technological trajectories is highly improbable. Finally, Berkers and Geels (2011) use the same notion of innovation cascades to describe a positive feedback innovation mechanism that has taken place among traditional small and medium-sized enterprises using innovations generated elsewhere (mostly equipment suppliers, but also government laboratories and universities). The authors make a passing remark on the fact that these cascades are different from those studies in scale-intensive and science-based industries and/or government utilities (ibid, p. 243), but they do not cite any of the above mentioned papers on innovation cascades. They contribute to the theory of technological transitions.

Technological transitions are major long-term technological changes. These technological transitions come along through several mechanisms: niche-accumulation, technological add-on and hybridisation (Geels, 2002). His idea of technological transitions is close to Schumpeter approach of innovation cascades. Technological transitions occur in all different types of industries, from science-based to scale intensive to government-supported sectors. However, "transitions are characterised by one major, radical innovation or discontinuity" (Berkers and Geels, 2011, p. 230), while innovation cascades are more characterised by a stream of radical innovations.

In this paper we contend, following Mokyr (2002) that innovation cascades in Western economies before the Industrial Revolution, such as the printing press, failed to promote sustained economic growth. They are different from present day high-tech (information technology and biotechnology) cascades. The reasons why innovation cascades before 1800 where short lived are many. First, the institutional environment did not contribute to its adoption but blocked the diffusion of innovation and the emergence of new radical ones: indexes of prohibited books and censorship were widespread. Also, universities and private companies did not conduct R&D, and there were no public research laboratories to push the cascade further. Radical innovation depended on the individual efforts of remarkable luminaries like Galileo or Da Vinci. At that time, the innovation centres of the world were just a few cities such as Amsterdam, London, Paris, and Venice, and within them there were few innovating organizations. Also, communications between those centres were slow and costly, and the scientific and technical knowledge of the times was scanty. Innovation came through serendipity, and was not the routine activity of many organizations as it is today.

After the Industrial Revolution innovation cascades became more frequent. One can find several of them associated with the rapid improvements in steel-making technology, the railway, the internal combustion engine, and chemicals to name some of the most important in the 19th and early 20th centuries.

Postwar innovation cascades are increasingly frequent in Western countries. The reasons are many. For one, the stock of knowledge grows by bounds and leaps. As a result, innovation, as measured by the number of patents and scientific publications increases continuously. So the scientific and engineering raw material for innovation is today much more abundant (Kortum and Lerner, 1999; Larsen and von Ins, 2010). Second, the rise of scientific collaboration (Greene, 2007) and particularly of international scientific collaboration increases the number of new combinations that may be produced on the basis of this new knowledge. The growth of international scientific collaboration may be explained by the diffusion of scientific capacity both within industrial countries and among emerging countries (Wagner and Leydersdorff, 2005). Also, rapid advances in communication and transportation technology increase today the chances that new combinations emerge from international and inter-regional collaboration. Third, the institutional landscape has enormously changed: in each advanced industrial and emerging country, thousands of innovative firms and hundreds of research universities, as well as public laboratories are now able to amplify and develop many technological trends in a way that was impossible to occur 200 years ago. Thus, all these elements launch positive and self-reinforcing feedback processes that are increasingly unstoppable. Other key innovation institutions contribute today that did not exist in the 15th or 16th centuries, namely policy incentives, such as those aiming to the commercialization of university research, policies increase the likelihood that scientific novelty is used in industry and launch an innovation cascade.

The previous world was one were technological trajectories and path dependencies were the name of the game. They still are numerous today, but innovation cascades, a world of self-reinforcing mechanisms, non-linear dynamics with many possible short-term equilibrium situations, make that technological trajectories are less evident than fifty years ago. Who could foresee the rise of Internet, or the advances in computational genomics thirty years ago? Technological path dependencies also seem to be often interrupted by these innovation cascades. The dictum "Natura non facit saltum" does not apply to these unpredictable cascades. The following table compares incremental and radical innovation, an important step towards defining innovation cascades (Table 3.2) . It is important to remind that there is no universally accepted definition of either incremental or radical innovation.

Table 3.2 Incremental and radical innovation defined

Dimension of radicalness	Incremental	Radical	Authors
Impact on the industry	Low	High	Acemoglu & Cao (2015)
Source of subsequent innovation	No	Yes	Ahuja & Lampert (2011)
Older technology remains substitute for new	Yes	No	Arrow (1962)
Cost reductions	Low	High	Green (1995)
Competitive advantage to adopters	Low	High	Kumar et al (2000)
Benefits brought if successful	Low	High	Kumar et al (2000)
Adoption risks	Low	High	Kumar et al (2000)
Technical uncertainty levels	Low	High	O'Connor et al (2013)
Market uncertainty levels	Low	High	O'Connor et al (2013)
Resource uncertainty levels	Low	High	O'Connor et al (2013)
Organizational uncertainty levels	Low	High	O'Connor et al (2013)

Innovation cascades break havoc with the rigid sequence of PLC and ILC. Continuous new technological and industrial developments branch out of the original products and services. In order to make the exact description of the series of radical innovation, the Innovation Cascade is re-defined here as follows:

An innovation cascade is a series of radical innovations that spans over a decade or more, and can be observed and measured through *patents and scientific and technical publication.*

And the hypotheses are drawn as follows:

Hypothesis 1: An innovation cascade is emerging in the solar PV sector;

Hypothesis 2: Transnational technology diffusion has contributed to the innovation cascade in the solar PV sector;

Hypothesis 3: The different demands in the different stages promote the innovation cascade in the solar PV sector.

Hypothesis 4: The solar PV is a typical "Mark I sector": it was born dispersed and its dispersion was maintained or even increased over time, a pattern that contradicts the PLC-ILC model.

Hypothesis 5: In science-based sectors, rapid changes in the science and technology fundamentals modify the contours of the life cycle, in accordance with history friendly models.

Hypothesis 6: In science-based industries, demand changes modify the contours of the life cycle, in accordance with history friendly models.

The hypotheses will be tested by employing the solar PV sector as the case. The paper will bring some aggregate s about the rise of the solar PV sector, and then it will illustrate one of the major present-day innovation cascades with the growth of this high-tech sector. The growth of solar publication and patenting is also presented. A table with the different disciplines, application and key companies will help.

3.2. Methodology

3.2.1. For innovation cascade

We studied the solar sector with an emphasis on innovation and production. Among our most important sources of data, we used the USPTO patent database for the period 1976-2013. The solar sector is not a sector, as defined by NAICS or SIC codes, but a set of industries with different codes (Table 3.3). They include solar cells (the heart of the solar equipment), but also batteries, modules, advanced materials and increasingly specialised glass. The vast majority of the patents concerned solar cells, but we decided to search for USPTO patents having "solar cell", "solar glass" or "solar battery" in the abstract. An initial manual search was revised by a computerised search and statistical analysis. Because the United States was the cradle of the sector and is still the most inventive country in the world, we take the American patent database as essential for our research.

Table 3.3 NAICS and SIC codes of the solar photovoltaic sector

SIC Code	NAICS Code	Description
3674	334413	Manufacturers of Copper Indium Gallium diSelenide (CIGS) solar cells and solar foldable, flexible panels and off-grid glass modules[3]
3211	327211	Flat glass manufacturers
5074	423720	Plumbing and heating equipment and supplies
1711	238210	Plumbing, heating and electrical equipment contractors

Source: US Department of Commerce

The total number of patents for the different years has been calculated for the trends of the development of innovation. Besides, patents in the different countries and different regions have been studied.

For tracking publication, we used the SCOPUS scientific database with similar keywords as for patents. Until July 18, 2015, there were a total of 111,173 such publications in Scopus. We used these databases to analyze the sector. The publications in the different countries and different regions have been calculated.

In order to compare the publications and patents on different continents and show the effect of technology diffusion, we classify the countries with the publications and patents in solar PV in three categories: North American includes US and Canada; Europe includes Germany, United Kingdom, France, Italy, Spain, Netherland, Switzerland, Sweden, Belgium, Russia Federation; Asia includes China, Japan, South Korea, India, Taiwan, Singapore and Malaysia.

[3] Products are Crystalline silicon panels, thin-film panels, multi-junction panels, crystalline silicon cells, thin-film cells, multi-junction cells and organic cells and panels. In sum, their activities are the manufacturing of solar cells and solar panels. As of December 2014, the US industry had 5 481 employees, 46 firms, and total revenues of 1 US billion. Annual growth for 2009-2014 was -7.3%, due to international competition.

We also analyzed data from the US National Renewable Energy Laboratory (NREL) concerning the most important advances in solar cell efficiency from 1975 to 2014. Any organization claiming superior efficiencies in solar cells needs an external judge. US NREL, as the largest PRO in the world in solar technologies, is considered the major arbiter in this area, followed by the German Fraunhofer Institute, and the National Institute for Advanced Science and Technology (AIST) in Japan. The NREL list of best research-cell efficiencies was used as a way of distinguishing major inventions from the large list of solar cell patents.(9)

As to production and markets, we used different sources such as the European Photovoltaic Sector Association reports, the Earth Policy Institute, NREL studies and specialised publications such as *GreenTech Media* and PVTech.

3.2.2. For evolution of the solar PV sector

3.2.2.1. Definitions

In order to describe industry evolution in the most precise way, the following concepts are defined:

---User innovators are the companies who directly benefit from the use of the solar PV products, but also conduct R&D and patent at least some of the results of their R&D investment; companies such as Boeing, Canon, EXXON, or Siemens are user innovators. Public laboratories and universities, as well as specialised small and medium sized enterprises conducting research and patenting, or those that install panels for individual or industrial companies and do not conduct research are not user innovators. In our definition, users and manufacturers may coexist under the same roof and within the same enterprise (Block et al, 2016).

---Integrator: solar cells are the heart of the solar photovoltaic systems, but are not the final product for most users. Other companies integrate the solar PV technologies into their products and then sell to the consumers; these include producers of solar roof panels, clocks, watches, pocket calculators, satellites, aircraft, solar tracking mechatronic equipment used in highways, telecommunications equipment and the like.

---Related diversification: the large companies usually spin-off dedicated firms to produce the solar PV products to the end consumers in other applications;

---Mass market: the end consumers are individuals and commercial organizations that buy solar panels for houses, industrial firms or highways; also, companies producing portable electronic products such as clocks, and pocket calculators.

---Niche market: the end consumers are in such special industries as aircraft, satellites, or other specific products.

---Specialized manufacturer: they are manufacturers just focusing on solar PV cell or solar panels manufacturing, without other focus or integration plan.

--- Feed-in-Tariffs (FIT); "A feed-in tariff (FIT) is an energy supply policy that promotes the rapid deployment of renewable energy resources. A FIT offers a guarantee of payments to renewable energy developers for the electricity they produce. Payments can be composed of electricity alone or of electricity bundled with renewable energy certificates. These payments are generally awarded as long-term contracts set over a period of 15-20 years." (US DoE, 2010) Those FIT are used not only to create incentives for the adoption of solar PV technologies, but also for wind and other renewable energies. They were adopted in Germany, Italy, Spain, Japan, and lately in China. In the USA, six states have implemented such tariffs.

3.2.2.2. Sampling and data collection

In order to review the industry evolution of the solar PV industry in terms of innovation, the patent data in United States Patent and Trademark Office (USPTO) are employed as the sample selection criteria. The data offered by the USPTO are selected because the United States assignees own nearly 50% of the solar PV patents, and over 75% of energy-storage patents. In addition, innovators based in other countries, mainly Japan, Germany, Taiwan or the Popular Republic of China also patent their inventions in the United States in order to protect them from potential infringers.

The samples are established in three categories:

1. The earliest assignees in the solar PV;

2. The top 10 biggest patent assignee companies; and

3. The top 10 biggest manufacturers specialized only in the solar PV cells and other solar system components such as solar high-tech glass, and solar energy storage systems.

For each samples in the above groups, we explore the information from their websites and the open information including the internet, the reports and the journals to find the major business, the solar PV business and their marketing positioning.

3.3. Results

3.3.1.Innovation Cascade in the solar PV sector

When the total number of patents and publications are studied, it can be observed that the growth rate of publications has begun to grow exponentially since 2000, and that of patents since 2010.   8 & 9 shows the exponential growth of innovation in the solar PV sector, one that we call an Innovation Cascade. Such growth started in the 1990s and keeps on rising today. This growth is partly due to government incentives to solar PV adoption, but also to solar R&D in private firms, academic and public research organizations.

When the technologies are studied, we observe several paths instead of one dominant direction from the cell efficiency evolution map from NREL (see Figure 2.9). Energy conversion efficiency is taken as the most important indicator to measure the technology progress. According to Green (2009), over the last two decades, terrestrial cell measurements have evolved to the stage where independent laboratories measure the same result for standard silicon cells within 1–2%. As a result of early initiatives by SERI (Solar Energy Research Institute, now National Renewable Energy Laboratory, NREL) which encouraged the development of high efficient silicon cells, several key silicon cell results were measured at NREL in the early 1980s, the beginning of what will be referred to as the 'modern phase' of silicon cell development. The calibration of NREL is often employed to show the progress of different categories of solar PV technologies. According to NREL statistics, the best research-cell efficiency evolved in the different paths.

There is neither a dominant standard nor a dominant design for the sector. When assessed based on cell efficiencies, the major evaluation measurement, radical innovations are emerging from time to time. It looks much more like in the innovation valley of the solar PV sector, the technology innovation fast-moving river evolves from rapids to waterfalls, and splits into several diverging flows that sometimes merge with other flows to form new estuaries. Thus, the hypothesis that there is an innovation cascade in the solar PV sector is supported. The hypothesis that the solar PV sector is characterized not by a decline of innovation but originally by a constant and now by a rising stream of innovations is strongly confirmed.

3.3.1.1. Innovation cascade due to the diversity of the innovation organizations

It is found that the most of the solar cells was initiated by the companies (see Table 3.4), the public research organizations (PROs), SMEs and universities in the different countries have initiated technological trajectories over the past half century. The patent analysis shows that the different organizations contributions simultaneously to the innovation pools. (See Table 3.5)

Judging by the total number of patents, large companies have been granted close to 60 % of solar cell patents, and small and medium-sized enterprises produced some 35% of them. Universities do not seem to play a major role in this high-tech fledgling sector, while the public research organizations contribute significantly.

Table 3.4 Initial innovative organizations in solar cells (1975-2014)

Type of solar cells	Original organization	Country	First year cell tested
Amorphous ScH (Stabilised)	RCA	USA	1976
CGIS (thin film cells)	University of Maine	USA	1976
Single crystal, single junction	IBM	USA	1977
CdTe thin film cells	Matsushita	Japan	1977
Single crystal SI cells	Mobil Solar	USA	1977
Two junction cells	North Carolina State	USA	1983
Single crystalline Si cells	Stanford University	USA	1984
Microcrystalline cells	Solarex	USA	1984
Dye sensitive cells	École polytechnique fédérale de Lausanne	Switzerland	1991
Three junction cells	NREL/Spectrolab	USA	1999
Organic cells	University of Linz	Austria	2001
Silicone heterostructures	Sanyo	Japan	2001
Three junction cells (MM)	Spectrolab	USA	2003
Thin film crystal GaAs cells	Ranboud University	Netherlands	2005
Organic tandem cells	University of Dresden	Germany	2008
Quantum dot cells	NREL	USA	2010
Perovskite cells	École polytechnique	Switzerland	2013

NREL (2014) Best research-cell efficiencies

Table 3.5 The major players in the sectoral system of innovation

Country	Universities		PROs		Private firms		Total	
	T. Pat	Key	T. Pat	Key	T. Pat	Key	T. Pat	Key
USA	78	14	60	31	2098	114	2236	159
Japan	11	0	23	1	957	22	991	23
Germany	8	4	22	7	353	5	383	16
Taiwan	31	0	59	0	130	0	220	0
S. Korea	11	0	39	2	160	2	210	4
France	0	0	6	0	32	0	38	0
Switzerland	2	5	0	1	34	0	36	6
Canada	0	2	0	0	35	0	35	2
China*	6	0	0	0	29	0	34	0
Netherlands	2	4	5	0	25	2	32	6
UK	0	0	0	0	30	0	30	0
Australia	15	17	0	0	7	0	22	17
Sweden	0	0	0	0	19	0	19	0
Austria	0	3	0	0	12	0	12	3
Italy	0	0	0	0	8	0	8	0
Total all countries	164	49	208	42	3929	145	4401	238

NB: Australia's University of New South Wales does not patent under its own name. Sums sometimes do not add up because of multiple assignees on the same patent. *China includes Hong Kong. Sources: USPTO and NREL

Large and small companies

The contribution of large firms has been fairly constant over the years. In fact, large companies such as AT&T (Bell Labs), but also Boeing, DuPont, IBM, Kodak, Mobil Solar, RCA and Westinghouse were among the first to enter the solar race (Perlin, 2002). This pattern was even more marked in Japan with early entrants such as Canon and Matsushita, and later entrants such as Mitsubishi, Sanyo, Sharp and Sumitomo. In

Germany, among the early entrants one finds large companies such as Robert Bosch, Siemens and Telefunken. Today global leaders are large companies (see Table 3.6).

Table 3.6 Top 10 PV modules suppliers, by sales, 2013

Rank	Name of company	Country
1	Yingli Green Energy	China
2	Trina Solar	China
3	Sharp Solar	Japan
4	Canadian Solar	Canada/China
5	Jinko Solar	China
6	ReneSola	China
7	First Solar	USA
8	Hanwha SolarOne	China
9	Kyocera	Japan
10	JA Solar	China

Source: www.pv-tech.org

Table 3.7 shows that large firms (over 500 employees) dominate technology invention in the solar PV sector. This is true for all major metropolitan areas except for Taiwan, where the three largest clusters have the Industrial Technology Research Institute (ITRI) as the main owner of solar PV technology. Since the 1980s, ITRI has become a major inventor in the area of semiconductors, and solar cells are specialized semiconductors. A capability ITRI developed in one sector of the microelectronics industry could be transferred to another sector of the same industry, for a different application.

Table 3.7 Solar cell PV patents by metropolitan areas and type of assignee

Metropolitan areas and prefectures	Large firm	Small firm	Univer-sity	PROs	Individual inventors	Number of patents
S. Francisco	219	124	15	10	1	369
L. Angeles	190	32	9	7		238
Greater Boston	77	27	21	1		126
Washington DC	6			88		94
New York, NY	70	8				78
Princeton, NJ,	50		5			55
Albuquerque, NM	52			2		54
Delaware Valley	38		14		1	53
Seattle	52			1		53
Dallas	43			2	3	48
Tokyo Pref.	216			1		217
Nara Pref.	209			1	1	211
Kanagawa Pref.	184		1	1	2	188
Kyoto Pref.	151			1		152
Osaka Pref.	105			2		107
Hyogo Pref.	73			2		75
Shiga Pref.	48					48
Munich	99	5	2	16		122
Frankfurt/Rhine	42					42
Seoul	128			15		143
Taipei	16		16	42		74
Hsin-Chu	9		11	28		48
Taoyuan/Zhongli	7		3	32		42
Total	2084	196	97	194	8	2637

Source: USPTO

SMEs have country-different performance in terms of contribution to innovative outcomes. US SMEs represented nearly half of the US companies that have been granted USPTO solar patents since 1976; they obtained about 14% of them. In Japan, SMEs were nonexistent among the innovators. In South Korea, with a similar industrial structure to that of Japan, chaebols hold the vast majority of US patents on solar cells.

Smaller firms are particularly active in Germany, the United States and Taiwan. Few of them are key or prolific innovators in other countries.

Universities and the solar sector

Out of some 4000 US patents granted for "solar cells" from 1976 up to January 1, 2014, only about 160 were granted to universities (4%). But these (low) s may be somewhat misleading. NREL has published a study on major increases in solar research cell efficiency over the last 40 years, and identified the organizations (academic, companies and PROs) responsible for such jumps. Out of 213 such events from 1975 to 2014, 49 (23%) correspond to universities; the University of New South Wales (UNSW) was in the lead with seventeen efficiency records, thanks to its prolific School of Photovoltaic and Renewable Energy Engineering (SPREE) founded in 1977 under a different name. UNSW does not patent under its own title, but transfers technology to the university commercial arm, independent firms and spin-offs, which have patented the technology by themselves. BP Solar, the solar energy arm of the British oil company BP, and the Chinese solar company Suntech Power, founded by a graduate of UNSW, are among the transferees of SPREE technology. The École polytechnique fédérale de Lausanne (EPFL) followed with five events. Holding three records each, were Georgia Tech, the University of South Florida in the United States, Linz (Austria) and Radboud University in the Netherlands. In all, American universities had eleven such events, Swiss universities had five, German and Dutch universities four each. In addition, several universities produced spin-off firms, including the Laboratoire d'énergie solaire et physique du bâtiment at EPFL, Stanford University in the United States, the Technical University of Dresden in Germany and the University of New South Wales. Cases of technology transfer from university to sector were also frequent, with EPFL and UNSW in the lead.

Public research organizations (PROs)

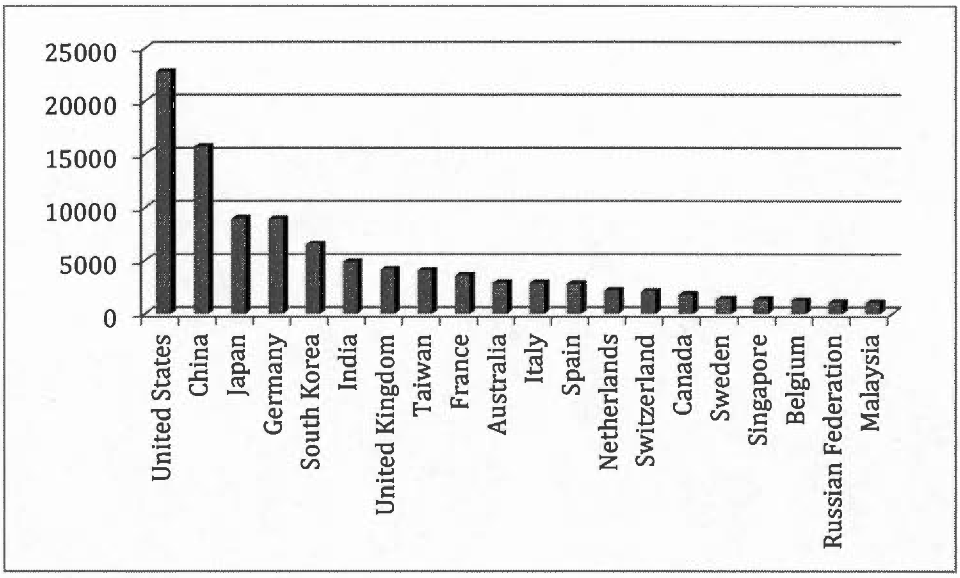
In the NREL study about key milestones in the efficiency progression of solar cells, PROs also occupy a prominent place, with 20% of events. NREL, a US research organization based in Colorado and funded by the Department of Energy, with over 1600 employees and close to 700 visiting researchers, interns and contractors, with an annual budget of US $271 million in 2014, gets the largest number of events (30 out of 44 PRO events). NREL hosts a National Center for Photovoltaics, whose mission is to make solar energy competitive with any other energy source by 2020. NREL started in 1977 as the Solar Energy Research Institute. Since its inception thirty-seven years ago, the cost of solar energy has declined by 96%. NREL transfers technology to the sector and the general public through different channels, including licensing, contract research, spin-offs, publication and conferences. Its patents are held by the Alliance for Sustainable Energy, based in Golden (CO), close to NREL.

Indeed, NREL is the most advanced United States PRO in solar energy, and German institutes follow. The Fraunhofer Institute for Solar Energy, with 1300 employees, is the largest European PRO in the area of solar energy. Located in Freiburg, Germany, it conducts research on materials, semiconductor technology, optics and photonics, chemical engineering, and other related areas. It is responsible for four major events in solar energy, but none of them is at the origin of a new type of solar cell. Only NREL has been involved in a larger number of such major events. A smaller institute, the Zentrum für Sonnenenergie und Wasserstoff-Forschung, established in Baden-Württemberg in 1988, has produced three events with its labs located in Stuttgart, Ulm and Widderstall. Yet none of these was the launching pad for a new technical trajectory.

In Taiwan, government research laboratories ITRI and INER have both built up a level of capability in PVs and this has been passed on to Taiwan firms entering the sector, either in the form of transferred technology or (mainly) in the form of skilled and trained technical staff. ITRI established a PV Technology Center in 2006, but its involvement in the sector goes back at least two decades prior to this, to 1987, when its Energy and Mining Research Division first began R&D on both monocrystalline silicon and amorphous silicon. Indeed, Taiwan's very first company involved in SCs, Sinonar Amorphous Company, was set up in 1988 employing ITRI technology and founded by two former ITRI staff members. Today, ITRI still holds nearly 20% of PV patents owned by Taiwanese assignees.

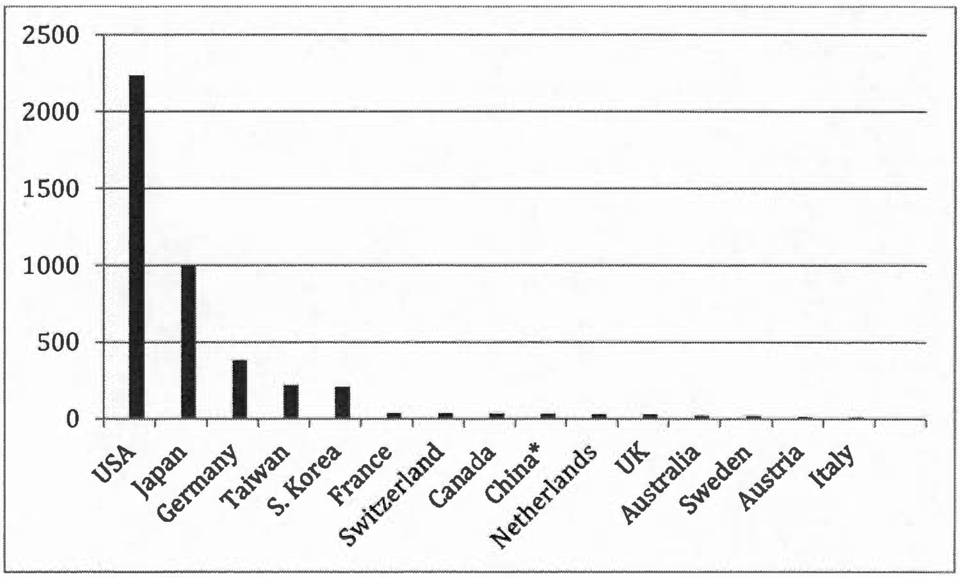
3.3.1.2. Innovation cascade due to transnational technology diffusion

The US is still the scientific leader in solar cells, but Japan and China are catching up. US leadership is also manifest in the number of patents. But Japan, Germany and South Korea are not far behind; following in a third cohort are India, United Kingdom, Taiwan, France, Australia, Italy, Spain, and several other countries. US innovation leadership is also evident through the study of rival technologies: 9 shows that most competing technological trajectories of solar cells occur within the United States, the world largest innovator. If the patents are studied overall, the US is the biggest innovator, Japan had the second largest number of patents, Germany, Taiwan and South Korea followed, and the other countries are distant competitors (see Figure 3.1 & 3.2).



Source: SCOPUS

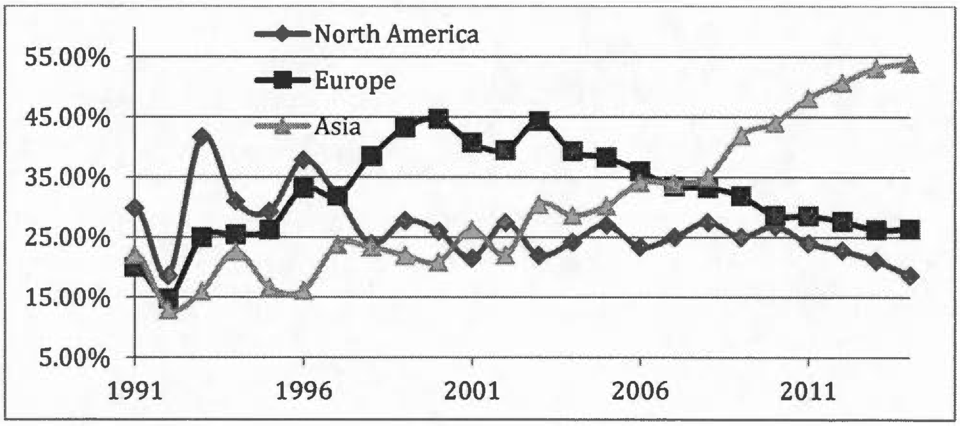
Figure 3.1 Solar photovoltaic publication in main countries (1955-2015)



Source: USPTO

Figure 3.2 Number US patents by assignee country (1976-2013)

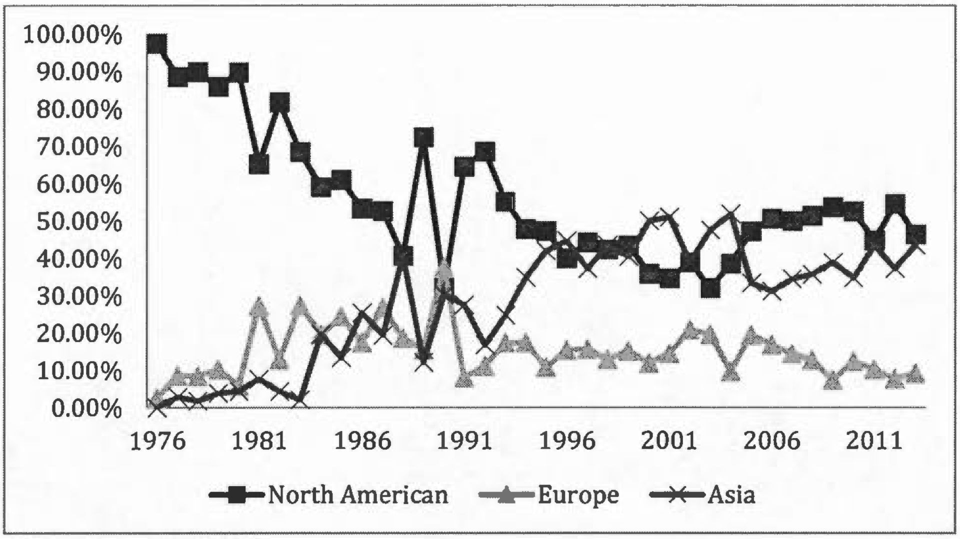
The transfer of some scientific action to Asia is clearly shown by the data of Figure 3.4 and 3.4. In terms of publications, there were three peaks in the last 16 sixteen years[4]: in the 1990-1997 period, inventions made in North America including US and Canada dominated the sector; between 1997 and 2007, Europe became the leader; after 2007 until now, Asia has led the publication trends, which perfectly corresponds to the patent trends. For the US patents, innovation in Asia keeps on growing since 1983 and European patents are still at a low level. Today, North America and Asia host the largest numbers of patents owners. Transnational technology diffusion is confirmed, and both the original and catching-up countries are contributing significantly to the innovation cascade. Hypothesis 2 is supported.



Source: Scopus

Figure 3.3 The percentage of world publications on the different continents

[4] Scopus data is not complete for the country of the authors before 1990 (for example, in 1980, there is a total of 963 publications but there are just 177 publications identifying the countries of residence of the authors; in 1986, there are 913 publications, but there are just 310 publications identifying the countries). To solve the problem, we just took the data after 1990 to note the publication trends.



Source: USPTO

Figure 3.4 The percentage of US patents on the different continents

3.3.1.3. Innovation cascade due to the different demands in the different stages

When the patent assignees in the different are studied, it can find several periods in its evolution.

The first one was – after the creation of the solar cell converting sunlight into electricity in the Bell Labs in 1954 - its application into satellites and aerospace products that require out-of-grid electrical supply. The United States hosted the main inventors and innovators in such companies as Hoffman Electronics, Signal Corporation, Communications Satellite Corporation, and Raytheon. The first solar cell powered satellite was launched in 1958 and was a total success (Perlin, 2002). At this time, specialised companies produced most solar cells and innovation. The cost of such electric power was very high, as the efficiency of these solar cells was low.

In a second wave of innovation, in the 1960s and 1970s new types of innovators appeared; they were user innovators, companies producing solar cells for pocket calculators, and other electronic material. Such innovators included Canon, Sharp and Toshiba in Japan, RCA and Texas Instruments in the United States. At the same time, some large energy companies, such as Exxon, and then ARCO in the United States became interested in solar energy for powering offshore oil and gas exploration and production. In Europe, Telefunken and other firms involved in the production of satellites became interested in solar PV technologies and conducted R&D and innovation. Australia also invested in solar PV in order to power telecommunications equipment in remote zones. The new wave of applications brought new innovators, most of them being both users and manufacturers.

As novelties piled up, solar cell efficiency grew and new innovators launched their products in the market, the cost of producing solar energy declined. A third wave of innovation arrived in the late 1980s and 1990s; in this period, earthly applications boomed. Rooftop solar panels and the first solar power plants connected to the grid appeared in California. Western European countries such as Germany, Italy and Spain adopted policy incentives, mostly feed-in tariffs (FIT) to increase the production of photovoltaic energy and reduce pollution through the use of clean technologies.

In the present wave, the fourth, several Asian countries such as China, Taiwan, Japan and South Korea have taken the relay. The European countries have reduced their support for the adoption of solar technologies, and curtailed their innovative effort. Not only East Asian countries manufacture today the majority of solar PV equipment, but they are also implementing incentives to produce more photovoltaic energy at home. However, the United States is still the most innovative country. China and Taiwan do not produce the most advanced solar equipment but rely on economies of scale to reduce cost; thus the rapid increase in adoption of inexpensive rooftop and grid-connected solar panels "crowds out" the most advanced, but more costly, US-produced equipment. Yet, the US Department of Energy (through its National Renewable Energy Laboratory) predicts that in 2020 solar PV energy will be competitive almost everywhere with conventional sources of energy (US DoE, 2010). It is already competitive in most areas of Spain, Portugal, Italy, California, Texas and large portions of Africa, Mexico, Central and South America. (See table 3.8)

Table 3.8 Four periods in the development of the solar PV technology

Period	Years	Most innovative nation	Most innovative organizations	Cases	Users
The birth of the technology	1950s-1960s (Lunar landing program)	United States	Dedicated solar cell producers	Hoffman Communications Satellite Corp.	Satellite producers In the USA, Canada and Europe
The first commercial applications	1960s-1970s (Some demands that the conventional energy cannot be realized)	United States, Germany, Japan	Mainly users-manufacturers, but also public labs and universities	Canon, Seiko, Sharp, Toshiba (JP), ARC, Boeing, Exxon, RCA Texas Instruments (USA), Telefunken (DE)	Pocket calculator producers; offshore oil and gas companies; Australia Telecom
Large scale applications	1980-1990 (mass market is emerging)	United States, Germany, Japan	User innovators manufacturers, dedicated solar equipment manufacturers; Public labs and universities	MiaSole, Solarex, Solopower SunPower Corp.	Rooftop users, first large grid applications, electronic equipment
Wide adoption of solar PV and entry of new component innovators	2000-> (mass market is expanding)	United States, Germany, Japan South Korea, China, Taiwan	User innovators manufacturers, Dedicated solar-equipment manufacturers; Public labs and universities	First Solar, Solo Power, Solarex, Evergreen Solar, Solaria (US), Samsung, LG (SK), Canon, Sharp, Toshiba (JP)	Large grid applications, space, electronic equipment, rooftop users

In addition to these user-manufacturer innovators, universities and government laboratories have for over sixty years contributed to the development of the solar PV technology. If in the 1970s and 1980s, the University of Delaware was a major contributor, later on the National Renewable Energy Laboratory in the United States, the Fraunhofer Institute in Germany, the University of New South Wales School of Photovoltaic and Renewable Energy Engineering and its ARC Photovoltaics Centre of Excellence, the MIT Photovoltaics Research Laboratory and others have become more prominent.

The solar PV sector is undergoing phenomenal growth in several countries. In 2014, those with the highest number of renewable energy jobs included China, Japan, the United States, India, and Germany. China was number one in terms of solar industries employment with 1,7 million people, followed by Japan, with 377,000. The United States had over 174,000 people employed in the different solar industries, according to the US Solar Energy Industries Association. The number is increasing by 20% a year, while the number of people employed in fossil fuels energy production would tend to decrease. Yet solar PV activity is moving towards Asia while declining in Europe. Yet, Germany has 100,000 employees in the solar industries followed by France with 60,000 and Italy with 45,000. In the world, there are 2.8 million people employed in the solar industries[5]. The sector is the largest employer in renewable energies in the world.

The hypothesis three has been supported.

3.3.2. Evolution of the sector

3.3.2.1. More diversified evolution path

By studying the earliest and current patent assignees(Table 3.9, 3.10, 3.11 and 3.12), it is found that different uses of solar PV technologies in an increasing number of products with the development of the sector such as:

- Satellites, aircraft, oil and gas offshore production facilities
- Calculators, watches, and other portable products
- Flat roof rigid panels for individual houses or industrial plants
- Sun-tracking solar systems using mechatronics
- Grid-connected systems (solar parks, photovoltaic power stations)

[5] UN Framework Convention on Climate Change, IRENA Report: Renewable Energy and Jobs 2016, Abu Dhabi, UAE.

- Green solar cities

- Emerging technologies such as

- Concentrator photovoltaics (CPV) uses curved mirrors to increase efficiency

- Floatovoltaics: floating panel systems, to save valuable land

- Grid integration systems, allowing the use of solar PV energy when needed and available

- High-tech glass, increasing the efficiency of the panels

- Solar energy storage batteries and accumulators

Table 3.9 the inventors of the solar cell technologies till 1976

Assignees till 1976	the first patent in solar cell	Founded Year	Specialized industry	Roles in the industry	the number of patents till 1976
Communications Satellite	1973	1962	satellite	user	12
Raytheon	1973	1922	defense contractor	integrator	9
US Government	1975			user	7
RCA Corporation	1976	1919	electronics (cease operation in 1986)	integrator	5
Texas Instruments Incorporated	1976	1951	Electronics, semiconductors	integrator	3
Dow Corning Corporation	1975	1943	chemicals, silicon derived polymers	integrator	3
Kabushiki Kaisha Toshiba	1974	1875	Electrical Equipment	integrator	2
Seiko Group	1974	1881	Instrument, watch	integrator	2
Motorola, Inc.	1973	1928	telecommunications	integrator	2
Alcatel-Lucent	1976	1872	telecommunications equipment	integrator	2
Hughes Aircraft Company	1976	1932	aerospace and defense	integrator	2
Bell Lab	1976	1925	Telecommunication	integrator	2
The Boeing Company	1976	1916	airplanes, rockets and satellites	integrator	1
General Electric	1976	1892	Power generation	integrator	1
Lockheed Martin	1972	1912	aerospace	integrator	1

Rockwell International	1972	1928	mechanic & aircraft & satellite	integrato r	1
Dresser Industries, Inc.	1976	1880	energy and natural resources	integrato r	1
Westinghouse Electric	1976	1886	nuclear power company	integrato r	1
Licentia Patent-Verwaltungs-	1975	N/A	NA		2
New England Institute, Inc.	1976	N/A	NA		1
Ragen Semiconductor	1976	N/A	NA		1
Sensor Technology, Inc.	1976	N/A	NA		1
Beam Engineering, Inc.	1976	N/A	NA		1

Table 3.10 Top 10 patents assignees and specialized mass-market manufacturers[6]

Top 10 User firms in terms of patents in solar PV	Number of patents in solar PV until 2013		Top 10 solar PV firms in terms of patents in solar PV	Number of patents in solar PV until 2013
Canon Kabushiki Kaisha	207		SunPower Corporation	64
Sharp Kabushiki Kaisha	91		SoloPower, Inc.	46
Samsung Group	84		MiaSole	26
Applied Materials, Inc.	81		Solarex Corporation	21
E. I. du Pont de Nemours and Company	78		Evergreen Solar, Inc.	13
The Boeing Company	65		Mobil Solar Energy Corporation	12
Mitsubishi Group	64		Solexel, Inc.	12
Siemens Aktiengesellschaft	63		Solyndra, Inc.	9
Sanyo Electric Co., Ltd.	63		Solaria Corporation	8
Raytheon	52		Stion Corporation	6

Source: USPTO

[6] US government is listed as #2 in terms of the patents numbers. But here delete US government and put the #11 patent assignee in the list for the sample of studies.

Table 3.11The role of top 10 assignees in the solar PV industry

Top 10 assignees	**roles in the sector**	**the industries as the users**	**Functions as suppliers**	**market-specialized in the solar PV industry**
Canon Kabushiki Kaisha	user innovation	camera		
Sharp Kabushiki Kaisha	from User-innovation to related diversification	radio		mass-market
Samsung Group	related diversification			mass-market
Applied Materials, Inc.	supplier		semicondcu tor equipement provider	
E. I. du Pont de Nemours and Company	supplier		higher performanc e materials	
The Boeing Company	niche-market manufacturer	satellite		Highest-Efficiency Multijunction Solar Cells for Spacecraft Power Systems
Mitsubishi Group	User-innovation to related diversification	satellite		mass-market
Siemens Aktiengesellsc haft	related diversification			mass-market
Sanyo Electric Co., Ltd.	related diversification			mass-market
Raytheon	user-innovation to mass-market suppliers	Apollo Guidance Computer	power storage and control	

Table 3.12 Top 10 specialized manufacturing assignees of the solar PV patents

Top 10 specialized assignees	founding year	Sources of the technologies
SunPower Corporation	1985	star scientists
SoloPower, Inc.	2005	from the related companies
MiaSole	2004 (but in December 2012, it became a member of the Hanergy family)	from the related companies
Solarex Corporation	in 1973(but in 1983, it is acquired by Amoco)	from the related companies
Evergreen Solar, Inc.	1994(in 2011, it is bankrupted)	Not available
Mobil Solar Energy Corporation	disappear	Not available
Solexel, Inc.	2005	not clear(no directly related sources)
Solyndra, Inc.	2005(but in 2011, it ceased operation)	Not available
Solaria Corporation	2003	not clear(no directly related sources)
Stion Corporation	2006	from the related companies

Also, a separate study of the US patents in energy storage between 1976 and 2015 found that this particular industry is fairly different from the other ones composing the solar PV sector. While the handful of very large producers of flat glass basically captured the solar glass industry, and the solar cell competition is international and opposes at least fifty companies of different sizes, and countries the energy storage industry is also very competitive, with very large firms (car producers such as Tesla, Ford and GM, and multi-technology corporations like Bosch, LG, Samsung and Siemens) and companies of different industries and technology assets.

The solar sector thus includes several different industries, and is characterized by large variation, and increasingly complex products. If at the origins, solar panels were covered with ordinary glass, and were fixed and unable to track sun movements, today they are becoming increasingly complex products. Most of these products are supported by the state through national research institutes, academic research, FIT, and the usual panoply of financial support of OECD and emerging country governments for R&D and innovation.

3.3.2.2. Critics of the PLC-ILC theories

We have examined different approaches that analyse industry evolution. The most cited, and decades-old one, is the PLC-ILC approach, proposed in the 1960s by Raymond Vernon, and developed by Steve Klepper in the 1990s. Both approaches argue that products are born in the richest countries – most often the United States - where the first imitators also appear. These products then adjust themselves to market conditions, through innovation until a dominant design emerges. At this moment, product innovation starts receding while process innovation increases. The new product is exported to less affluent countries where a second cohort of imitators appears. Economic concentration rises and large firms dominate the industry. The entire industry tends to be delocalized to emerging countries where costs are smaller than in the original innovating country. In these PLC-ILC models, as soon as the dominant design is widely adopted, innovation declines.

The sectoral innovation system proposed by Malerba (2002) builds on the PLC-ILC perspective and adds a few important dimensions. It argues that the institutions, the markets and the technological conditions under which they are born model sectors. Sector perspectives are more convenient than industry ones: most modern complex products and services are composed of different industries. They are seldom composed by just one industry, narrowly defined by SIC or NAICS codes. In addition, other authors (Niosi, 2000; Saviotti, 1996) have noted the phenomenon of rapid product variation, a phenomenon that does not disappear in science-based industries and sectors, as argued by the PLC-ILC approach; on the contrary, variation increases over time, and so does product innovation. Product variation often requires the contribution of products and services from other industries. High-tech solar panels require advanced glass, and/or mechatronics sunlight trackers, while using a particular type of semiconductors (solar cells).

In addition, product variation produces industrial growth by the expansion of industries that participate in the new product (Metcalfe et al, 2006). Such expansion translates into aggregate economic growth. In the same direction, Saviotti and Pyka (2004) argued that economic growth occurs most often by the creation of new sectors.

The evolution of the solar PV sector has confirms the hypotheses 4, 5 & 6 we postulated for this chapter. Some aspects of the PLC-ILC approach are substantiated: the industry moved from the United States to Europe and now is moving to East Asian countries. But innovation is not receding – quite the contrary – due to the support by governments in the three cohorts of countries.

3.4. Conclusion and policy recommendation

3.4.1. The influencing factors model

Based on the evolution of the solar PV sector, the influencing factors model has been forwarded. (see Figure 3.5)

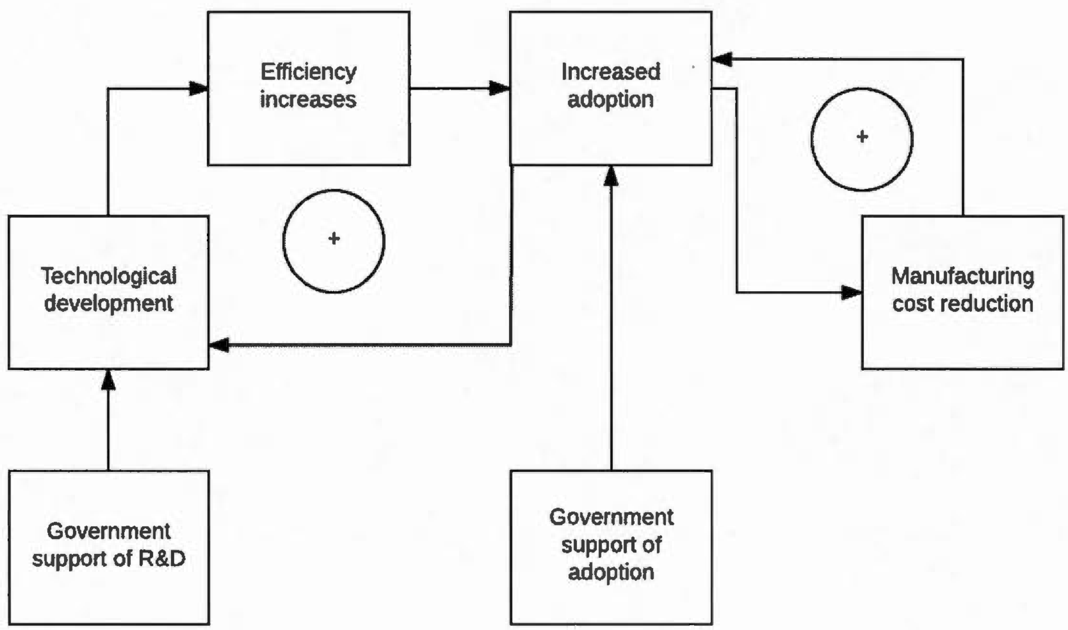


Figure 3.5 The influence diagram of the solar PV sector innovation and production system

3.4.2. policy and managerial implications

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The data analysis confirms the hypotheses 4, 5 &6 that we postulated in this chapter. The number of innovators and producers keeps expanding over time, and no dominant design is in sight in solar cells, with so many technologies competing for a rapidly growing market.. The industry produces an ever-increasing number of solar panels, and the number of different batteries for these renewable energy systems also keeps growing. Innovation expands and has been growing for the last fifty years, no end appears as of today. However, some aspects of the PLC-ILC approach are substantiated: the industry moved from the United States to Europe and now is moving to East Asian countries. But innovation is not receding – quite the contrary – due to the support by governments in the three cohorts of countries.

The policy and managerial implications are substantial. If the industry followed a rigid sequence, the policy opportunities would not be so important. Conversely, if science-based industries follow a dense and variegated bushy pattern instead of a linear arrangement, then policy opportunities are many. In the case of the solar sector, governments may decide to support one or the others of the solar cell paths, or participate in one of the components, such as solar cells, advanced glass, new batteries, micro-grids, solar trackers or even software optimizing the use of the solar equipment within large grids.

At the firm level, companies (and governments) have the choice: they may try to position themselves as suppliers of key components for product assemblers (i.e. solar cells, solar glass, batteries), within global supply chains, or enter in the adoption phases and become just adopters.

CHAPTER IV

THE CATCH-UP OF THE CHINESE SOLAR PV SECTOR

4.1. Introduction

Catching-up is the essential part of the economic development process of countries behind the technological and economic frontiers, which involves learning and mastering ways of doing things in the leading countries of the era (Mazzoleni and Nelson,2007). Practices in advanced economies do usually provide a model, but what catching-up countries achieve inevitably differs in various and important ways from the existing templates.

The debate about catching-up was launched as a macro-economic issue and was centered on productivity as the main indicator of catching up since 1960s. Gerschenkron (1962) explicitly described the development problems of continental Europe during the second half of the 19th century as that of catching up. Abramovitz (1986) has made the concept of catching-up part of the standard vocabulary of development economists, and stimulated a number of empirical studies. Freeman (2002) used the examples of the development of United Kingdom in Britain in the 18th century and the United States in the second half of the 19th century to underline the importance of continental, national and sub-national innovation systems for catching-up. At the same time, the debate on catching-up has been moved from macroeconomics to sectoral level. According to Kitschelt (1991), the description of sweeping aggregate national patterns may hide considerable policy variance across industrial sectors within each country, and the success of industrial strategies may depend more on sectoral governance structures than on national ones. Furthermore, national conditions constrain the learning processes of both industrial capabilities and governance structures. Sectoral and national-level conditions interact in shaping governance structures and innovation strategies, so besides national-level conditions, catching-up study on sectoral level is useful. Most of the sectoral-level catching-up is related to technology-based view (Porter, 1990; OECD, 1992; Hobday, 1995; Kim, 1997a and 1980).

Lee and Lim (2001 and 2004) have identified three different patterns of catch-up: a path-following catch-up, which means the late-comer firms follows the same path taken by the forerunners; a stage-skipping catch-up, which means that the late-comer firms follows the path but skips some stage, and thus saves time and investment funds; and a path-creating catch-up, which means that the late-comer firms explore their own path of technological development.

For the path-following catching-up, there are abundant research results. In-depth case studies of countries catching up in the production and use of particular technologies have been made (see especially Ames and Rosenberg, 1963;Habakkuk, 1962; Von

Tunzelmann, 1978; and many others), and some of the international trade and growth models are established (see Posner,1961; Gomulka, 1971, Cornwall, 1977, Dosi and Soete, 1988). All the findings put the emphasis clearly back on the historical context and the institutional framework within which the process of imitation/technological catching-up takes places. It includes the importance of 'developmental' constraints, primarily economic (such as the lack of financial or natural resources) or more political in nature, the role of immigration (Scoville, 1951) and other 'germ carriers', the crucial role of governments (Yakushiji, 1986) and the role of historical accidents. But according to Arthur (1988), the path-following catching-up characterizes the increasing returns associated with industrialization and development which make the conditions of development so paradoxical: previous capital is needed to produce new capital, previous knowledge is needed to absorb new knowledge, skills must be available to acquire new skills, a certain level of development is required to create the infrastructure and the agglomeration economies that make development possible. It is within the logic of the dynamics of the system that the rich get richer and the gap remains and widens for those left behind.

There are not many cases of stage-skipping catch-up and path-creating catch-up so far, but obviously, the catch-up of Chinese solar PV sector is not in the track of path-following catch-up, it should be in the scope of either stage-skipping or path-creating catch-up. China has been the country with the highest production of solar cells for several years since 2007 and listed as the biggest added market in the world since 2010. Furthermore, when several big companies in Europe closed their manufacturing of solar cells, Chinese solar PV cell manufacturers acquired the related facilities worldwide. It is very interesting to explore the development of the Chinese solar PV sector to get the exact understanding of the special catch-up.

Zhang and Gallagher (2016) found that main drivers for PV technology transfer from the global innovation system to China are global market formation policy, international mobilization of talent, the flexibility of manufacturing in China, and belated policy incentives from China's government. Zhang and White (2016) found that the global entrepreneurship can contribute to the development of a local ecosystem, in addition to their passive and involuntary role as a source of spin-offs by making the research of China's solar PV ecosystem. The early entry start-ups developed very well in terms of production capabilities by overcoming the great "liabilities of newness", building an effective organizational capability and establishing the legitimacy of the private Chinese solar PV firm as a viable organizational form, both domestically and abroad. Luo et al (2014) found that returnees positively influence patenting activity and also promote neighboring firm innovation in Chinese Photovaltaic sector, it is verified that firms with returnees in leadership roles do more patenting. Fu (2015) found that till now, the private firms are the major force in undertaking R&D and transforming scientific into production technologies and ultimately commercializing them for the market. Zhang et al(2014) defined that the growth of both solar PV manufacturing capacity and deployment in China followed a very erratic path. The most important reason are events which shape the wider policy priorities of China's government. Secondary factors include the government's poor management of the policy interaction between the domestic solar PV manufacturing industry and the deployment of solar PV across the country, as well as policy learning within government. Zhang et al(2013) and Zhao et al (2013) found that China's solar PV power which is less cost-competitive has benefited less from the law and relevant policies. It was not until 2009 when the government rolled out measures to boost its domestic solar market for the purpose of weaning the country's solar PV industry off dependence on overseas market that solar PV power market in the country started to grow rapidly.

In this study, the development of Chinese solar PV sector before 2011 is explored because nearly all the catching-up processes are accomplished before 2011, and the later developments are aimed at maintaining the leadership in terms of market position.

4.2. Literature review

Some studies have probed in detail the key processes involved in catching up (Hobday, 1995; Kim, 1997, 1998; Kim and Nelson, 2000) and some factors have been formulated to explain how the catching-up happened, such as governmental support (Perez and Soete, 1988; Lee, 2005;Mazzeloni and Nelson, 2007), a reasonable level of productive capacity (Perez and Soete, 1988; Lee, 2005, Liu, 2008), sufficient endowment of qualified human resources in the new technologies (Perez and Soete, 1988; Lee, 2005, etc.), location advantages (Perez and Soete,1988) and intellectual property rights regimes (Mazzeloni and Nelson,2007). Here, the literature from these standpoints will be employed to study the Chinese solar PV sector.

4.2.1. The new techno-economic paradigm

From the standpoint of a macro-environment, the technology-related catch-up always appears within the new techno-economic paradigm. The term of techno-economic paradigm is introduced by Perez (1984) and it shows that the new technology diffusion has many impacts across the economy and eventually also modifies the socio-institutional structures. Such a meta-paradigm is the set of the most successful and profitable practices in terms of choice of inputs, methods and technologies and in terms of organizational structures, business models and strategies, and it can bring the valuable opportunity for catching-up. Five technological revolutions in 200 years including the industrial revolution in England started in 1771, the age of railways, coal and the steam engine started in 1829, the age of steel, electricity and heavy engineering started in 1875, the age of oil, the automobile, petrochemicals and mass production started in 1908 and the age of information technology started in 1971 are all the good new techno-economics examples(Perez, et al, 2011). According to Perez and Soete (1988), each new techno-economic paradigm required, generated and diffused new types of knowledge, skills and experience and provided a favourable environment for easy entry into more and more products within these systems. Paradigm changes have historically allowed some countries to catch up and even to surpass the previous leaders. Lee and Lim (2001) believe that by taking advantage of new techno-economic paradigms, some countries make quick progress and save time because they achieved some leapfrogging or skip some stages or even created their own path which is different from the forerunners. Lee (2005) also stated that the arrival of a new techno-economic paradigm could serve as a pull factor for leapfrogging.

According to Perez and Soete (1988), the life cycle of such a techno-economic paradigm is composed of a series of interrelated technology systems. There are four phases in the technology life-cycle model: introduction, early growth, late growth and maturity phases (See Figure 4.1, Source: Perez and Soete, 1988; Lee, 2005).

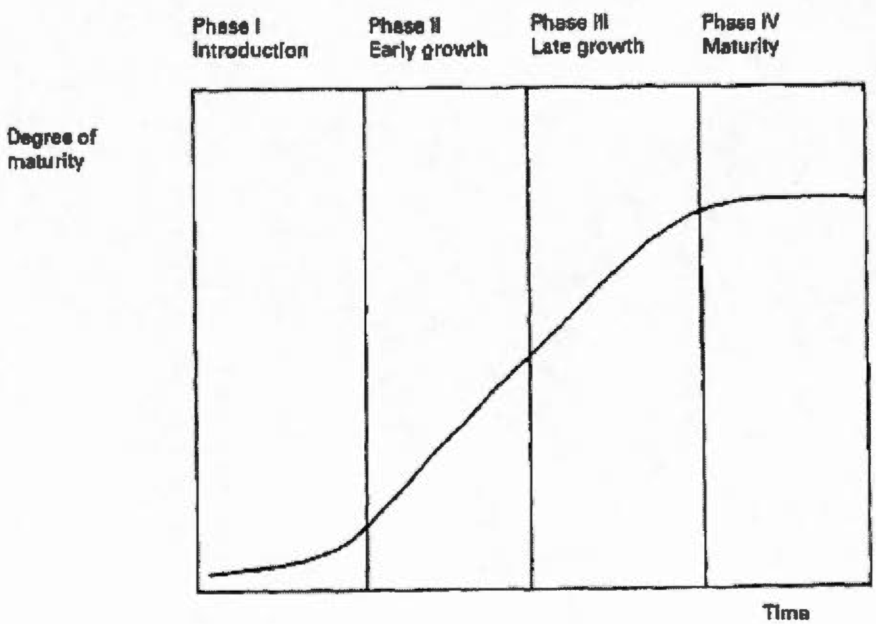


Figure 4.1The life cycle of technology

One of the important reasons for studying the new techno-economic paradigm is that it can temporarily open the window of opportunity for catching-up if some requirements are satisfied (Perez and Soete, 1988; Lee, 2005). By matching the development trends of production and patents of the solar PV sector worldwide with the shape of the life cycle of technology, it can be seen that the early years of the 21st century represent the introduction phase of the solar PV sector, which means that the new techno-economic paradigm of solar PV sector is beginning. This new techno-paradigm provides the valuable opportunities for developing countries to catch up. So what it would take for developing countries to catch up or what does it in the early growth?

4.2.2. Government support

It is not new that governmental involvement is important for developing countries to catch up (Perez and Soete, 1988; Archibugi and Pietrobelli, 2003; Lee, 2005; Mazzeloni and Nelson, 2007). The development of solar PV sector worldwide has provided the rich experience in this domain in German and China (Grau, et al. 2012).

Teubal (1997) has classified the industrial policies into two categories, one is Vertical Technology Policies (VTP) and the other is Horizontal Technology Policies (HTP). The formers target one specific sector and supporting one specific technology as the standard nationwide. The latter is aimed at supporting various classes of socially desirable technological activities (SDTAs), such as firm-based R&D and innovation, technological infrastructure (both 'basic' and 'advanced'), and the transferring and adoption of new technologies. Both are deemed effective to promote SDTAs across sectors and technologies, their importance deriving from being central components of government inducement of technology-based structural change in a wide variety of conditions (for newly industrialized countries, NICs), including situations with scant capacity to identify strategic sectors or technologies.

Are HTP or VTP better for the catch-up countries in the new techno-economic paradigm? There are two risks with leapfrogging: the risk involved in choosing the right technology or standards and the risk of creating initial markets (Lee, 2005). As governments can play the important role of facilitating the adoption of specific standards and thereby influencing the formation of markets at the right times, public support from governments is crucial, especially for a new techno-economic paradigm. But in the introduction phase of the new techno-economic paradigm, nobody including government knows what is the suitable technology standard for the sectoral development and how to promote the formation of the market because there is lack of previous experience. In these circumstances, it is better to get direct government "help" in a general way. It comprises government subsidies of all sorts, preferential interest rates, R&D grants, tax reductions, protective barriers, and any other form of direct or indirect absorption of what would otherwise have been a cost to the firm (Perez and Soete, 1988).

So here is our first hypothesis: for catch-up in the introduction stage of new techno-economic paradigm, government support with HTP is more feasible.

4.2.3. Entrepreneurs benefit from the transnational technology diffusion

Nelson and Phelps (1966) put forward the hypothesis that the level of the gap between the technology frontier and the current level of productivity is closely dependent on the level of human capital. Welch (1975), Bartel and Lichtenberg (1987), Benhabib and Spiegel (1994), Foster and Rosenzweig (1995) and Castles Davidson (2000) documented the role of human capital in facilitating technology adoption. As to human capital in the new techno-economic paradigm, more attention should be paid to the entrepreneurs who is benefiting from the transnational technology diffusion. There are very substantial implications for economic growth and development involved in whether a nation's scientific infrastructure leads to the emergence of numerous entrepreneurs with foreign education bacground and is conducive to their involvement in the commercialization of their discoveries.

According to Perez and Soete (1988), much of the knowledge required to enter a technology system in its early phase is public knowledge available at universities, although many of the skills required must be invented in practice. This implies that, given the availability of well-qualified university personnel, a window of opportunity opens for relatively autonomous entry into new products in a new technology system in its early phases, which is more important for international technology transfer, especially when the diffusion of major new technologies is hampered in some of those countries by the heavy investment outlays in the more established technologies, the commitment of management and the skilled labour force to them and even by the research geared towards improving them. In this situation, when the entrepreneurs with advanced university training abroad in specialized areas came back to their less-developed home country, they may become the seeds to promote the industrial development in the less-developed country, so that the catching-up can be accelerated.

So here the second hypothesis is drawn: In the introduction stage of new techno-economic paradigm, entrepreneurship with the educational experience in the developed country is one of the essential components for catch-up.

4.2.4. Production capability vs. technology capability

It is no doubt that technology has played the important role in the catching-up. Many studies show that more than 50 percent of economic growth in advanced countries stems from technological innovation (Grossman, 1991). But the technology capability can only be improved by integrating knowledge in the production process. Perez and Soete (1988) stated that a real catching-up process can only be achieved through acquiring the capacity for participating in the generation and improvement of technologies as opposed to the simple 'use' of them. This means that being able to enter either as early imitators or as innovators of new products or processes need the integration capability organically consisting of technology capability and production capability.

In order to better explore the drivers of catching-up, some papers have made the distinction between production capacity and technological capacity. According to Bell and Pavitt (1992), production capacity covers the knowledge and organizational routines apt to run, repair, incrementally improve existing equipment and products, while technological capabilities involve the skills, knowledge and organizational routines needed to manage and generate technical change. It increasingly happens that the kind of activities that foster the accumulation of the latter involves specialized R&D laboratories, design offices, production engineering departments, and other organizations. By measuring the degree of catching-up separately in terms of world market shares and in terms of technological capabilities, Lee and Lim (2001) try to explain the different records and prospects of Korean industries in the national catching-up. They found that the differentiation between production and technology capability can be used to explain why some industries have achieved a remarkable catching-up or leapfrogging and continue to have good prospects for the near future, whereas others are facing serious difficulties after a certain level of catching-up.

But the technology capability and the production capability are interactive and inseparable. Industrial development is the process of building technological capabilities through learning and translating them into product and process innovations in the course of continuous technological change(Pack and Westphal,1986). From a strategic perspective, the task of the latecomer is to devise ways of catching up by securing access to the knowledge and technology controlled by advanced firms in advanced countries. This requires them to understand the character and driving forces behind the industrial dynamics that govern the spread and diffusion of industrial processes and technologies around the world(Mathews, 2006).

Liu (2005) found that the most important capability for Chinese sector development is that Chinese companies can integrate market knowledge, technology opportunity and alliance capability in a fast way. Lee (2005) setup a common element of catching-up, i.e., to enter new markets segments quickly, to manufacture with high levels of engineering excellence, and to be first-to-market by means of the best integrative designs. Lee and Lim (2001) added that although technological capabilities are one of the most important elements, among the many determinants of market competition, such as manufacturing efficiency, marketing, logistics, and so on, success in market competition can earn the firm the extra revenues much needed for R&D investment. So it seems that integrative production capabilities, consisting of both technological capabilities and product capabilities, are very important for catching-up.

Here the third hypothesis is drawn: In the introduction stage of new techno-economic paradigm, integrative production capabilities integrated with technological and production capabilities are important for industrial development.

4.3. The Chinese solar PV sector

4.3.1. Government support before 2011

It is widely accepted that the development of solar energy sector is strongly dependent on the governmental supporting policies such as the market support programs, which is acting as the main driving force for the development of PV sector by serving customer needs with the competitive cost. Since the 1990s, several countries, especially in Europe, have setup market support programs to create the corresponding market (Table 2.1).

Chinese vertical sector policies for the solar PV sector before 2011 has been as follows:

- In 1996, Chinese Brightness Program scheduled to run with the aims of providing 100 watts of PV electricity to about 23 million poor people with no electricity at that time until 2010was setup.

- In 2006, government began to invest money into several solar energy projects such as the Township Electrification Program and the rooftop program in Shanghai and Wuxi. Also, Renewable Energy Law was taking effect at the beginning of 2006. By law, China planned to increase its renewable energy consumption to a full 10%

by 2010 (which is accomplished) and required grid operators to accept the electricity from registered renewable energy producers. A fund was set up to offer financial incentives to encourage the development of renewable energy projects and some very clear penalties for non-compliance were included(Ma, 2012).

- On July 24,2011, the Chinese central government settled the feed-in tariff (FIT). But by comparing it with the law in other countries[7], the Chinese support appeared too weak. Due to the lack of a detailed regulation on the duration, the regional variation, the project application process and how to access the electricity grid, the Chinese FIT law had a quite limited effect for promoting the Chinese PV sector (Liao and Xu, 2012).

When comparing the market support programs with those of developed countries including Germany, Italy, Japan and the United States, we cannot find any advantages in support policies in China, which are either more innovative or more workable than other countries before 2011 (Table 4.1). Without the establishment of a solid domestic market, 90% of the Chinese solar PV products were exported from 2005 until 2010, and then went down since 2011(Figure 4.2).

But even without the strong vertical sector policies (not to mention vertical technology

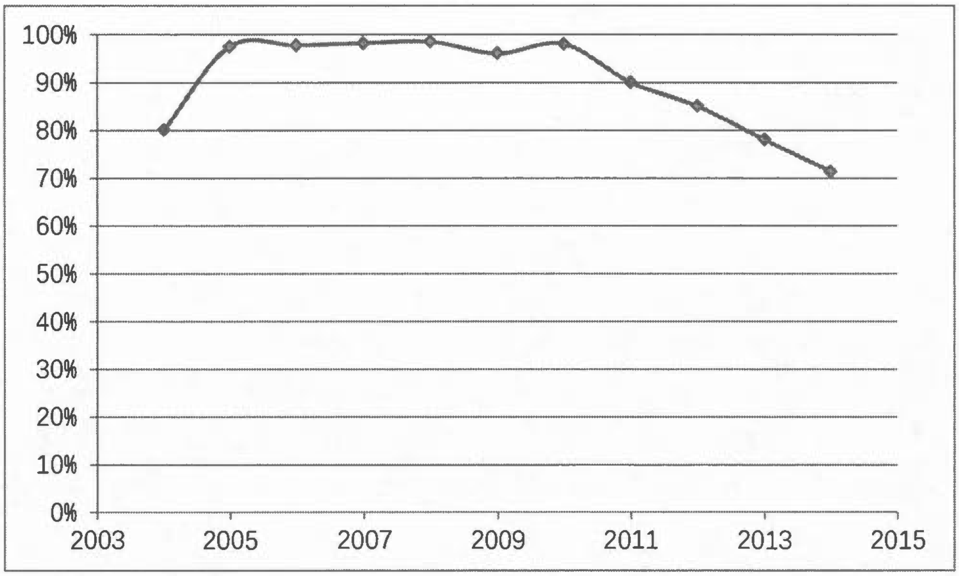
[7]Germany introduced the law in 2004, which proved to be very effective and regarded as the main driver for further cost reductions and a transition to economies of scale. Japan, the United States, Spain and Italy also issued the regulation following Germany to support the photovoltaic industry including a subsidy tariff provisions and fixed the share percentage for electricity enterprises to buyout.

policies), why can the Chinese solar PV sector start, survive and then thrive?

Table 4.1 Comparing the industrial supporting policies in different representative countries

Policy categories	**Germany**	**Japan**	**U.S.**	**China**
Feed-in tariff	Available	N.A.	Available in California	Available but not workable
Net metering system	N.A.	Available	Available	N.A.
Investment subsidy	Available	Available	Available	Available
Tax reduction	Available	Available	Available	Available
Rooftop program	Available	Available	Available	Available just for pilot program

Source: Liao and Xu (2012)



Source: data before 2011 are from China Chamber of Commerce for Import and Export of Machinery and Electronic Products(Yin, 2011), data 2012-2014 are from Chinese Academy of Engineering quoted from National Energy Administration

Figure 4.2 The percentage of exports in Chinese solar PV equipment production

Fortunately, although there are no effective VTP at the national level, some regional innovation policies that aim at supporting the development of high-tech industries in general helped the development of Chinese PV sector.

Until 2012, about 70% of Chinese PV cells were manufactured in the province of Jiangsu. It is interesting to see what they have done to promote the development of the sector. Wuxi, where Suntech (the biggest producer of Chinese solar PV sector before 2012) is located, is in the province of Jiangsu. Wuxi, one of the several well-developed cities in the province, has its distinctive regional innovation system and horizontal innovation policies. Similar to Shanghai Zhangjiang mode[8], the Wuxi innovation-promotion model is characterized by the openness in terms of establishment of a friendly and warm microenvironment to encourage innovation and entrepreneurship: the performance is assessed not just based on the highest rate of GDP growth; it tries to establish the links with the Top 500 entrepreneurship in the World and provide the Chinese abroad with capital to attract them to return to China; it creates seed funds and incubator funds with the intention of long-term development but not short-term profit; it encourages risk-taking and tolerates the failure of innovation; it provides the package of professional services including financing, law, accounting, headhunting, marketing, equipment leasing and retail; and it establishes the infrastructure for a high quality of life for the high-tech talents and entrepreneurs. With the HTP packages, the Wuxi government has become a strong supporter of the solar PV firms in the beginning stage, such as Suntech.

It is said that the establishment of Suntech has shortened the technology gaps between Chinese solar PV sector and those in the developed countries for at least 15 years[9]. In

[8]In China, three categories of regional innovation systems models are regarded as being effective, i.e. the Beijing Zhongguancun model dominated by the government and with the characteristics that most of R&D activities are conducted by governmental research organizations, the Shanghai Zhangjiang model is promoted by the government and marketed together, in which companies conduct actively R&D integrated with the strong industrial base and the effective interaction in the Yangtze River Delta economy zone, and the Shenzhen model in the province of Guangdong is characterized by the technology transferring from the outside of the company and then absorbed internally with the driving of the strong innovative and entrepreneurial spirit.

[9]http://www.china-apt.cn/news/news_show.aspx?id=1712

the process of initiating Suntech, support from Wuxi local government is essential:

- Dr. Zhengrong Shi got the financial and social network support from Wuxi Government when he came back from Australia as a poor student. At that time, he just collected US$ 400,000 by himself as the initial capital for launching the business. But this amount is far from what is needed to launch a solar PV manufacturing factory; it is not even enough to buy the producing equipment. In such circumstance, government officers not only persuaded the six local companies, Jiangsu Xiaotian Co. Ltd, Wuxi Guolian Trust Co. Ltd, Wuxi Shuixing Co.Ltd, Wuxi High-tech Investement Co.Ltd, Wuxi Ventural Capital Co.LTd and Wuxi Shanhe Co.Ltd, to invest US$6 million in cash in Suntech by taking 75% share of Suntech, but also persuaded all the six investors to reward Dr. Shi with US$1,600,000for his patents and technologies as the corresponding shares in Suntech. All the help was so vital for Dr. Shi that without the help from the government, he would not have been able to start Suntech.

- The most valuable incentive is that just before Suntech was listed in the New York Stock Exchange, the Wuxi government withdrew from the board of directors, giving more decision power to Dr. Shi to play in the world arena.

The Wuxi government has provided a lot of other help including tax returns, financing, good benefit packages for experts recruited, etc. What the Wuxi government has done is nothing uniquely related to the PV sector but a common practice with Horizontal

Technology Policies. In the initial stage of catch-up with the technology choice risk and market formation risk, it is wise to provide the HTP in a wider scope to support all the possible industries, and let the strongest win while some are eliminated by the market.

When the Chinese central government did not issue very strong supporting policies, the horizontal technology policies at the regional level provided the most valuable support.

4.3.2. Human resources

Crystalline technology (c-Si) (the first technological generation for PV sector) accounts for more than 90% of the actual PV systems in the market. The reason why its presence is so high is because it has used most the technological and R&D efforts of the semiconductor industry for the electronics sector since the 1960s. All the Chinese PV companies adopted c-Si technology for manufacturing before 2011. In the process of technology transfer, entrepreneur with the education experiences in the developed countriess with the experience of studying and working in the developed countries play a very important role.

It is widely accepted that Suntech was the original technology base in the early years of the development of solar PV sector in 2000s, and most of the technologists and engineers in the late-established companies have worked for Suntech[10]. Dr. Zhengrong Shi, the former president and CEO of Suntech, is the key person not only as the founder but also as the technology developer. Actually, Dr. Shi is the typical Chinese scholar entrepreneur with study and work experience abroad. After obtaining his bachelor's and master's degrees in China, Dr. Shi was sent by the Chinese government in 1988 to study at the University of New South Wales, Australia. He got a Ph.D. in 1991on innovation of poly-silicon thin-film solar cell technology. As one of the best Ph.D. students of Professor Martin Green, winner of the "The Right Livelihood Award" in 2002, Dr. Shi achieved performance excellence first in his studies and then in his work on thin-film technology innovation in Australia. During his career as executive director at the research centre in the university and Australia Pacific Power Co., Ltd., Dr. Shi personally held 6 USPTO patents[11]. In 2001, Dr. Shi returned to China and setup Suntech Power Co., Ltd. He knew the PV technology and the production of the modules so well that he had the confidence to buy second-hand production equipment from the U.S. He established the working teams and guided the workers to manufacture the solar PV cells. At that time, all the technologies and the production capabilities of Suntech were technologically and efficiently superior to the other PV companies and this brought the big change for the whole Chinese PV sector and also was the key factor for the later success of Suntech itself.

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[10] A CEO's comments on the bankrupts of Suntech , 2013-04-22, http://news.imeigu.com/a/1366636502643.html,

[11] The patent number in USPTO are: US Patent 5942050, US Patent 6624009 B1, US Patent 6420647 B1, US Patent 6538195 B1, US Patent 6551903 B1, US Patent Application Publication US 2009/0007962 A1

Dr. Jianhua Zhao, classmate and colleague of Dr. Shi's in Australia, with a similar study and work experience as Dr. Shi, also later founded and developed CSUN Corporation, a NASDAQ-listed leading manufacturer of solar cells and modules.

To some extent, it is that group of the returned scholar entrepreneurs who explored the opportunities and developed the sector. Their knowledge and experience obtained in the developed countries are the most important factor for the catch-up of solar PV sector in China.

It is estimated that there was a total of 400-500 thousand workers in the PV cell and module manufacturing sector in 2012 in China, most of them from three sources[12].

- Domestic researchers in universities transferring from relevant areas. Many universities have established research institutes on PV, for example, the Green Building and Energy Center in Tongji University, the Solar Energy Materials Laboratory in Guangzhou Institute of Energy subordinating to Chinese Academy of Sciences, the Solar Energy Research Institute of Shanghai Jiao Tong University, the Solar Systems Research Institute in Zhongshan University, etc. Most scientists in these research organizations transferred from the related domains such as physics and materials science, which is becoming an important driving force of

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[12] Workforce of Chinese PV industry, 2011-08-16, http://www.360doc.com/content/11/0816/20/7197533_140887040.shtml,

technological innovation of the sector.

- The employees transferred from the semiconductor and other related industries. In these related industries, the employees are well trained and have relevant knowledge, and experienced a similar mode of sector development and change. Not only at the beginning but also in the late stages, more and more skilled workers in the semiconductor, electronics and other industries are fleeing to the photovoltaic sector since the sector has become more and more attractive.

- Technicians and workers from school-enterprise cooperative training programs. Many PV companies sought to launch the cooperation with the institutes of technology to get qualified workers, thus some colleges have been setup: Suntech College in Wuxi Institute of Technology sponsored by Suntech and CSI Photovoltaic Technology College in Changshu Institute of Technology sponsored by Canadian Solar Inc. (CSI). There are some companies cooperating with local educational institutions, although not in title, but with a consensus or alliances to get the students to be qualified for PV industries. Xinyu College hired some engineers and technicians from LDK Solar Hi-Tech Co., and Jiangxi Sun Optoelectronics Technology Co. has sent some employees as part-time teachers to train the students.

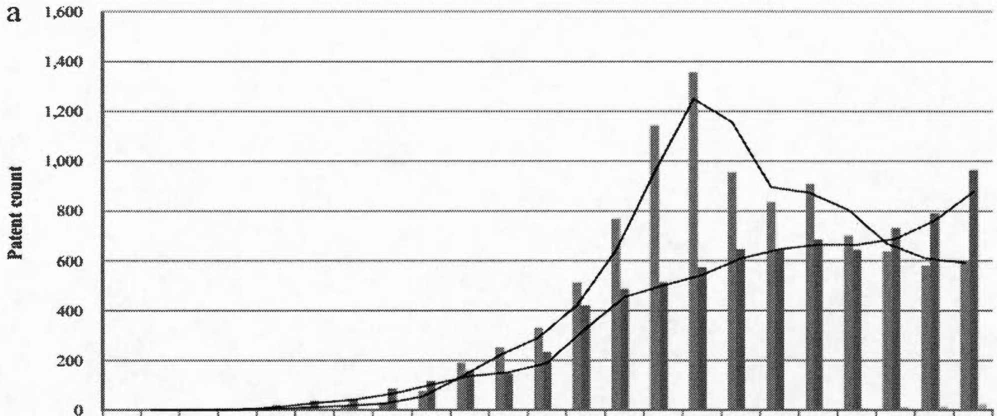
The review of the sector shows that it is the entrepreneur with the education experiences in the developed countries that played key roles for initiating and developing the

Chinese solar PV sector. With its entrepreneurship spirits and risk-taking efforts, the sector can develop and thrive, the demand for human capital can be created, and human capital can be accumulated in China, all of which are basic elements for catch-up.

4.3.3. Integrative production capability

The technology capability of Chinese solar PV is not so strong. By establishing a new database of 19,105 solar photovoltaic patents taken out by Taiwan, Korea and China at the USPTO over 24 years (1984–2008), Wu and Matthews (2012) analyzed the knowledge flows revealed in these patents using a set of 12 International Patent Classification technology categories, and they found that China still exhibits a low degree of patenting in the emerging new generations of technology (Figure 4.3 & 4.4).

a

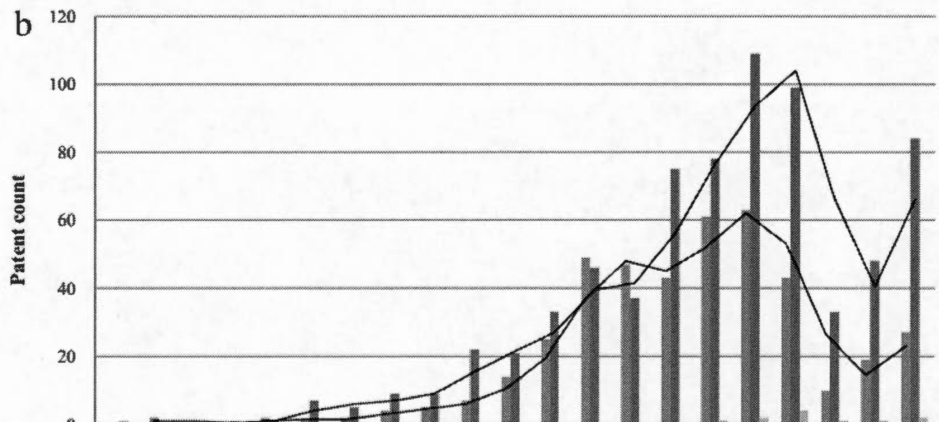


	1984	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Taiwan	1	2	2	5	5	14	20	32	77	190	252	330	512	768	1143	1356	955	836	909	700	637	581	602
Korea	0	1	0	4	20	38	46	87	117	158	146	233	421	487	514	572	646	646	685	644	732	790	965
China	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0	1	1	3	4	8	12	14	24

Source: USPTO, Wu and Matthews(2012)

Figure 4.3 Annual US patents granted to Taiwan, Korea and China in 1G solar PV

b



	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Taiwan	0	0	0	0	2	1	2	4	5	7	14	25	49	47	43	61	63	43	10	19	27
Korea	0	2	0	1	1	7	5	9	9	22	21	33	46	37	75	78	109	99	33	48	84
China	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	4	1	1	2

Source: USPTO, Wu and Matthews (2012)

Figure 4.4 Annual US patents granted to Taiwan, Korea and China in 2G solar PV

The big pressure of manufacturing with low costs has impeded the pace of improving the solar energy transforming efficiency, which is the key measurement for technology progress in the solar PV sector. Even though the first generation of Crystalline technology is much inferior to the thin-film technology in terms of transformation rate and the requirement of the silicon as the raw materials, even though the entrepreneur with the education experiences in the developed countriess like Dr. Shi have the expertise and even the patents in thin-film (the second generation of solar PV technology) themselves, they cannot make their products by using the technologies in the second generation. Actually, when Suntech was already big enough to try the second generation, all the efforts of Dr. Shi who has the technology expertise and professional preference to develop the products in the most updated technology in thin-film technology failed.

- After he established the production line on thin-film technology in May of 2007 in Shanghai, the financial crisis in 2008 had reduced the price of polycrystalline as the raw material of crystalline technology from US$400 to US$50. It greatly reduced the manufacturing cost of the first generation technology, which made the manufacturing with this technology bring much higher profit than the second generation. At the same time, Applied Materials Co. in the US, whose products are regarded as the most suitable equipment for manufacturing thin-film products, declared that they withdrew the business of thin-film solar cell manufacturing equipment in July of 2010. Due to these two reasons, the efforts of Suntech in the thin-film sector did not bring any advantages; Dr. Shi decided to change from the thin-film technology to crystalline technology to rescue the sunk cost.

- Suntech setup Sichuan Suntech with Sichuan University to deploy the R&D on thin-film solar cell in 2009. But despite the investment of several hundred millions in RMB, there was no distinctive progress until 2012.

Adopting the industrial technologies is paradoxical. On one side, more and more adequate supply of silicon has released much pressure from the raw materials for manufacturing crystalline solar cells and modules, which make the production cost of first-generation technology to decrease more and more, making the product price more competitive. On the other side, the higher transformation rate has made the sector evolve into thin-film, i.e. the second generation. The Chinese solar manufacturers are facing difficulties in upgrading the technologies because they lack a way to balance production cost and technology advancement.

Technology development is becoming more and more systematic, and the efforts of one or several companies cannot support and push the technology to evolve much further. But the successful entrepreneur with the education experiences in the developed countriess, especially those with scientific background in advanced technologies, cannot contribute their technologies advantages fully.

With the weak technologies capabilities, Chinese companies tend to focus more on the technologies to improve the efficiency of the manufacturing process than on the PV technology development itself. Innovations in the Chinese PV sector are mainly related to PV manufacturing equipment such as module laminators, wafer eth/bath and monocrystalline wafer pullers, which aimed at technologically reaching the most efficient per dollar manufacturing process of the market, and neglected some important areas such as system components like inverters, batteries and control electronics which typically make up about 25% of systems costs.

It is reported that Chinese companies have had a history of being able to enter the market of different industries very rapidly and aggressively (Liu,2008). They realized the situation by technologically reaching the most efficient per dollar manufacturing process of the market, by combining a highly skilled cheap labour force and local low-priced manufactured automation equipment. By using the turnkey equipment, cheap qualified labour and low administrative costs, Chinese companies could build large PV manufacturing plants and China became the biggest manufacturing country in the world just within six years of starting operations in 2001.The Chinese PV sector has caught the PV market opportunity by quickly forming the productive capability. This strategy has given China a great competitive advantage over western companies in the new techno-economic paradigm.

4.4. Conclusion and discussion

Based on the study of Chinese solar PV sector till 2011, the results of testing the three hypotheses have been drawn:

- The first hypothesis states that in the introduction stage of new techno-economic paradigm, government support with HTP is more feasible, and it is true.

- The second hypothesis states that entrepreneur with the education experiences in the developed countriess with an education background abroad are one of the most important components for catch-up, and it is true.

- The third hypothesis states that integrative production capabilities integrated with technological and production capabilities will be important for industrial development, and it is false. In the catch-up stage, production capabilities are more important.

In fact, the situation of the Chinese PV sector has changed a lot since 2011.With the European debt crisis worsening, the European photovoltaic market, which always depended on governmental subsidies, has decreased due to fewer governmental subsidies. The 70% decrease of the demand from Europe has brought even fiercer competition among the Chinese solar PV manufacturers with lower price and lower profits. On November 8, 2011, the U.S. Department of Commerce officially initiated anti-dumping and countervailing duty investigations of the Chinese exports to the U.S. solar cell. SolarWorld, the U.S. solar equipment manufacturer, asked the U.S. government to charge a 49.88 to 249.96 percent levy anti-dumping tax and countervailing duties to Chinese exporters, which makes the situation of China's photovoltaic sector even worse. With several unfavourable factors, the Chinese solar

PV sector has entered into a difficult stage.

According to Lee and Lim (2001), sustained long-term increase in market shares is very difficult if it is not accompanied by increases in technological capabilities. If these firms do increase their technological capabilities, they will find it more and more difficult and expensive to buy the more advanced technologies needed for higher-level market shares. Perez and Soete (1988) stated that whether the endogenous generation of knowledge and skills will be sufficient to remain in business as the system evolves is the big problem, which requires not only constant technological effort but also a growing flow of investment. Development is not about individual product successes but about the capacity to establish interrelated technology systems in evolution, which generate synergies for self-sustained growth process.

Although Chinese PV companies have done well in the global markets, it is hard to see whether the advantage in the initial stage can be maintained in the later phases. They may lose their market position very rapidly in the future by lacking the necessary R&D input on thin-film or even the other future generations of the disruptive technologies that are of steeper learning curve and may change the market situation very fast. So it can be concluded that catching-up in production only is not enough; otherwise, if the technological basis of the sector changes, the catching-up effect disappears. Even in a specific sector, becoming a leader in production without a sound effort on the innovation front may become a very unstable and passing production leadership.

But Chinese Solar PV has the big potential of developing further due to the following reasons:

- Considering that more than 70% of the Chinese solar PV products are exported to other countries, Chinese solar PV has a very big domestic market untapped. It is expected that increased PV presence in China would result in more experience for the sector itself, and efficiency and quality improvements would naturally follow. After 2011, some policies to stimulate the domestic consumption begin to work well.

- Technology capabilities are on the way of being strengthened. According to Wu et al (2012), in the new generations of solar PVs (2G and 3G) technologies, China emerges as a leader assessed by the local-citation amongst the three countries, and 83% of the patents are owned by academia and tend to be more science-based, which indicates that China could well be pursuing a leapfrog strategy straight to the newer technologies.

Whether China can maintain the market position and at the same time upgrade the technologies for manufacturing is still in doubts. We will present our other studies to track the development of Chinese solar PV sector later.

CHAPTER V

ANCHORED CLUSTERS: THE RISE AND FALL OF SOLAR PV AGGLOMERATIONS

5.1. A theoretical introduction

High-tech industries tend to cluster in geographical regions. Different explanations for such agglomerations have been proposed, including the role of big corporations acting as magnets, such as large systems integrators (Perroux, 1972), externalities provided by many firms and institutions in innovative clusters (Porter, 2000, close to Marshall), knowledge-producing anchor tenants or large research intensive corporations according to Agrawal (2003), or public research institutions in Feldman (2003). The national innovation system (NIS) approach has added its own perspective, calling these agglomerations "regional innovation systems" (RIS) (Boschma, 2005; Cooke, 2001; Niosi, 2005). In a rare demonstration of unanimity, studies argue that high-tech firms in biotechnology, information and communication technology and nanotechnology[13] tend to agglomerate in a few regions in each industrial or emerging country (Swann et al, 1998; Audretsch, 2001; Niosi and Bas, 2001; OECD, 2001; Niosi, 2005; Shapira

[13]Nanotechnology « ... is the application of science to the development of new materials and processes through the manipulation of molecules and atoms. » N. Brown (2003): The Cambridge Phenomenon, p. 41

and Youtie, 2012; Mangematin and Errabi, 2012; Kupriyanov et al, 2014). Anchor tenant firms and research institutions were most often considered the originators of these high-tech innovative clusters. The main reason for the agglomeration and the long-term evolution of these anchored clusters were basically knowledge externalities produced by these R&D intensive organizations.

High-technology anchor tenants are identified as large R&D intensive firms, or research universities and public research organizations (PROs), as defined by their patenting activity, with a strong focus on a particular technological field(Agrawal, 2003; Feldman, 2003; Link et al, 2003; Niosi and Zhegu, 2010; Schultz, 2011). Anchor tenants support patenting activities of both anchor and non-anchor firms in the cluster. Anchored clusters have been identified in information technologies, biotechnology, aerospace and nanotechnology. Table 5.1 includes some for the most accepted definition of anchor tenants in the literature.

Critics have underlined the fact that these clusters are often poorly defined both in geographical and industrial terms (Amin and Robbins, 1990; Martin and Sunley, 2003). What exactly are clusters: metropolitan areas, cities, provinces, states, or all of the above? How many different and/or related industries does an agglomeration have to host in order to qualify as a cluster? Does a biotech cluster need only biotechnology and venture capital firms, research universities and venture capital? Is there a minimum threshold in terms of employees, sales or number of organizations necessary for being called a cluster? To what extent do these collocated industries need to be related in order to represent a cluster? Porter (2003) launched the idea and proposed a method of measuring relatedness based on employment. Yet, it was Boschma et al (2012), based on Frenken (2007), who used SIC and harmonized industrial system codes to measure relatedness. They found that related variety increased the chances of regional economic growth and resilience.

Table 5.1 Definition of anchor tenants

Anchor tenants defined
Korhonen and Snakin (2001): "An anchor tenant is an influential organization in the system that drives its main material and energy flows. And hence can serve as the key actor in the environmental management effort of the system." Korhonen (2001):" In this paper, a regional industrial ecosystem that relies on a power plant as its key organization, as an anchor tenant, is considered in the context of energy production and consumption." Link et al (2003, p. 1218): "An anchor tenant is a firm that generates positive demand externalities by attracting additional tenants and stimulating traffic within a commercial operation (typically a shopping mall or industrial park)." Feldman (2003, p. 320) "The Anchor Firms are more established firms with product lines that predate the biotechnology revolution but have current efforts involving biotechnology. More generally, regional anchors may encompass other institutions such as universities, government labs, research institutes and other entities." Niosi and Zhegu (2010, p. 263) "The anchor tenant is an organization, often a large innovative firm or a research university or public laboratory that produces knowledge externalities in the region where it is located." Schultz (2011, p. 560) "An anchor tenant is a firm traditionally heavily engaged in R&D with research interests in a technology being developed in the geographic area".

In addition, clusters often grow, but sometimes decline, and even disappear, without attracting much attention. Yet, some scholars have analyzed the rise of new clusters in competition with established ones (Maskell and Malmberg, 2007; Shapira and Youtie, 2008;Menzel and Fornahl, 2009), as well as the decline of some of them (Hassink, 2010; Suire and Vicente, 2009; Østergaard and Park, 2015).

In anchor-tenant regions, based on a large corporation, the anchor has a major influence on the dynamics of the cluster. It may, for instance, create new firms through spin-off formation and these spin-off firms perform better than other firms attracted to the cluster (Klepper and Thompson, 2007). Also, having a variety of innovative firms and knowledge-producing institutions seems a major factor for growth and resilience (Agrawal et al, 2014). However, the exit of the anchor tenant may play havoc with the cluster (Østergaard and Park, 2015). Conversely, in bottom-up RIS, established on a large number of small and medium enterprises, the withdrawal of venture capital support to new technology-based firms may also weaken the cluster. Rapid technological change and lock-in in inferior technologies can be a decisive factor in the decline of the regional innovation system, whether anchored or not (Boschma, 2005). In addition product life cycle (PLC) and sector life cycle (ILC) theories emphasize the fact that, as the product and the sector matures, a shakeup occurs that reduces the number of active firms, and tends to move the sector towards emerging countries, thus contributing to the decay of existing industrial regions in advanced countries. Such a process has been observed several times in the decline of the US rustbelt; the case of Detroit, once the world capital of the auto sector, is a case in point. Audretsch and Feldman (1996) suggested that in the early stages of a sector, the propensity to agglomerate geographically is strong, but this propensity declines as the sector matures. This process may be unfolding in high-tech sectors such as ICT. Other authors have pointed to regional policy failures as important factors of decay: inappropriate policy designs may also explain the weakening of some regional innovation systems.

In summary, studies of high-tech RIS have recently focused not only on the birth and growth of these systems, but also on the factors that may weaken and eventually destroy them. These factors may be internal to the agglomeration, such as lock-in into inferior technologies, the withdrawal of venture capital or the exit of the anchor tenant, but also external such as the attraction of the anchor to other regions, or the migration of technology to new regions in a PLC-ILC process. Similarly, clusters are found to promote entry, but are not necessarily conducive to promoting firm growth or survival (Frenken et al, 2015). In biotechnology regional innovation systems based on research universities, spin-offs from these higher education institutions tend to have more patents than other firms, but are not necessary more profitable or more resilient (Niosi and Banik, 2005). Thus, anchor tenants are a favourable factor to the development of a high-tech cluster, but they are neither a necessary nor a sufficient condition.

So the hypotheses are formulated as follows:

Hypothesis 1: Solar clusters agglomerate around large R&D intensive companies (the anchor tenant hypothesis in Agrawal's version)

Hypothesis 2: Solar clusters agglomerate around research universities and public R&D laboratories (The anchor tenant hypothesis in Feldman's version).

Hypothesis 3: Solar PV clusters are often semiconductor agglomerations, because solar cells – the heart of solar PV systems - are based on semiconductor related industries (the Porter/Frenken/Boschma hypothesis).

Hypothesis 4: Solar clusters are located in large metropolitan areas where many technologies and regional innovation systems coexist (the Jacobs hypothesis)

Hypothesis 5: Solar clusters are located in specialized regions (the Marshall hypothesis)

5.2. The Solar PV clusters

The solar PV sector is composed by four industries. The primary one is the solar cell sector. Solar cells are specialized semiconductors transforming sunlight into electricity. The second sector is solar glass; much more recent, this highly concentrated sector has only four major players, all of them large corporations: Guardian and Corning in the United States, British Pilkington (now a Japanese subsidiary) and French St.-Gobain. The third sector is composed of the providers of solar batteries-a fairly dispersed trade. The fourth is another dispersed sector, the one that provides metal supports for solar panels, including both metal folding and welding and mechatronics companies. The vast majority of patents are in solar cells, followed by solar glass.

Our first question was: do solar PV innovative firms agglomerate, like those in other advanced technologies, and if they do, what explains the patterns of growth, change and decline? Thus, we were interested in the dynamics of solar clusters.

Solar clusters are important because solar PV technology is positioning itself as the most likely winner in the competition between different renewable technologies that include geothermic, hydroelectric, tide, and wind. The first three of these sources of energy cannot be used in many different areas of the world for natural reasons. Conversely, the rapid advance of solar photovoltaic technologies makes them increasingly efficient in many different climates and at different levels of sun exposure. Today, solar PV technologies are competitive with any other source of energy in countries with high solar exposure, such as Italy, Spain, Portugal, and Greece, and large parts of China, Japan, and the United States, not to speak of many developing countries in Africa, Asia and Latin America. In addition, distributed energy structures minimize the cost of transmission facilities. Moreover, present day solar technologies produce electricity during the day at the times of peak demand, while improvements in battery technologies allows its conservation during the night. Furthermore, the production of electricity close to the users' location reduces the losses of electricity on transmission lines. Finally, compared to its closer competitor, wind technology, solar PV uses fewer resources such as land and capital (US National Academy of Science Panel on electricity from renewable resources, 2010).

5.3. Methodology

In order to find out what kind of regional agglomerations, if any, could be found in solar PV technologies, we used solar patents granted by the USPTO. We found other methodologies, such as production s by cluster, basically impossible to use. Many solar PV companies are private firms, particularly in the downstream segments of the sector such as the assembling and installation of solar panel. There are no s on these manufacturing and service companies. In addition, data about industrial production of solar panels or cells, are often too aggregated both in industrial and geographical terms, and therefore unusable.

We employed the US Patent Office s instead of the European Patent Office database because the United States has been the cradle of the sector between the 1950s and the 1970s, and is still the most important country in terms of invention in its key component: solar cell patents. In the most recent segment of solar glass, only four companies in the world have obtained patents, and two of them are based in the United States. Also, only the USPTO database allows us to find the location of inventors.

We distinguished solar PV patents from other ones through keywords in the abstract, such as "solar cell", "solar cells", "solar glass" and "solar glasses". US and international patent classifications are fairly useless, because solar cells are specialized semiconductors, and their production methods overlap with those of other semiconductors.

In order to classify the patents into the different clusters, the following methodologies are employed:

- Counting of the number of patents:

The counting is based on the city in the address field and the counts of distinct patents. For the patents with the multiple inventors in multiple locations, each location will be counted once even there are several inventors in that location. For example, for a patent with 8 inventors linked to 4 different cities (4 inventors in four different cities), it is counted once for each city. In our study, we looked at the count of patent across all the companies, and due to the subject of cluster in which too less patents cannot be named as the cluster, we stop the cleaning at around 9 distinct patents per cities, which representing 63% of total patents in USPTO.

- Data incomplete:

The information of City is not fully complete, and we meet the following problems and we adopt the corresponding solutions:

1) The patent by US as assignee country is just traced back up to 2006, and all the other

previous years are in the different states, we have to merge the two parts of data together;

2) There are several companies for which the information of locating city is lacking, so we have to search the company information in their website to compensate the information;

3) Both the locations of inventors and corresponding assignee names are identified. The inventors' location will be counted for the patents in certain metropolitan area, but the patentees in that area will only include the companies as the assignees in that area.

- From city to metropolitan area to country

What we got is the individual cities, but the conclusion has to be metropolitan area. So we redefined and group the cities into different metropolitan areas, the following criteria is employed:

For US: 381 metropolitan areas:
http://en.wikipedia.org/wiki/List_of_Metropolitan_Statistical_Areas (Great San Francisco, Great Los Angeles, Great boston and New York are named after merged the nearby metropolitan areas)

For Japan: 14 metropolitan areas,

http://en.wikipedia.org/wiki/List_of_metropolitan_areas_in_Japan_by_population

For Germany: 11 metropolitan areas

http://en.wikipedia.org/wiki/Metropolitan_regions_in_Germany

For South Korea: 17 metropolitan areas

http://en.wikipedia.org/wiki/List_of_cities_in_South_Korea(metropolitan cities and provinces are indicated as the different metropolitan areas, so totally 17 are found)

For Taiwan: 7 metropolitan areas

http://en.wikipedia.org/wiki/List_of_metropolitan_areas_in_Taiwan

- The definition of cluster

There are totally 103 metropolitan areas are identified, only the metropolitan area with more than 42(Nearly 1% of global patents) are defined as cluster. In this way, there are totally 23 clusters all over the world, which is 10 in USA, 7 in Japan, 2 in Germany, 1 in South Korea, 3 in Taiwan.

5.4.Results

5.4.1.The solar PV clusters in the worldwide

A preliminary analysis of the countries involved in solar PV technology patenting from 1976 to 2013 found that five of them represented the vast majority of the patents: the United States, Japan, Germany, Taiwan and South Korea were the leading inventors. Other Western OECD countries such as Australia, Canada, France and Switzerland also made important contributions (see Table 5.2).

We defined clusters as metropolitan regions, based on the definition and geographical delimitation used in each country. In the United States, we are dealing with "metropolitan areas"; in Japan they are "prefectures".

A first result was that solar PV technologies cluster like other high-tech agglomerations: the vast majority of the patents in each country were large metropolitan areas such as Greater Boston and the Greater Los Angeles metropolitan area in the United States; Tokyo, and Kyoto-Osaka in Japan, Seoul in South Korea, Munich in Germany, and Taipei in Taiwan. The only cluster that did not correspond to a metropolitan area was Silicon Valley, the largest of them all (see Table 5.3).

A second major result was that in each cluster, at least one major corporation and sometimes more than one, or a large PRO, obtained the largest share of the patents(Table 5.4). Solar PV regions are "anchored" by large firms, with one exception: in Taiwan, where the largest patentee, the anchor, is the Industrial Technology Research Institute (ITRI). In Sydney, which is a much smaller cluster, the largest innovator is the University of New South Wales School of Photovoltaic and Renewable Energy Engineering and ARC Centre of Excellence for Advanced Silicon Photovoltaics and Photonics, founded in 1975. The difference between solar clusters in Australia and Taiwan is that government-led industrialization in Taiwan did not stop after providing R&D funds to public institutions, but moved from invention to innovation to sector (Amsden and Chu, 2003), while Australia only funded academic research, and was less involved in the choice of the corporate user of its technology. Thus Taiwan is among the largest patentees in solar PV technology and the second largest exporter of solar equipment; Australia has few patents and little production of this equipment.

Table 5.2 USPTO solar PV patents by country, 1976-2013

Country	Solar PV patents granted by the USPTO		Solar PV patents granted by the USPTO (cumulative %)
	Number	Percentage of world total	
USA	2187	48.83%	48.83%
Japan	1023	22.84%	71.67%
Germany	414	9.24%	80.91%
Taiwan	221	4.93%	85.85%
S. Korea	211	4.71%	90.56%
UK	50	1.12%	91.67%
France	40	0.89%	92.57%
Switzerland	43	0.96%	93.53%
China*	38	0.85%	96.63%
Canada	34	0.76%	95.02%
Netherlands	34	0.76%	95.78%
Australia	33	0.74%	94.26%
Sweden	19	0.42%	97.05%
Austria	18	0.40%	97.45%
Belgium	16	0.36%	97.81%
Israel	12	0.27%	98.08%
Italy	10	0.22%	98.30%
Denmark	9	0.20%	98.50%
Others	67	1.50%	100.00%
Total all countries	4479	100.00%	

*China includes Hong Kong

Table 5.3 Solar patents by main metropolitan area (MA), 1976-2013

Country	Metropolitan area or prefecture	Number of solar PV patents	% of global solar PV patents	% of national solar PV patents	Total % of national solar PV patents*
USA	Great S. Francisco, CA	369	8,24%	16,87%	53,41%
	Great L. Angeles, CA	238	5,31%	10,88%	
	Great Boston, MA	126	2,81%	5,76%	
	Washington DC	94	2,10%	4,30%	
	New York, NY	78	1,74%	3,57%	
	Princeton, NJ	55	1,23%	2,51%	
	Albuquerque, NM	54	1,21%	2,47%	
	Delaware Valley, DE	53	1,18%	2,42%	
	Seattle, WA	53	1,18%	2,42%	
	Dallas, TX	48	1,07%	2,19%	
Japan	Tokyo	217	4,84%	21,21%	97,56%
	Nara	211	4,71%	20,63%	
	Kanagawa	188	4,20%	18,38%	
	Kyoto	152	3,39%	14,86%	
	Osaka	107	2,39%	10,46%	
	Hyogo	75	1,67%	7,33%	
	Shiga	48	1,07%	4,69%	
Germany	Munich	122	2,72%	29,47%	39,61%
	Frankfurt/Rhine	42	0,94%	10,14%	
S. Korea	Seoul	143	3,19%	67,77%	67,77%
Taiwan	Taipei MA	74	1,65%	33,48%	74,21%
	Hsin-Chu MA	48	1,07%	21,72%	
	Taoyuan- Zhongli MA	42	0,94%	19,00%	
Total		2637	58,87%		

*Some overlaps are among the different metropolitan areas due to multiple inventors for one patent

A historical analysis of the patenting sequence in each region confirms the anchor-tenant hypothesis. The large corporations (like Canon in Japan, ITRI in Taiwan, and the University of New South Wales (UNSW) in Australia were the first inventors in their respective clusters. In addition, the anchors were typically large multi-technology corporations such as Samsung and LG in Seoul (the only cluster in that country), Canon, Kyocera, Mitsubishi and Sanyo in Japan, Telefunken, Bosch and Siemens in Germany (Granstrand et al, 1997). In the United States, with the largest number of clusters, large firms such as Applied Materials, ARCO, Boeing, DuPont, EMCORE, IBM, Lockheed Martin, Raytheon and Spectrolab are the anchors in most clusters. Universities played a minor role in the growth of the technology, compared to large firms, with the already mentioned exception of the small UNSW cluster in Australia (Han and Niosi,2016). In the US, Silicon Valley had a university (UCSF) and a large number of companies innovating in solar PV technologies.

Related variety also counts. In a study of the US semiconductor sector and its clusters over more than three decades, Ketelhöhn (2006) found that California, Massachusetts and New York hosted the most important US semiconductor clusters, but not the states of Delaware, New Mexico or Washington DC. In Asia, Seoul (South Korea), Tokyo and Osaka (in Japan), Hsin-Chu and Taipeh (in Taiwan) all are among the major semiconductor clusters in East Asia. Thus, out the thirteen largest solar PV clusters, the semiconductor sector is a major employer in nine of them. Many of the large patentees in solar cells are also important ones in semiconductors (Table 5.4).

Table 5.4 Main patentees by regional clusters

Country	Metropolitan Areas (MA)	Main patentee (anchor)
USA	Great San Francisco	Sunpower, Applied Materials, Solopower, Miasole, Solexel,Nanosolar, Solyndra, Solaria
	Greater Los Angeles	Hughes Aircraft, Atlantic Richfield, TRW, Hughes Electronics, Spectrolab, CALTEC, The Aerospace
	Greater Boston	Varian Semiconductor Equipment, Mobil Solar Energy Corp., MIT, Evergreen Solar, Spire
	Washington DC	US governmental agencies (NASA, US Army)
	New York MA	IBM Corp. (Armonk, NY), General Electric Co., RCA Corp. Plasma Physics, Union Carbide
	Albuquerque	Emcore Solar Power, Sandia National Laboratories
	Delaware Valley	E I du Pont de Nemours, University of Delaware
	Seattle	Boeing, Allsop, Inc.
	Dallas	Texas Instruments, Exxon Mobil Corp.
Japan	Tokyo Prefecture	Mitsubishi, Showa Shell Sekiyu, Semiconductor Energy Laboratory Co., Nippon, Kabushiki Kaisha Toshiba
	Kyoto Prefecture	Canon Kabushiki Kaisha, Panasonic, Matsushita Electric Industrial, Kaneka
	Osaka Prefecture	Sharp Kabushiki Kaisha, Matsushita Electric, Sanyo Electric, Panasonic
Germany	Munich	Siemens (abandoned in 2012)
	Frankfurt/Rhine-	Licentia Patent-, Merck KGaA, Nukem
S. Korea	Seoul Capital	Samsung, LG
Taiwan	Taipei-Keelung	ITRI, Atomic Energy Council - Institute of Nuclear Energy Research, National Taipei University of Technology
	Hsin-Chu	ITRI, National TsingHua University, National Chiao Tung University
	South-TW-Park	ITRI, Eternal Chemical Co., Ltd., National Kaohsiung University of Applied Sciences
	Central-TW-Park	ITRI Nexpower Technology, TSMC Solar

5.4.2.The different performances among the different clusters

When the patents in the different clusters are counted and the percentage of the big and small companies patents from the total patents are counted (see Figure 5.1, 5.2 and 5.3) , it is found that there are three categories of clusters are there in the world.

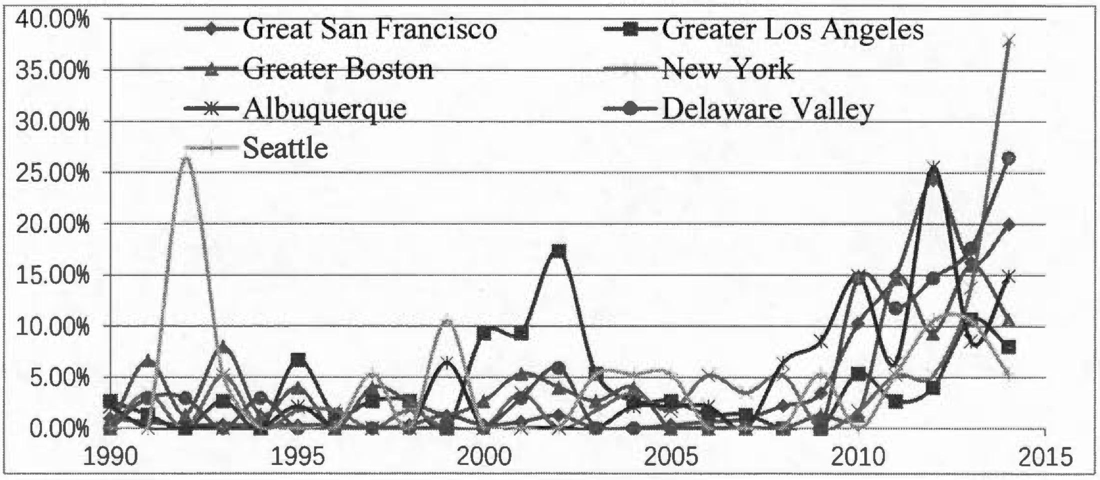


Figure 5.1Patents distribution trends in US

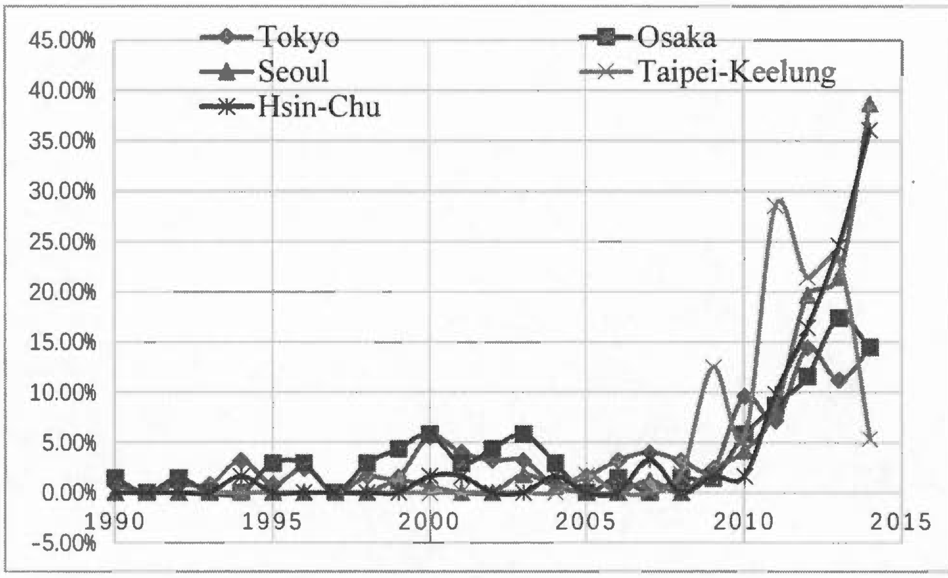


Figure 5.2 Patents distribution trends in Asia

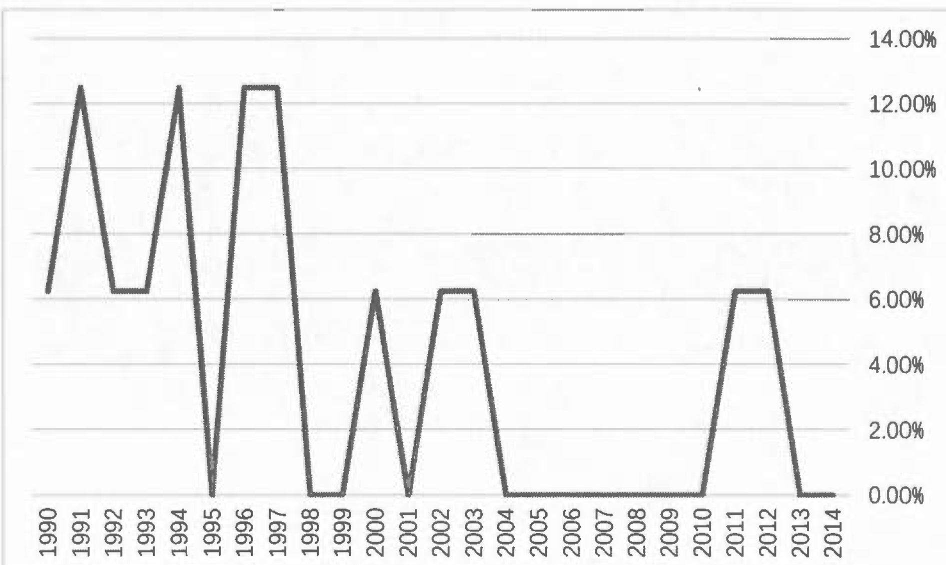


Figure 5.3 Patents distribution trends in Munich as the representative cluster in Europe

The resilience of US clusters: In the United States, we did not find a similar dismembering of the clusters when an anchor tenant abandoned the solar PV sector. In that country, it is easier than in Europe to form new companies; thus the closure of a large firm's laboratory or plant was most often followed by the creation of new firms in the same region. Another major element of cluster stability was its geographically established labour pool, often fuelled by university researchers. Public backing for the sector was also evident in the constant support of the Department of Energy (DOE), mainly through direct grants to innovative small and medium-sized firms. In the United States, no government laboratory played such a major role as in Taiwan's ITRI, but the National Aeronautics and Space Administration (NASA) in Washington DC, Sandia National Laboratories in Albuquerque, and several universities contributed to reinforce these anchored clusters.

Another characteristic of the US solar PV sectoral system was the fact that the main public laboratory dedicated to solar PV and other renewable energy technologies, the National Renewable Energy Laboratory (NREL), located in Golden, Colorado, a suburb of Denver, did not generate a cluster. Up to early 2015, the NREL had produced one solar PV spin-off company in that geographical area (TDA Research). NREL had over 500 patents, but just 38 US solar PV patents, and over 11000 articles, but only over 200 solar PV articles in the SCOPUS database. On the Laboratory's Internet site, twelve technical success stories in different areas related to renewable energy are presented. None of them is in solar PV technology. Nevertheless, NREL is a world reference in the measurement of the efficiency of solar cells. The reason for this apparent anomaly is that US national laboratories have very different missions in the

American national innovation system (Crow and Bozeman, 1998). Some of them are producing science, other have defence missions, still others are working to provide support to sectors, and among these one finds very different combinations of missions and resources. NREL provides support to the renewable energy sector, but direct promotion of economic growth is not among its missions.

Another key element in the regional agglomerations of PV solar is that venture capital has never been a major supporter of these technologies. Venture capital, mostly an American industry, has funded ICTs, biotechnology and nanotechnology, but solar PV, which seems to promise returns in the long term, is was far from venture capital sector priorities and its short-to-medium term vision. As of today, using US National Venture Capital Association s, we find that the funds allocated to solar PV are in downstream activities such as solar panel manufacturing and installation, not so much invested in discovery, R&D and technical development. The fact that the United States has been at the frontier of this technology for fifty years is due to federal government support through ARPA-E [14], DARPA, [15] SBIR [16], the DOE [17] and other public sector organizations. Also, large US private firms in aerospace and ocean oil and gas exploration requiring a source of energy far below energy grid cost have invested in solar technologies. Thus, the only cluster where one finds dozens of small and medium

[14] ARPA-E, the Advanced Research Projects Agency-Energy is a US government agency whose mission is to fund advanced energy projects; it reports to the Department of Energy.

[15] DARPA, the Defense Advanced Research Projects Agency is an organism within the US Department of Defense whose mission is to fund R&D projects with military uses.

[16] SBIR, the Small business innovation Research Program is a US federal program that intends to develop R&D activities in small and medium size firms.

[17] The US Department of Energy (DOE) supports the development of solar technologies through different programs, the most important being the SunShot Initiative, but also through the SBIR Program.

sized innovating solar PV firms is Silicon Valley, a cluster quite different from almost all others in the world in terms of entrepreneurial culture. In Germany, the federal government supported the development of solar cell technology under the aegis of Telefunken, AEG, and later Siemens, for aerospace uses. Since the 1980s, German aerospace companies such as MBB also invested in solar PV cells. But explosive growth arrived only in the mid-1990s (Jacobsson et al, 2004). The feed-in tariff nurtured even further the development of a local German sector in a few clusters. With the subsequent economic crisis after 2007, the reduction of government feed-in tariff subsidy and Chinese competition, the interest of German companies began to fade away.

The growth of Asian clusters: In a sense, in its managerial practices NREL is at the very opposite of Taiwan's ITRI. ITRI has been the locomotive of the industrialization of the Chinese island, having spun off dozens of companies out of its more than 6000 patents. ITRI is a multi-technology laboratory whose forte are information and communication technologies, including semiconductors, thus solar cells (Amsden and Chu, 2003). NREL has fewer patents, and therefore less technology to transfer, and seems much less eager or ready to create a cluster of spin-off companies around its facilities.

Supported by their private sector anchors, Japanese and South Korean anchored clusters have kept growing, as governments chose renewable energy – and particularly solar – as their future energy sources. The private sector anchors are large electronic firms, major producers of semiconductors.

First in Japan and later in other South East Asian countries, the production of pocket calculators, watches and other portable devices requiring a movable source of energy has impelled companies, since the 1960s, to adopt solar PV technologies. More recently, after 2010, as the efficiency of the PV solar systems approaches parity grid cost, several countries in the region, namely China, Japan, South Korea and Taiwan, are investing heavily in R&D and innovation, at the same time as the European Union countries, and particularly Germany, the European leader, curtail their innovation effort.

The decline of the European Union clusters. Many factors contributed to the decline of large German and smaller European clusters. In Germany, the exit of the three largest firms (Telefunken first, and then Bosch and Siemens) triggered the decline of these inventing regions. Private sector anchors had had a large role in the growth of the clusters, but after 2013, large private anchor tenants abandoned the sector. In fact, the major threat to the continuity of the solar PV regional innovation systems, at least in Europe, is the decline of public sector support. During the economic crisis, governments reduced the feed-in-tariffs that had nurtured the PV clusters (Glover, 2013). Chinese competition was also a major factor.

5.5. Conclusion and policy implications

Like other sectors based in advanced technologies, solar PV firms tend to cluster in metropolitan areas, particularly large diversified ones. The main bearers of innovation efforts are large established corporations, users of solar technologies, such as electronic firms, aerospace firms, and oil and gas companies with offshore exploration activity. These are the anchors of most clusters. The only exceptions are the Taiwanese clusters, where national laboratories (mainly ITRI) are the anchors. Last but not least is Silicon Valley, the largest PV solar regional innovation system in the world. Silicon Valley is widely seen as a class by itself among clusters. Its entrepreneurial culture, including high technical expertise, informality and minimization of hierarchy may explain its resilience in spite of a recent period of adverse market conditions (Saxenian 1994;Kenney, 2000). Thus, hypothesis 1 is largely confirmed, but hypothesis 2 is only valid for the Taiwanese clusters, due to its particular development strategy based on a large government laboratory, and publicly led industrial development (Hsu et al, 2003). Whatever the specific histories, our solar clusters are clearly anchored ones. Their anchors are most often semiconductor firms and a public laboratory only in Taiwan (as stated by hypothesis 3)

Thus, we find organizational diversity in solar PV clusters. Yet, authors are divided on the issue of how much organizational diversity is conducive to cluster growth and resilience. For some (Mangematin and Errabi, 2012), organizational diversity is an obstacle to cluster growth. For others, diversity allows for the combination of more ideas and business models, in different ways, thus allowing for resilience, variety and growth (Chaminade, 1999; Agrawal et al, 2014). Our s tend to support the Jacobs hypothesis as modified by Frenken et al (2007) and Boschma and Iammarino (2009): large diversified metropolitan regions (Boston, Los Angeles, Munich, New York, San Francisco, Seoul, Tokyo, and Osaka) are the hosts of majority solar PV clusters, particularly when the anchors are active in related technologies (semiconductors).Policy implications are clear: in order to foster a solar PV cluster, governments must be sure that a variety of agencies and firms populate the cluster: large multi-technology corporations, and small firms, government laboratories, and research universities.

Even if after 2008 solar PV technologies have known exponential growth in terms of innovation and patents, some clusters are closing down, due to the exit of their anchor tenants. This cluster decline happened most evidently in Germany as one after the other, aerospace, automobile and electronics companies closed down their solar PV plants and R&D laboratories. The EU recession, the euro crisis, and increasingly restrictive subsidy policies continue to drive down prices and reduce EU markets. In addition, China's rapidly growing solar PV sector that now represents over 50% of global solar panel production, tends to depress world prices, and outcompete potential competitors, at least in terms of price. In 2013 Chinese solar panels supplied over 80% of the EU market (Vega, 2013). In addition, the United States and East Asia concentrate most of the semiconductor sector; the EU is an increasingly marginal producer of these electronic devices.

Advanced technology clusters may thus diminish and disappear particularly when their stability depends on just a major multi-technology company that may retreat either from the sector or from the country (Table 5.5). Thus, a more diverse cluster, hosting research universities, large multi-technology corporations, public laboratories, SMEs and venture capital, such as Silicon Valley, may be more resilient than clusters based on one or two large firms (Table 5.6 and Figure 5.4).

In order to explain why regions differ in resilience, Martin and Sunley (2015) put forward three types of factors: compositional, collective and contextual. The contextual factors are multi-scale and they include wider conditions and forces, such as national policies and circumstances, and even international influences. After exploring the different development paths, we have identified the following factors that influence the resilience of the solar PV clusters.

In a sector that has been fuelled by public long term patent investments, the decline of public support (or its persistence) are among the main factors explaining the resilience of the sector. The clusters are anchored either by very large firms involved in semiconductors and other electronic products requiring solar energy, or by public laboratories being the arm of public policy.

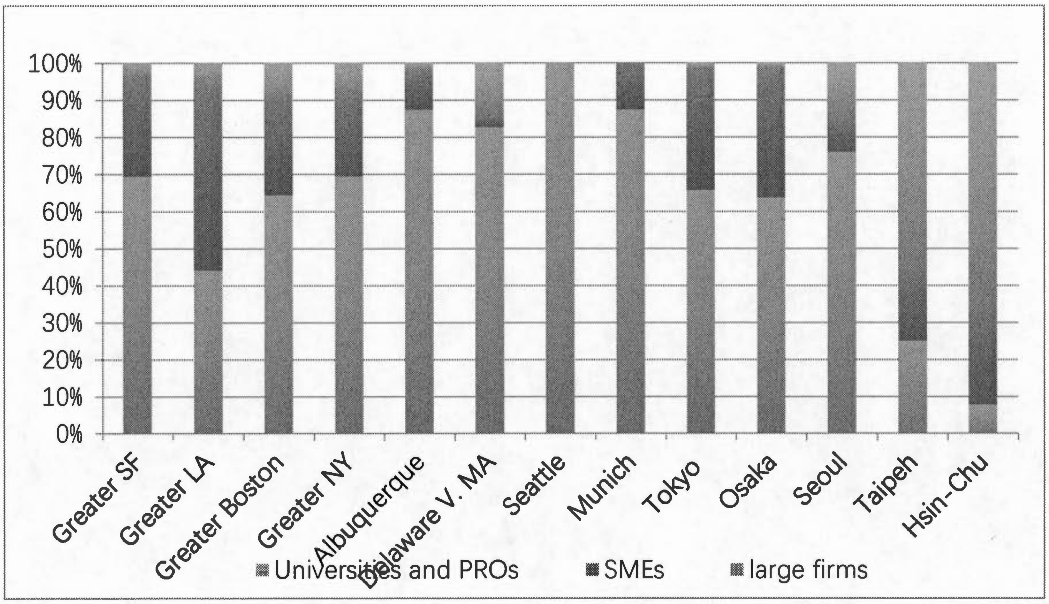
Table 5.5 Factors influencing the growth and resilience of solar PV clusters

Factors	United States	Germany	Japan, South Korea, Taiwan
Anchor tenant	Yes	Not anymore	Yes
Availability of feed-in-tariffs	Yes	Not anymore	Yes
Collocation of semiconductor and solar cell R&D and production	Yes	Yes	Yes
Emphasis on other renewable energy industries	Yes	Not anymore	Yes
Availability of venture capital	No	No	No
Status of solar PV clusters	Growing	Declining	Growing

Table 5.6 Large and small organizations as patentees by cluster (1976-2013)

Cluster	Large firms	Universities	PROs	Total
Greater S. Francisco MA	223	86	12	321
Greater Los Angeles MA	33	37	5	75
Greater Boston MA	49	19	8	76
Greater NY MA	41	13	5	59
Albuquerque MA	42	5	1	58
Delaware Valley	29	1	5	35
Seattle MA	19	0	0	19
Munich, Germany	14	2	0	16
Tokyo Prefecture	82	41	2	125
Osaka Prefecture	44	24	1	69
Seoul Capital Area	130	15	26	168
Taipei-Keelung MA	14	12	30	56
Hsin-Chu MA	5	19	41	61

Source: USPTO



Source: USPTO

Figure 5.4 Solar PV clusters according to main type of patentees

CHAPTER VI

STAR SCIENTISTS IN PV TECHNOLOGY AND THE LIMITS OF ACADEMIC ENTREPRENEURSHIP

6.1. Introduction

Numerous scholars study the technological competencies of new technology-based spin-offs. Zucker, Brewer, Darby, and Peng (1994) and Zucker and Darby (1996) launched a small but influential addition to this line of thought, arguing that the biotechnology revolution is mainly the result of star scientists' efforts. Zucker et al (1994, 1996) found that star scientists transferred their advanced knowledge to new technology firms through different channels, including participating in the scientific committees of these firms and even serving as founders or advisors. According to them, a star scientist is someone who discovers 40 or more genetic sequences and publishes at least 20 articles reporting these discoveries.

In subsequent years, some authors studying biotechnology decided to adopt this notion of star scientists and not produce original definitions (Sapsalis, Van Pottelsberghe, and Navon, 2006; Tzabbar and Kehoe, 2014). Others turn to patents and publications (see Table 6.1). For example, Niosi and Queenton (2010), studying Canadian biotechnology firms, define biotech superstars as those who appear as inventors in more than five patents and author of more than one major publication per year.

Although the vast majority of articles on star scientists focus on biotechnology, the concept migrated, albeit modestly so, to other high-technology disciplines such as nanotechnology, chemistry, computer and electrical engineering, and materials (Lowe, and Gonzalez Brambila, 2007; Trippl, 2011; Tartari, Perkmann, and Salter, 2014).

So the question for the chapter is how to define the star scientist in the solar PV sector? What are the contributions of the star scientists and university spin-offs in the solar PV innovation?

Our research finds only one scholarly work on star scientists in the solar photovoltaic (PV) sector, but the author of that work (a thesis) does not build a definition (Colalat, 2009). Fuller and Rothaermel (2012) define star scientists as faculty founders of new technology ventures and apply this definition to several industries, including the photovoltaic sector. Fuller and Rothaermel (2012) mention SunPower, a photovoltaic spin-off from Stanford University in California that Dr. Richard Swanson, a professor of electrical engineering founded, as a case in point. Table 6.1 summarizes the definitions and key bibliographies on star scientists.

Table 6.1 Star scientist definitions

Author	Sector or technology	Definitions
Zucker,and Darby, 1996	Biotechnology	"Those discovering more than 40 genetic sequences and/or authoring 20 or more articles reporting such discoveries up through early 1990.
Sapsalis et al., 2006	Biotechnology	There is no definition of stars
Lowe,andGonzalez Brambila, 2007	Six disciplines from biology and chemistry to computer and electrical engineering, and materials	Stars are highly productive scholars that become entrepreneurs. There is no mention of patents or the discovery of genetic sequences in the definition
Groysberg, Lee, and Nanda, 2008	Wall Street research analysts	"/.../disproportionately productive and valuable" people (p. 1213)
Niosi, and Queenton, 2010	Biotechnology firms and academics	Biotech superstars are those with more than five patents and more than one major publication per year
Trippl, 2011	All scientific disciplines in university	"Stars scientists are defined here as authors of highly cited research papers, identified by the number of citations they generated in journals in the ISI databases in the period 1981-2002". (P. 1654)
Fuller, and Rothaermel, 2012	All high-tech scientific academic disciplines	Faculty founders of new tech ventures are star scientists
Oettl, 2012	Immunology	Stars are people with high levels of scientific productivity (publications) and helpfulness. Highly productive individuals who do not help colleagues are "lone wolfs", not "stars"

Moretti, and Wilson, 2013	Biotechnology	"...those patent assignees whose patent count over the previous ten years is in the top 5% of patent assignees nationally."(ibid, p. 3)
Tzabbar, and Kehoe, 2014	Biotechnology (industrial organizations)	"Star employees have been defined as individuals who demonstrate disproportionately high levels of productivity" (P. 452). There is no definition of what high productivity may be.
Hoser,2013	Nanotechnolog y	Those academics with the maximum number of citations
Tartari et al, 2014	All scientific disciplines in university	"We define star scientists as academics in our sample in the top 1% of the distribution of citations in their discipline, and the top 25% of the distribution for grants received from the EPSRC"

University spin-offs (USOs) are one of the important channels through which star scientist can contribute to the growth of high-tech firms. Pirnay, Surlemont and Nlemvo (2000) define USOs as follows:

"…/new firms created to exploit commercially some knowledge, technology or research results developed within a university".

The scientific domain itself does make sense for the performance of USOs. A large percentage of academic spin-offs relate to biotechnology and health sciences. Mowery, Nelson, Sampat and Ziedonis (2001) calculate that some 75% of the patenting and licensing at three of the most research-active universities in the United States(US), namely, the network of the University of California, Columbia and Stanford, are in biomedical research, particularly biotechnology. The second most important sector is computer software. The article does not mention solar technology. Similarly, in an annual survey of intellectual property generated in Canadian universities, health sciences appear as number one, although not as prominently as in the US. Again, the survey does not mention the solar photovoltaic (PV) sector (Statistics Canada, annual).

Local venture capital also appears to be a determinant of growth. Using a large sample of US academic spin-offs supported by venture capital, Zhang (2009) finds that most of them focus on two areas: biotechnology and information technologies. In addition these spin-offs tend to remain geographically close to their alma mater.

USOs from different US universities perform very differently. More entrepreneurial universities have much better scores as licensors of technology to academic spin-offs. Walter, Auer and Ritter (2006) argue that network capabilities and entrepreneurial orientation are key variables explaining the performance of these USOs. Further, Powers and McDougall (2005) find that universities with experienced (older) technology transfer office (TTOs) incubate more successful spin-offs. More productive faculty members (in terms of articles and citations) also contribute to more successful spin-offs. Early collaboration with sector also contributes to spin-off growth.

6.2. Hypotheses

On the basis of literature reviews, the chapter draws the following hypotheses:

H1: Technological content (i.e., the relevant industrial sector) is a major determinant of the likelihood of creation of a USO. More specifically, the likelihood of creation of a solar PV USO is lower than that of biomedical and information technology USOs.

H2: Venture capital has a strong industrial sector component. Venture capital supports much more often biomedical and information and communication technologies (ICT) spin-offs than solar PV ones.

H3: More experienced universities and TTOs will produce more successful USOs.

H4: Star scientists will engage in more successful solar PV USOs.

6.3. The solar PV sector

The solar photovoltaic sector started modestly in Bell Labs in the 1950s when three researchers developed the silicon transistor. Today, the silicon cell is still the main component of solar PV technology (Perlin, 2002). The first application was in space, in the late 1950 and 1960s, with satellites requiring a reliable long-term source of electricity, even if the cost of that solar energy was high. A second major application, in the 1970s, was in sea buoys and sea oil and gas exploration and exploitation, far from conventional sources of electricity. At this time, large hydrocarbon companies, such as ARCO, BP and Shell, started investing in solar PV R&D. As the cost of solar PV energy started to decline following technological advances, the sector began to interest companies such as Telecom Australia, as a mean to provide telephone connections in a country close to 8 million square kilometres in area and with lots of sunshine but with a population of only 12 million in the early 1970s. At the same time, Japanese companies such as Canon, Sharp, and Sanyo invested in solar technology to power their hand calculators and similar devices.

Universities joined the solar bandwagon later. In the 1980s, the University of New South Wales (UNSW), under the guidance of Dr Martin Green, started conducting research on solar cells to improve their efficiency. At the same time, Dr Allen Bennett at the University of Delaware (UD) provided an impetus to academic research on PV technologies. Soon, these two pioneers launched the first academic spin-offs, Pacific Solar in Sydney Australia and AstroPower in Glasgow, Delaware, in1995. AstroPower sold its assets to GE in 2004, and GE handed these assets to Taiwan's Motech in 2009. The main UNSW spin-off, Pacific Solar, experienced ups and downs and finally closed its doors in the late 1990s.

By that time, several other universities, mostly in the United States but also in Europe (Germany, Switzerland), started conducting R&D on solar PV technologies in a multi-agent race to increase solar cell efficiencies. Today, the University of Konstanz in Germany and the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland stand among the top contributors. Star Professor Michael Graetzel at EPFL is the Chairman of the Technical Advisory Board at an Australian spin-off company, Dyesol, which acquired one of EPFL's spin-off companies, GreatCell, a firm that made use of Dr. Graetzel's discoveries in the field of dye solar cells.

Germany has lost some interest in the solar PV sector due to a reduction in government feed-in tariffs and Chinese competition. In 2009, the largest German start-up, Solon Technologies, went bankrupt, and soon the two largest German companies involved in the area, Robert Bosch and Siemens, sold or closed their solar PV facilities. However, government R&D laboratories remained active, with the Fraunhofer Institute in Freiburg being Europe's number one public research institute in the area. The Fraunhofer Institute created close to 15 solar PV spin-off companies, some of which are still alive.

Since 2000, Asian competitors have become more involved. Japan has developed a policy to foster the creation of university spin-offs, a phenomenon that seldom occurs in that country. However, as of 2015, there are few spin-offs from Japanese universities in the solar PV sector. All of them are working on niche products.

In Taiwan, the Industrial Technology Research Institute's (ITRI) policy is to import and develop advanced technology and spinoff technology-based firms concentrating on solar PV, after focusing on semiconductor products and processes. DelSolar (2004), located in the Hsinchu Science Park, is ITRI's first and only PV spin-off. In 2005 DelSolar merged with NSP, another Taiwanese company, to become the largest solar PV technology firm in Taiwan.

Whereas South Korea seems almost impenetrable to solar academic spin-offs, China's Academy of Science and some Chinese universities are very active, TsingHua University stands over the others.

Asian and US governments are increasing their investment in solar PV R&D, but venture capital is historically fairly reluctant to engage in a sector that promises returns only in the long term and is plagued by high volatility. Only in the last few years did some VC investment return to the sector, mainly in the United States, and mostly in the downstream segments of the sector, such as companies that assemble and install rooftop modules. Upstream companies, with strong R&D capabilities and patents, in which star scientists are usually involved, are struggling to obtain private sector funds and only survive due to public funds, such as those from the US Department of Energy, the Advanced Research Project Agency (ARPA), and the Small Business Innovation Research Program (SBIR) programs. The decline in the price of oil and gas since late 2014 is doing nothing to reverse the trend.

6.4. Methodology

This work focuses mainly on patents, publications and venture capital, as well as on the construction of lists of new spin-offs and start-ups in the solar cell sector.

The authors use the United States Patent and Trademark Office (USPTO) database and the keywords "solar cells", "solar cell", "solar glass", "photovoltaic cells" and "photovoltaic cell". Removing the overlaps, the authors find some 4,400 granted solar PV patents between 1976 and December 2013. The use of the USPTO database is because close to 50% of the solar PV patents originate in the United States and competitors in Japan, Germany, Taiwan and the People's Republic of China also apply for patents in the United States to protect their inventions from potential infringers.

Following the most widely used definition of a star scientist, the authors first analyze the articles of star scientists. There are 105,484 articles on solar technologies in Scopus as of 17 February 2015. Within this group, there are 109 stars with more than 100 articles with "solar cell" as the search query for the "Article title, abstract, and keywords" (see Table 6.3).

For venture capital, the authors use the secondary venture capital association reports as proof.

6.5. Results: Stars scientists in the photovoltaic industries

6.5.1. Definition of star scientist for solar PV sector

Analyzing the correlation between the number of articles in Scopus and the number of patents by academic scientists in USPTO and Espacenet, the correlation coefficients are just 0.043 and 0.22, respectively. The reason for this high-tech "anomaly" is that at least in North America, solar technology receives enormous knowledge externalities from several other industries, including semi-conductor firms and large glass producers investing in the specialty technical glass used in PV equipment. Thus, for the solar PV sector, unlike biotechnology or other disciplines, most of the research activity takes place in firms, with not so much in universities. In photovoltaic cells, universities have just 589 US patents, whereas companies have more than 3800. There are almost 41,800 articles in SCOPUS on photovoltaic cells. Just over 55% of them include authors from universities. For photovoltaic glass, of the 3,600 articles in Scopus, some 2,073 (or 57%) include academics among the authors. In addition, photovoltaic glass requires large manufacturing plants and R&D activity. The four main patentees are very large American, European and Japanese companies (Guardian Industries and Corning, both from the United States, the French Saint-Gobain and Nippon Sheet Glass, with its British Pilkington PLC subsidiary). In Germany, some universities conduct solar technology research, particularly Albert Ludwig, Konstanz and Martin Luther universities. However, the number of German academic patents is very low. Only seven appear in the USPTO database, all granted after 2004. The assignees are the Universities of Konstanz and Albert Ludwig Freiburg. A few other academic patents appear in ESPACENET, making a total of 15.

To reflect academic expertise, our definition utilizes articles and patents, and our definition is as follows:

> *In the solar photovoltaic sector, academic star scientists are university or institutional researchers with at least four photovoltaic sector patents in the USPTO and/or over 100 SCOPUS publications.*

The cutting point of the patents and the publications are based on the following two criteria with the statistics of the patents and publication in Table 6.2.

- 80/20 principle: The total number of the paper or papers which scientists take is the 80% of the papers or patents that all the scientists within the university have made;

- The star scientists cannot be too many. So if there is the big difference between the number of paper or patent, the upper one will be taken. The cutting point is based on the distribution of patents among patent holders.

Table 6.2 Statistics for cutting point of the criteria for star scientist

Patents	Total till the number of patents	Number of scientist	Total	% from total	papers	Total till the number of papers	Total	% from total
4	273	15	589	46.35%	100	16896	22990	73.33%
3	429	52		72.84%	90	18481		83.94%
2		158						

6.5.2. The difference between solar PV and other high-tech disciplines

The solar PV sector produces far fewer patents than the biomedical and ICT industries. A simple perusal of the Organization for Economic Cooperation and Development (OECD) patents database shows that, between 1976 and 2011, OECD countries requested some 175,720 PCT priority patents in biotechnology, compared to 13,984 in solar PV technology. The difference, which is more than 12 times, is staggering, even when adding approximately 500 patents from China, Singapore, and Taiwan not granted in the USA.

Academic patents in solar PV technologies are fairly scarce. There are 589 university or institute patents. Removing overlaps, this amounts to barely more than 10% of the 4400 solar cell patents. In comparison, there are some 90,000 USPTO patents granted to assignees with the word “university". One half of 1% of them are solar PV patents.

6.5.3. Venture capital in solar PV technologies

In the USA, which hosts 50% of the world’s venture capital, biomedical and ICT technologies relegate solar PV technologies to the bottom of the list by a wide margin. US National Venture Capital Association (NVCA) who published the s in 2014 puts software at the top, with 41% of the total investment of 48 billion, followed by biomedical and life sciences, with 18%, and other sectors. The s do not even mention energy or clean energy, let alone solar PV technology. A Mercom Capital Group report (2015), estimating s for investments in solar PV technology, put the global total at US$1.3 billion for venture capital (most of this amount goes to downstream activities such as solar roof panel installation for residences in the United States, corresponding to two companies) and US$26.5 billion for corporate investment. In 2013, global investment s for solar PV were only US$643 million from US$9.6 billion for clean technology. We conclude that governments should support this emerging technology whose benefice is going to be global improvements in climate and environment in the medium and long term. Private venture capital is not interested in nurturing a clean environment.

6.5.4. University patents

The US universities and public laboratories dominate in terms of academic solar technology patents, with 292 of them. MIT, the University of Delaware, North Carolina State, the University of California, Caltech, Princeton and Stanford appear at the top of the list.

In Taiwan, where assignees have 136 US patents, ITRI tops the list with 57, followed by the Atomic Energy Council (22) and National TsingHua University (13).

In South Korea,, Dongguk University, the Korean Institute for Science and Technology (KIST), the Korean Research Institute for Science and Technology and Sungkyunkwan University own more than 50% of the 82 public sector solar PV patents.

There are few academic patents in other countries. Australia would be a contender, but UNSW has only two patents under its name. Private firms and the University intellectual property arm presented several of its novelties. China (9), Canada (8), Germany (7), and a few other countries follow. The distribution of academic papers is much greater in other technologies than in solar PV.

6.5.5. Star scientist performance

Stars in the solar PV sectors do not focus solely on PV technology; nearly half of their academic work is in the other related fields. The average percentage of articles with the title or abstract containing “solar cell” is just 56% of their total papers, and the correlation coefficient between the number of articles with the title or abstract containing “solar cell” and the total number of articles is 0.32. For star scientists, the correlation coefficient between the percentage of papers with "solar cell" and the total number of patents in USPTO and Espacenet are 0.051 and 0.022, respectively, which indicates that the stars with more papers are not very active in solar PV entrepreneurship.

Among the 109 star scientists, the authors remove nine employed by companies because this work focuses on academic entrepreneurship. This procedure leaves just 100 stars belonging to 22 countries. Stars in different countries have different forms of entrepreneurship. Most of the stars outside of US are not high on USPTO patent lists but have several patents in their own countries, especially the stars in Asian nations, such as Japan and China. Among the 22 stars in the US universities, 8 of them have experience setting up a business or working experience in companies, with their academic expertise directly serving in the commercialization of the technology. In contrast in Japan, finding entrepreneurial activity among stars is difficult, except in terms of local patenting. Considering that very huge companies dominate the PV sector in Japan, large companies employ in one way or another most of the academic Japanese stars, and stars are not so much engaged in entrepreneurial activity by themselves.

6.6. Conclusions and policy implications

Star academic entrepreneurship and relative venture capital are most active in biotechnology, other human health sectors and ICT, including software. Solar PV is another situation. Since the inception of the technology in the 1950s and 1960s, several factors restrict the creation of solar USOs, including the scarcity of research funds (in comparison with biomedical technologies), niche markets and the modest interest of academic researchers on the subject, with only a few active universities outside the US, such as UNSW in Australia and EPFL in Switzerland. Comparatively, there are few university patents on solar PV technologies. In addition, venture capital is fairly reluctant to invest in the field, except in Silicon Valley. New solar PV technologies do not attract much interest, and there are few start-ups. Thus, the authors find moderate evidence of support for hypotheses 1 and 2: both academia and venture capital privilege life sciences and ICT at the expense of renewable energy technologies. Only a few countries, such as Australia, China, Japan, Taiwan, and the US, are fuelling innovation in this sector, most often with public monies.

Being comparatively new, the PV sector requires the accumulation of knowledge in related fields, such as semiconductors and glass technologies, advanced batteries and mechatronics. Under these conditions, scientists have greater potential to become star scientists in life sciences, ICT and nanotechnologies than in PV technologies. Today, the distribution of solar PV star scientists is global, but they are seldom entrepreneurs.

The authors cannot accept hypotheses 3 and 4. Universities surrounded with venture capital (mainly Silicon Valley but also Greater Boston and Los Angeles) may produce more successful spin-offs (see Table 6.5). Conversely, prestigious academic institutions in the area of solar PV technology, such as EPFL and UNSW, do not produce similar numbers and successful spin-offs. The findings do not justify extending the idea that successful stars engage in more successful spin-offs in the field of solar PV technologies.

Academic entrepreneurship is not widespread in the PV sector, even in US universities where academic entrepreneurship in bio- and nanotechnologies and ICTs is very active. Furthermore, most of the successful firms that are established directly or use knowledge produced by star PV scientists in PV are being acquired or shut down. To make the scientific and technological achievements of star scientists well commercialized, the corresponding procedures for technological transfer between academic units and firms should be well designed and operated. Venture capital and a good regional economic landscape may also be necessary conditions for the development of successful new ventures.

From a theoretical point of view, we argue that the concept of a star scientist has to be integrated in the resource-based and competence theories of the firm to which the star scientist approach belongs. In many high-tech companies, star scientists are one of the key resources for growth.

From a public policy point of view, the overwhelming presence of large firms compared to spin-offs from academic institutions makes us think, similar to Mowery et al (2001), that academic entrepreneurship applies to a reduced set of technological domains. Solar PV technologies are not a central part of this set. The conditions of these technologies, namely their high risk, long-term payoffs and strong competition from huge corporations, may doom any policy aiming to create academic spin-offs from the start.

Table 6.3 The authors with more than 200 documents in Scopus[18]

Authors within search of "solar cell" in Scopus	Documents with "solar cell"	Country	Organization	Total documents	Total citations
Gätzel, M.	518	Switzer-land	École Polytechnique Fédérale de Lausanne	993	131061
Green, M.A.	444	Australia	UNSW	639	19015
Poortmans, J.	295	Belgium	Universiteit Hasselt, Faculty of Science, Diepenbeek	408	4622
Konagai, M.	272	Japan	Tokyo Institute of Technology	514	5295
Nazeeruddin, M.K.	271	Switzer-land	École Polytechnique Fédérale de Lausanne, CH	386	37927
Schock, H.W.	266	Germany	Helmholtz-Zentrum Berlin für Materialien und Energie (HZB), Berlin, Germany	340	8728
Zhao, Y.	247	China	Ministry of Agriculture of the People's Republic of China, Key Laboratory of Plant Nutrition and the Agri-environment in Northwest China, Beijing.	1410	26226
Hagfeldt, Anders	242	Sweden	Uppsala Universitet, Department of Chemistry-Ångström, Uppsala, Sweden	323	26211
Schropp, R.E.I.	235	Nether-lands	TechnischeUniversiteit Eindhoven, Department of Applied Physics,	388	5021

[18] The full list of stars with more than 100 articles would be too long to be included in this paper, there are totally 105 star scientists with 100 articles each.

			Eindhoven, Netherlands		
Li, Yongfang	233	China	Beijing National Laboratory for Molecular Sciences, Institute of Chemistry, Zhongguancun	569	18437
Rau, U.	231	Germany	ForschungszentrumJülich (FZJ), Julich	281	5960
Luque-Lopez; Antonio	230	Spain	Escuela Técnica Superior de Ingenieros de Telecomunicaci6n, Madrid, Madrid, Spain	442	8874
Ballif, C.	226	Switzer-land	Ecole Polytechnique Fédérale de Lausanne	304	5170
Krebs, F.C.	217	Denmark	DanmarksTekniskeUniversitet, Department of Energy Conversion and Storage, Lyngby	365	18928

Table 6.4 The number of academic star scientists in terms of solar PV papers in different countries

Country	Number of stars	Location	Universities
Germany	17	Breisgau (5)	Fraunhofer-Institut fur SolareEnergiesysteme (5)
		Berlin (4)	Helmholtz-Zentrum Berlin fürMaterialien und Energie (4)
		Julich (3)	ForschungszentrumJülich (3)
		Hannover (2)	Universitat Hannover (2)
		Dresden (1)	TechnischeUniversitat Dresden (1)
		Erlangen (1)	Friedrich-Alexander-Universität Erlangen-Nürnberg (1)
		Stuttgart (1)	Institute for Photovoltaics (1)
US	15	CA (4)	Caltech (1), UCSB (1), Stanford(1),UCLA (1)
		CO (4)	NREL (3), Colorado State University (1)
		DE (1)	University of Delaware (1)
		OH (2)	University of Toledo (2)
		MD (1)	University of Maryland (1)
		NY (1)	State University of New York at Buffalo (1)
		PA (1)	Pennsylvania State University (1)

		Washington, DC (1)	Naval Research Laboratory (1)
Japan	15	Tokyo (5)	Tokyo Institute of Technology (2), National Institute of Advanced Industrial Science and Technology (2), University of Tokyo (1)
		Kyoto(3)	Ritsumeikan University (3)
		Kitakyushu (2)	Kyushu Institute of Technology (2)
		Tsukuba (2)	National Institute for Materials Science Tsukuba (2)
		Chofu (1)	Japan Aerospace Exploration Agency (1)
		Kawaguchi (1)	Japan Science and Technology Agency (1)
		Nagoya (1)	Nagoya Institute of Technology (1)
China	12	Beijing (3)	Key Laboratory of Plant Nutrition and the Agri-environment in Northwest China of Ministry of Agriculture (1), Institute of Chemistry CAS (2)
		Quanzhou (3)	Huaqiao University (3)
		Guangzhou (2)	Sun Yat-Sen University (1), South China University of Technology (1)
		Chengdu (1)	University of Electronic Science and Technology of China (1)
		Hefei (1)	Hefei Institutes of Physical Sciences, CAS(1)
		Shanghai (1)	Shanghai Institute of Technology (1)

		Tianjin (1)	Nankai University (1)
Switzerland	7	Dubendorf (1)	Forschungs institution fur Materialwissenschaften Und Technologie Eth-Bereichs (1)
		Lausanne (6)	Ecole polytechnique fédérale de Lausanne (6)
		Stockholm (1)	The Royal Institute of Technology (1)
Netherlands	4	Eindhoven (2)	TechnischeUniversiteit Eindhoven (2)
		Delft (1)	Delft University of Technology (1)
		Utrecht (1)	Debye Institute (1)
Spain	4	Madrid (2)	Escuela Técnica Superior de Ingenieros de Telecomunicación (1)
		Madrid (1)	Universidad Politécnica de Madrid(1)
		Tarragona (1)	Instituto Catalán de Investigación Química (1)
South Korea	3	Jongno-gu (2)	Sungkyunkwan University (2)
		Seoul(1)	Korea University(1)
Australia	3	Sydney (2)	UNSW (2)
		Canberra (1)	Australian National University (1)
		Leuven (1)	KatholiekeUniversiteit (1)
Sweden	3	Uppsala (2)	Uppsala Universitet(1), Angstrom Laboratory(1)

Taiwan	3	Taipei (1)	National Taiwan University (1)
		Hsin-chu (2)	National Chiao Tung University Taiwan (2),
United Kingdom	3	London (2)	Imperial College London (2)
		Oxford (1)	University of Oxford (1)
Belgium	2	Diepenbeek (1)	Universiteit Hasselt (1),
Denmark	1	Lyngby (1)	DanmarksTekniskeUniversitet (1)
Austria	1	Linz(1)	Johannes KeplerUniversität Linz (1)
Singapore	1	Singapore City (1)	National University of Singapore (1)
France	1	Paris (1)	EDF Institut de Recherche et Dévelopement sur l'Energie Photovoltaïque (1)
Malaysia	1	Bangi(1)	UniversitiKebangsaan Malaysia (1)
Ethiopia	1	Addis Ababa (1)	Addis Ababa University (1)
Slovenia	1	Ljubljana (1)	University of Ljubljana (1)
Israel	1	Rehovot(1)	Weizmann Institute of Science Israel (1)
Saudi Arabia	1	Jeddah (1)	King Abdulaziz University (1)

Source: SCOPUS

Table 6.5 Solar PV academic patents by country, state and university

Country	State	University	Number of USPTO solar PV patents
USA			292
	MA	MIT	42
	DE	University of Delaware	29
	NC	North Carolina State University	22
	CA	University of California	21
	MI	Midwest Research Institute	21
	CA	California Institute of Technology	13
Taiwan			136
		ITRI	57
		Atomic Energy Council	22
		National TsingHua University	13
South Korea	NA		82
		Dongguk University	17
		KIST	13
		KRICT	10
Switzerland	NA		10
		École polytechnique fédérale de Lausanne	10
China	NA		9
		TsingHua University	7
Canada			8
	ON	University of Toronto	3
Germany			26
	NA	University of Konstanz	5
		Fraunhofer Institute	19
All other countries			45
Total			598

Source：USPTO

CHAPTER VII

THE LIMITED INNOVATION OF SMALL BUSINESSES IN THE SOLAR PHOTOVOLTAIC SECTOR IN THE US:

IS THE SMALL BUSINESS INNOVATION RESEARCH (SBIR) PROGRAM A BOON FOR SMALL BUSINESSES IN THE US?

SBIR in US is heralded as major program to support innovative new technologies by SMEs that will grow as a result by selling products and services in the market. Instead we found, in the solar photovoltaic sector, that SMEs supported by the Department of Defense and National Aeronautics and Space Administration are mostly acting as internal services of these federal agencies: their products serve mainly, if not exclusively, these two defense-related organizations. Their future growth is thus curtailed. The paper calls for a more accurate analysis of the Small Business Innovation Research program and perhaps other innovation policies.

7.1. Introduction

Small and medium businesses significantly reinforce the performance of innovation-focused economies by creating technical and organizational novelty, employment and economic growth (Robson and Bennett, 2000; Jutlaet et al., 2002; Foreman-Peck et al., 2006).The revolutionary breakthroughs continue to come predominantly from small entrepreneurial enterprises, and by bringing vigorous competition, particularly in high-tech industries, entrepreneurial enterprises force incumbent firms to innovate in order to survive (Baumol, 2004).

But small businesses do not always work like that. For those in the solar photovoltaic (solar PV) industry, things are different. The industry was initiated by the innovation of very large user firms and even forty years after the first US patent, large corporations still dominate industrial innovation. Technological innovation in the solar PV industry is mostly controlled by large firms. Also, in contrast to the situation for biotechnology, star scientists in solar photovoltaic technology, regardless of their contribution, are comparatively minor players (Han and Niosi, 2016). Moreover, the late-entry specialized manufacturers (the manufacturers just focusing on solar PV cell or solar panel manufacturing, with no other focus or integration plan) from start-ups are quite fragile. Among the top ten specialized manufacturer assignees from their earliest USPTO (United States Patent and Trademark Office) patent until now, half of them were acquired or ceased operation. Developing in the solar PV sector is not an easy task for small businesses.

As that in the other emerging sector, Small Business Innovation Research (SBIR) and the Small Business Technology Transfer (STTR) program in the US, an important government incentive for small businesses in the US, has supported 772 projects in solar cells by the end of 2014. Why is small business in the solar PV industry still quite weak in spite of a government support program similar to that in the other industry? By sampling the award-winners of the SBIR program, this paper examines the factors that might have influenced the SBIR awards of the post-entry entrepreneurial small business related to the solar PV industry, so that the policy function of the SBIR in this specific sector can be described.

The paper is composed of five parts. The introduction is followed by literature reviews, factors influencing the innovation performances are extracted and the hypotheses are established. Data is collected and quantitative analysis is employed to identify the factors significantly influencing the chances of being awarded the SBIR grants. The results are described, and the discussion and conclusion are presented in the last two parts.

7.2.Literature review

Generally, the innovation performance of small businesses is mainly attributed to the following factors: type of entrepreneurship, clusters, markets targeted and public funding.

The characteristics of previous employment have a major influence on entrepreneurial entry (Buenstorf and Klepper, 2009). Categorised by the "knowledge context" which serves as the basis for the creation of a new firm, there are three kinds of innovative new ventures: employee entrepreneurship, academic entrepreneurship, and user entrepreneurship. Agarwal and Shah (2014) argue that academic- and user-founded firms are more likely to introduce product innovations, while employee-founded firms would introduce both product and process innovations. And they also theorize that the knowledge sources of entrepreneurship are critical in determining who profits from innovation, how they do so, and the manner in which industries evolve due to type and source of their knowledge. In terms of survival rates, employee founded firms outperform all other entrants (Klepper, 2002, 2007; Agarwal et al., 2004; Franco and Filson, 2006; McKendrick et al., 2009). Given the importance of knowledge inheritance from parent to employee founded firms, studies unsurprisingly find that parent firms with superior technological or market know-how generate more progeny, who subsequently enjoy higher survival rates (Brittain and Freeman, 1986; Klepper, 2002; Agarwal et al., 2004; Klepper and Sleeper, 2005).

Hill and Naroff (1984) examined a sample of 102 high technology firms listed in the Million Dollar Directory from 1978 to 1981 and found that firms within the Silicon Valley and Boston clusters (both very large clusters) had significantly higher actual returns than a sample of similar firms located elsewhere. DeCarolis and Deeds (1999) found a positive relationship between the amount of IPO dollars raised and the "strength" of a location in the U.S. biotechnology industry. Porter and Stern (2001) noted that innovation and the commercialization of new technologies takes place disproportionately in clusters. Sorenson and Baum (2003) contended that the location in which a firm resides determines many important elements in its business environment. Gilbert et al (2008) found that ventures located within geographic clusters absorb more knowledge from the local environment and have higher growth and innovation performance. McCann and Folta (2011) concluded that younger firms and firms with higher knowledge stocks benefit more from agglomeration. There is no research on the relationship between locating in the solar PV clusters and venture performance yet.

Radosevic (2007) argues that entrepreneurship is driven by complementarities arising from the favorable interaction of technology, market and institutional opportunities. In the absence of one of these, entrepreneurial opportunities cannot be realized. As one of the important opportunities for the entrepreneurship, the existence and the type of market opportunities may greatly impact on the nature of entrepreneurship that emerges, which in turn may be greatly influenced by the role of the institutional system in conveying information and creating incentives among similar or identical technological opportunities.

Small businesses often require external help in order to grow and compensate for financial and technological liabilities. Most rich countries have created incentives to help small business to grow (Bhidé, 2000; Vossen, 1998). Among the direct subsidy incentives directed to small and medium sized enterprises in OECD countries, the US Small Business Innovation Research program (SBIR)is often considered one of the most successful. This program reserves a percentage of federal agencies' R&D budgets for research projects conducted by small businesses covering three phases over time from financing exploration of the technical feasibility of an idea or technology, the proof of concept, through financing the pre-prototype and the evaluation of the potential for commercialization, to support the move from the laboratory into the marketplace. By facilitating commercialization, SBIR has provided a substantial contribution to higher employment and sales growth (Lerner, 2000), entrepreneurship promotion (Elston et al., 2011; Qianet al., 2014), national competitiveness enhancement (Audretsch, 2003), higher rates of commercial success (Archibald and Finifter, 2003; Siegel et al., 2003), broader economic transformation (Keller and Block, 2013), and positive net economic and social benefits to society (Audretsch et al., 2002a; Allen et al., 2012).

Previous studies show that some factors influence the small business to obtain the SBIR grants: type of entrepreneurship, geographic clusters, employment and external funding; these factors are quite similar to those that influence their innovation performance.

Empirical evidence suggests that the SBIR has influenced the career paths of scientists and engineers by facilitating the start-up of new firms. Case studies show that half of the scientists indicated that the SBIR award influenced their decision to start the firm. Without SBIR, 20% of them would not have started the firm, and another 40% would not have continued the firm (Audretsch et al., 2002b). SBIR program funds are distributed predominantly to start-ups whose owner has a post-graduate education (Galope, 2014). In biomedical industry, SBIR firms associated with these scientists or with university research perform significantly better than other SBIR firms in terms of follow-on venture capital funding, SBIR program completion, and patenting (Toole et al., 2007; Link and Ruhm, 2009). Age of firms: The established technology-based small firms have the highest successful rate among the nascent firms for SBIR-supported R&D endeavors (Gicheva et al.,2016). The odds of being granted SBIR R&D subsidies are also higher for those who had prior R&D experience and owned patents at the start of their business operations. (Galope, 2014)

Firms clustered with SBIR winners are more likely to enter the program and to win awards in multiple time periods than are isolated firms (Wallsten, 2001; Kolympiris and Kalaitzandonakes, 2013). It is also found that start-ups located in states that are not known for their R&D performance are more likely to receive SBIR funding (Galope, 2014).

Firms with more employees and which appear to do more research win more SBIR grants, but the grants do not affect employment. (Wallsten, 2000).

While the SBIR awardees and matching firms did not differ significantly in the likelihood of receiving venture capital in the years prior to the awards, in subsequent years the awardees were significantly more likely to receive such financing. This pattern, however, was not uniform. The superior growth of SBIR awardees was confined to firms based in ZIP codes with substantial venture capital activity. These patterns were more pronounced in high-technology industries (Lerner, 2000). SBIR firms attracting private equity investments are significantly more likely to license and sell their technology rights and engage in collaborative research and development agreements. (Link et al., 2014)

Despite the good evaluation of the SBIR program, there are some shortcomings: enhanced commercial success from the SBIR program appears to have come at the expense of a decrease in the search for technical competence and basic research (Archibald and Finifter, 2003). The grants crowd out firm-financed R&D spending dollar for dollar (Wallsten, 2000; Link and Ruhm, 2009). While small businesses have a unique set of tools and knowledge of the marketplaces, this limited eligibility only for small business may omit potentially valuable sources of dissemination (Diana and Bennett, 2015). Surprisingly, start-ups that did not sell goods and services are more likely to receive SBIR grants (Galope, 2014). The direct impact of SBIR funded projects on employment is small, especially when compared to the mean number of employees in the firms (Link and Scott, 2012).

Based on the literature reviews, seven hypotheses are drawn are as follows:

Hypothesis 1: Firm age influences the awarding performance of small business relating to the solar PV industry;

Hypothesis 2: Number of employees influences the awarding performance of small business relating to the solar PV industry;

Hypothesis 3: Being located in a cluster influences the awarding performance of small business relating to the solar PV industry;

Hypothesis 4: Type of entrepreneurship influences the awarding performance of small business relating to the solar PV industry;

Hypothesis 5: Type of market targeted influences the awarding performance of small business relating to the solar PV industry;

Hypothesis 6: Number of patents influences the awarding performance of small business relating to the solar PV industry;

Hypothesis 7: Availability of external investment influences the awarding performance of small business relating to the solar PV industry.

7.3. Method

A quantitative study is employed to answer the research question.

7.3.1 Data

The data was drawn from the SBIR awards database in the middle of 2015, so the data goes up from the first awards to the end of 2014. Small firms with more than one award of SBIR on the solar cell, a total of 142 small firms (nearly 20% of the awardees have disappeared, 114 firms still exist), compose the sample. The data from the SBIR databank include the city, state, agencies and branches which awarded the funds, project phases and awarded amounts in the SBIR/STTR program. The data are classified under the name of the awarded firm by summarizing the number and the amounts of the awards, the variables of location (C, Table 3.7 is used to identify whether the firms are located in the cluster or not), the number of awards (Q) and total awarding amounts (T).

There are seven other variables, including Market positioning (M)[19], Entrepreneurship types (E), Age (A), number of Employees (N), the availability of external funding (F), Patents of USPTO (P), and whether the firm bankrupted or not(B). For the small companies which are assigned the patents, the number of patents before and after the first SBIR award are identified. By the name of the awarded firms, we searched for information on the above eight variables for each firm on the websites of the firms

[19] Market positioning is put forward and coded here is because the distinctive percentage of the suppliers involved with the military & space are awarded the SBIR/STTR awards. As the mass market is just emerging in the majority of the US, this niche market is worthy of being studied. It is even act as the novel finding of the paper..

which obtained awards, in public reports and in industrial publications. There are a total of 10 variables for analysis (see Table 7.1).

The influence diagram of the different factors are in Figure 7.1.

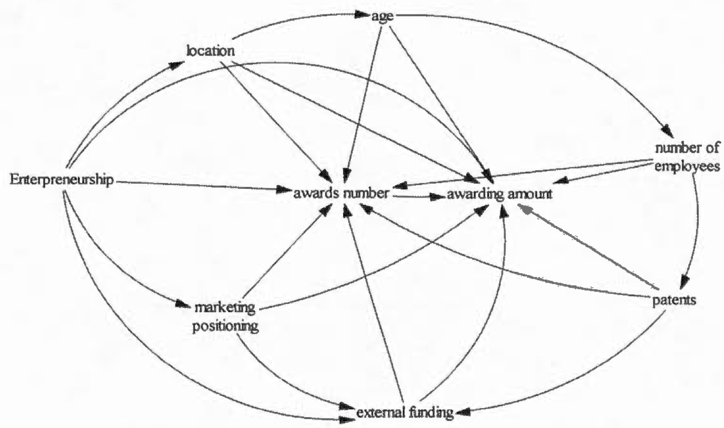


Figure 7.1 Influence diagram for SME innovation

Table 7.1 Variables for analysis

Variables	List	Abbreviations	Type of variables	Values for variables	Remarks
Dependent	Number of awards	Q	Numeric		
Dependent	Total amount of awards	T	Numeric		
Independent	location	C	Nominal	in a cluster =1, not in a cluster=2	There are a total of 11 clusters for the solar PV industry in US (See Table 3.7, defined by the USPTO patent analysis)
Independent	Market positioning	M	Nominal	Mass market =1, Suppliers involved with the military/space markets =2, other suppliers =3	
Independent	Entrepreneurship types	E	Nominal	academic entrepreneurship=1, employee entrepreneurship (with founders who worked for solar firms before) = 2, non-related entrepreneurship (with founders who did not work for solar firms before, solar firms including big firms who had branches or spin-offs in the solar domains) =3	

	Age	A	Numeric		
Independent	number of employees	N	Numeric		Most data are either from their company's website or from the SBIR's website, and some sources are from Linkedin, Bloomberg or Manta.com for verification.
Independent	the availability of external funding	F	Nominal	with Venture Capital =1, public listing in the stock market = 2, no external capital available = 9	
Independent	Patents of USPTO	P	Numeric		From USPTO
Independent	Bankrupted or not	B	Nominal	still existing = 9, bankrupted = 1 and acquired = 2	

7.3.2. Data analysis

In order to explore the significant factors that influence the innovation performance of SMEs for the solar PV industry, the number of awards by SBIR for solar cell(Q) and amount of awards(T) are set as the dependent variable, and other variables are set as the independent variables.

First, the correlation coefficients between the dependent and independent variables were calculated one by one (See Table 7.2). The correlation coefficient between Q and T is 0.92, so here just take the number of award(Q) as the independent variable.

Table 7.2 Correlation coefficients between the dependent and independent variables

		AwardNum	AwardAmount
Market	Pearson Correlation	-.450**	-.386**
	Sig (2-tailed)	0	0
	N	115	115
entrepreneurship	Pearson Correlation	0.151	0.138
	Sig (2-tailed)	0.195	0.238
	N	75	75
cluster	Pearson Correlation	0.122	0.088
	Sig (2-tailed)	0.15	0.296
	N	142	142
AwardAmount	Pearson Correlation	.920**	1
	Sig (2-tailed)	0	
	N	142	142
age	Pearson Correlation	.233**	.188*
	Sig (2-tailed)	0.007	0.031
	N	132	132
employeenum	Pearson Correlation	0.071	0.042
	Sig (2-tailed)	0.414	0.628
	N	133	133
Externalfunding	Pearson Correlation	0.166	0.126
	Sig (2-tailed)	0.076	0.178
	N	116	116
PatentsUSPTO	Pearson Correlation	0.179	0.152
	Sig (2-tailed)	0.052	0.101
	N	118	118

**. Significant at 0.01(2-tailed)

*. Significant at 0.05(2-tailed)

Second, as not every individual firm has the complete data for every variables, the total number of studied cases are below 100(for example, there are just 75 cases firms has the data on entrepreneur), so here Fuzzy-set Qualitative Comparative Analysis (fsQCA)was tried. fsQCA was introduced by Ragin (2000) and it offers a set-theoretic approach to causality analysis, in respect to conditions and outcome. The fuzzy based development from the original QCA means fsQCA explores how the membership of cases in causal conditions is linked to membership in the outcome (Schneider and Wagemann, 2010). Features of fsQCA include its ability to model the concept of conjunctural causation: the idea that combinations of various causal conditions, rather than one condition alone, are linked to the outcome (Schneider and Wagemann, 2010). Further, fsQCA also has the potential to capture the idea of equifinality, where more than one combination of causal conditions may be linked to the same outcome (Fiss, 2011). The fsQCA v2.5 software was employed to find the necessary solutions.

The interval scales are dispersed, so the calibrations are done for variables Q, A, N and P. Then the Quine-McCluskey Algorithm is employed to identify consistency and coverage.

Thirdly, Analysis of Variance (ANOVA) is employed to see whether there is some difference among the different groups for the individual factors.

7.4. Results

Our study includes 142 small businesses that have been awarded at least two SBIR awards. As of 2015, 12 of them were bankrupt, 16 were acquired, which means nearly 20% of the small businesses who engaged in solar cell technologies innovation have disappeared by 2015.

7.4.1. Descriptive statistics

Among the 114 Small businesses still existing, 44.7% (51 small businesses) obtained two awards, while nearly 25% obtained more than four awards; 100 small businesses are solar equipment suppliers, and only four of them are specialized manufacturers. Among 100 suppliers, eight of them are only involved in the space or military market, some others are indirectly related to the space or military market.

Only the information on the entrepreneurship of 70 small businesses was found. Out of 70 firms, two are NASA spin-offs, 26 are established by academic entrepreneurs, 35 are former-employee entrepreneurs and seven of them are non-related entrepreneurs. Most of them are equipment suppliers for the solar PV industry, their initial entrepreneurship is not in the solar PV domain.

65 awardees are not located in a solar cluster, and another 49 are located in a cluster. 10% of small businesses are aged less than 8 years, 20% are aged 9-14 years, and 65% 15-24 years. Small businesses with employees of less than 6 represent about 25% of the samples; the same percentage applies to the other three groups of small businesses,

with a number of employees of 7-12, 13-35 and more than 36 respectively.

Only 29 small businesses have patents in solar cells, out of which nearly 70% have not more than 3 patents in solar cell(s). Only three companies obtained venture capital as external funding, and six of them were publicly listed.

7.4.2. FsQCA analysis

Because only existing companies are selected for the analysis, B is removed; T is highly correlated with Q, so T is removed; There are only 3 awardees obtaining the VC, and 6 awardees publicly listed on the stock market, so F is removed due to the very low frequency. So there are only 7 variables left. In order to see which factors are contributing to the numberof SBIR awards for the solar PV industry, these 7 variables including the number of awards(Q) as the dependent variables are analyzed with fsQCA.

The fuzzy truth table of configuration of 6 independent variables is in Table 7.3.

Table 7.3 Truth table for configurations when considering TEA outcome

m	e	c	n-c	p-c	a-c	Number	Raw consist.	PRI consist.	SYM consist
1	0	0	0	0	0	13	1.1812	0.2548	0.2748
1	1	0	0	0	0	12	0.4239	0.2256	0.2325
1	1	0	1	0	0	9	0.5906	0.4005	0.4031
1	0	1	0	0	0	7	1.1052	0.2015	0.2048
1	1	1	1	0	0	6	0.6750	0.4397	0.4672
1	1	1	0	0	0	5	0.5552	0.3695	0.3794
1	1	0	1	0	1	5	0.6585	0.4699	0.4829
1	1	1	1	0	1	4	0.6977	0.5363	0.5439
1	1	0	0	1	0	4	0.7523	0.6012	0.6012
1	0	1	1	0	0	4	1.0325	0.3707	0.3945
1	1	1	0	1	0	3	0.8950	0.8558	0.8558
1	0	0	1	0	0	3	1.0346	0.5457	0.5576
1	1	1	1	1	1	2	0.8395	0.7629	0.7629
1	1	1	0	0	1	2	0.6336	0.3842	0.3842
1	1	0	1	1	1	2	0.6157	0.3675	0.3676
1	1	0	0	0	1	2	0.5466	0.2855	0.2855
1	0	1	1	1	0	2	1.0101	0.5983	0.6087
1	0	1	1	0	1	2	1.0250	0.5613	0.6698
1	0	0	1	0	1	2	1.0331	0.5200	0.5200
0	0	0	0	0	0	2	1.0046	0.0000	0.0000
1	1	1	1	1	0	1	0.7979	0.6738	0.6738
1	1	1	0	1	1	1	0.8753	0.8056	0.8056
1	1	0	1	1	0	1	0.8430	0.6964	0.6964
1	0	1	1	1	1	1	1.0055	0.7320	0.7320
1	0	0	1	1	1	1	1.0000	1.0000	1.0000
1	0	0	0	0	1	1	1.0492	0.3365	0.3365
0	1	0	1	0	0	1	1.0018	0.0000	0.0000
0	0	1	1	1	1	1	1.0002	0.0000	
0	0	1	0	0	0	1	1.0021	0.0000	0.0000
0	0	0	1	0	0	1	1.0025	0.0000	0.0000

The results of standard analysis by using the fuzzy truth table are presented in Table 7.4. We can see that the combination A&N&M / N&C&M is the one that has the best consistency and their coverage is not negative. Both configurations include N&M, so it can be concluded that the companies with more employees and targeting a specific market have more SBIR awards.

Table 7.4 Sufficiency analysis results

	Raw coverage	Unique coverage	Consistency
~p-c*~c*m	0.378881	0.060708	0.392220
~a-c*e*m	0.422187	0.026102	0.529908
a-c*n-c*m	0.464900	0.012062	0.703049
n-c*c*m	0.298794	0.023136	0.730305
c*e*m	0.335179	0.053787	0.584482
~a-c*~p-c*~n-c*~e	-0.776351	0.030453	1.492209
~a-c*~p-c*n-c*~c	0.224639	0.000989	0.606514
a-c*p-c*n-c*c*~e	-0.922287	0.009887	1.007126
Solution coverage:		0.930591	
Solution consistency:		0.467700	

In order to see whether there are differences between groups for the extracted variable N&M, ANOVA is used. We concluded that there is a significant difference between the groups (Table 7.5): suppliers involved in the military market have more awards that others(Table 7.6).

Table 7.5 ANOVA analysis of market position

Q

	sum of squares	Df	mean square	F	sig.
Between groups	480.000	2	240.000	12.829	.000
Within groups	1964.250	105	18.707		
Total	2444.250	107			

Table 7.6 Quantity of awards V.S. market position

Q

Market position	Average	N	Standard deviation
Mass manufacturer	5.75	4	5.188
Suppliers in military	11.75	8	11.793
Other suppliers	3.75	96	3.095
Total	4.42	108	4.779

To explore innovating capabilities, the patents that SBIR awardees are assigned before and after the first SBIR award have been explored (Table 7.7). We found that 80% of patents for solar of SBIR awardees are assigned after their first award; there is a significant difference before and after the first awards (Tables 7.8 and 7.9). The innovative performance is significantly enhanced with SBIR awards for small businesses in the solar PV sector in the US.

Table 7.7 SBIR awardees with patents

Company name	AwardNumber	PatentsUSPTO	Earliest award	Earliest patents	Patents after awarding	Patents before awarding
Emcore Corp.	2	9	1990	2003	9	0
Energy conversion devices, inc.	6	12	1997	1980	1	11
Spire Corporation	22	14	1984	1982	11	3
Banpil Photonics, Inc.	4	12	2007	2012	12	0
MicroLink Devices, Inc.	39	8	2007	2011	8	0
Entech, inc.	5	7	1991	1985	3	4
Konarka technologies, inc.	5	7	2002	2006	7	0
Solarmer Energy Inc.	3	6	2011	2013	6	0
Composite Technology Development, Inc.	7	4	2008	2011	4	0
Magnolia Solar Inc.	5	4	2010	2014	4	0
Deployable Space Systems, Inc.	10	4	2008	2014	4	0
International solar electric technology	14	3	1991	1990	2	1
Kopin Corporation	8	3	1989	1991	3	0
JX crystals, inc.	6	3	1993	2008	3	0
Crystal Systems, Inc.	4	3	1984	1999	3	0
Applied Solar Energy Corp.	3	3	1995	1988	1	2
Thermacore, inc.	2	3	1992	1981	1	2
Essential Research, Inc.	9	2	1997	1996	1	1
Anvik Corporation	5	2	2003	2000	1	1
Integrated Micro Sensors	5	2	2007	2008	2	0
Gratings	6	1	1995	2005	1	0

Iowa Thin Film Technologies	6	1	1990	1995	1	0
Itn Energy Systems, Inc.	5	1	2004	2012	1	0
EpiWorks, Inc.	4	1	2005	2015	1	0
Plant pv	4	1	2011	2015	1	0
Epir technologies inc	3	1	2007	2014	1	0
Agiltron, inc.	2	1	2011	2012	1	0
Deposition sciences, inc.	2	1	1991	2000	1	0
Nano-c, inc	2	1	2008	2014	1	0

Table 7.8 Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	After award	3.2759	29	3.21710	.59740
	Before award	.8621	29	2.19942	.40842

Table 7.9 Paired Samples Test

	Paired Differences					t	df	Sig.(2-tailed)
	Mean	Std. deviation	Std. error Mean	95% Confidence interval of the difference: Lower	Upper			
Pair1 after - before	2.41379	4.05777	.75351	.87030	3.95729	3.203	28	.003

7.5. Discussion

Hypothesis 5 is accepted. Hypothesis 2 is accepted only when combined with Hypothesis 5. The other five hypotheses are rejected.

Among 95% of the SBIR awardees who are equipment contractors, it is significant that military equipment suppliers obtain more awards. Since 63.8% of awards and 66.2% of the grants are distributed by either the Department of Defense (DOD) or the National Aeronautics and Space Administration (NASA) (see Figure 7.2 & 7.3), it might be inferred that SBIR awards for the solar PV sectors are primarily intended for internal military use. Some other results support this conclusion as well: although six awardees have been publicly listed, five of them obtained most of the awards from the other government agencies instead of DOD and NASA(See Table 7.10). As a whole, few small specialized manufacturers targeting the mass market receive SBIR support. All findings confirm the conclusion that most of the grants and the funds invested in SBIR went to agencies whose mission within SBIR is to develop technology for the same agencies (internal use) (Allen et al., 2012).

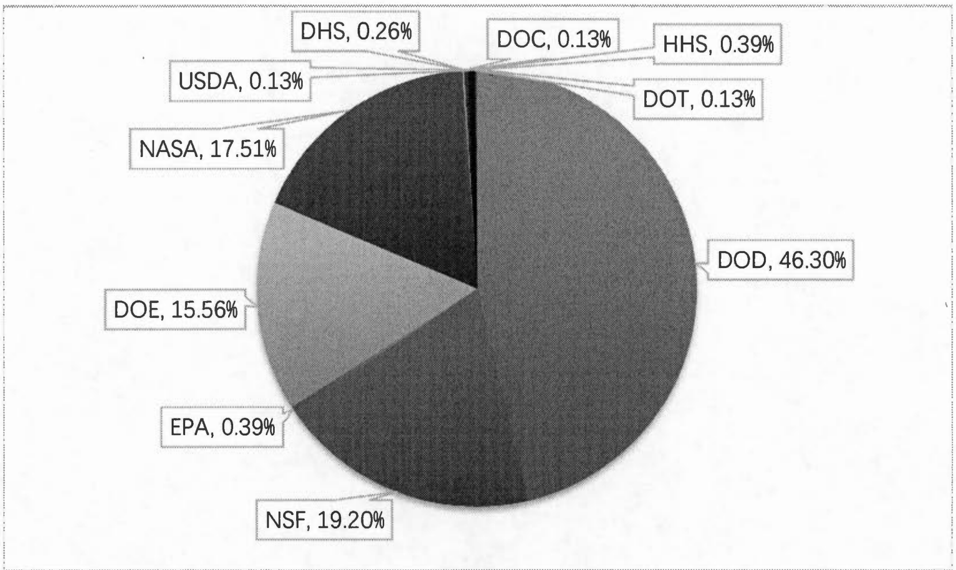


Figure 7.2 SBIR awards in solar PV from the different government agencies (out of total number of awards)

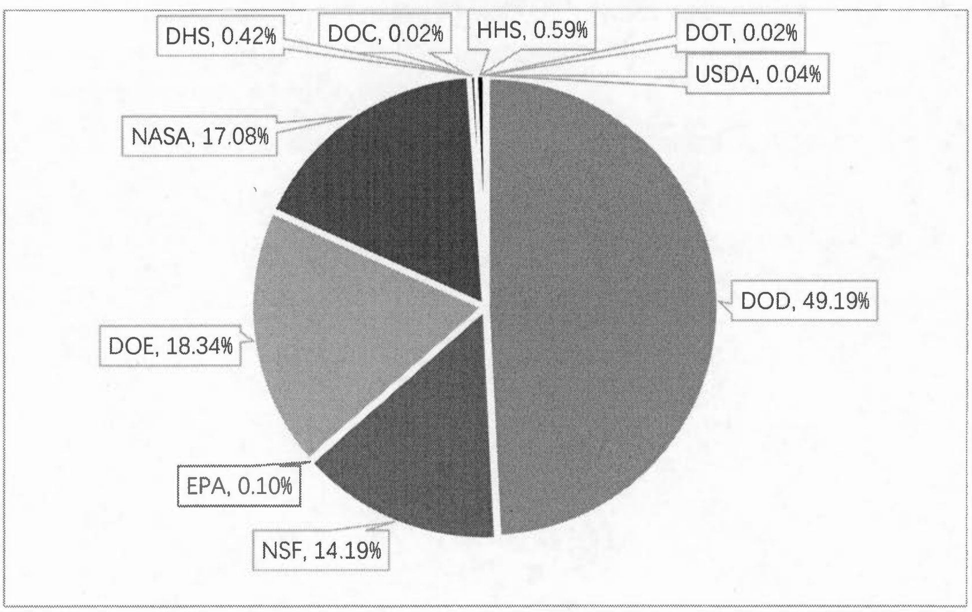


Figure 7.3 SBIR awards in solar PV from the different government agencies (out of total amount of awards)

Table 7.10 The SBIR awards of six public listed awardees

Public listed awardees	Total SBIR awards	DOD/NASA awards	Other agency awards
Spire Corporation	22	13	9
Luna Innovations	9	3	6
Kopin Corporation	8	8	
Applied Nanotech	3	1	2
Emcore	2	1	1
Illuminex Corporation	2		2
Total awards	46	26	20

In addition, only 3 awardees (around 3%) funded by SBIR received venture capital, which is greatly different from the NIH awardees. (In the 1992-2005 period, out of a total of 1536 NIH SBIR awardees, 185 firms (or 12%) received venture capital, 25% of the top NIH SBIR awardees received venture capital funding after the second SBIR award (Wessner, 2009). Lerner (1999, p. 285) concluded: "The superior performance of awardees was confined to firms in regions with substantial venture capital activity and was pronounced in high-technology industries. Multiple awards did not increase performance". For the solar PV sector, only a few SBIR DOD awardees received venture capital, and the little venture capital they received was confined to firms located in the main VC clusters, such as Silicon Valley, Route 128, Los Angeles, and the corridor Boston-NY-Washington DC. Thus, inthis specific sector, DOD or NASA funded projects with their products aiming at the niche markets did not interest venture capital or angels. The market for these firms and their products is restrained, and this restriction may explain why the percentage of DOD-supported firms having obtained venture capital is so low. Few of these entrepreneurial firms are developing products for large markets. Their profitability and potential growth are necessarily affected.

Link and Scott (2010) state that through the SBIR program the government is redirecting R&D resources toward the development of technologies that the market alone would not have developed. In its solicitations of SBIR proposals and subsequent funding of awards, the government is organizing, coordinating and allocating scarce resources among competing uses. When the mass market is not ready, SBIR support can promote the development of solar PV technologies, but when the mass market is ready, the competing uses from the government will prevent the dissemination and diffusion of the technologies, and even introduce barriers to industrial development.

With technological progress, the cost of manufacturing and installing a photovoltaic solar-power systems has decreased by about 20 per cent with every doubling of installed capacity(Bloomberg New Energy Finance, 2015).According to Lorenz et al., (2008), during the next three to seven years, solar energy's unsubsidized cost to end customers should equal the cost of conventional electricity in parts of the United States (California and the Southwest) and in Italy, Japan, and Spain. These markets have in common relatively strong solar radiation, high electricity prices, and supportive regulatory regimes that stimulate solar-PV capacity growth that drive further cost reductions. These conditions set in motion a virtuous cycle: growing demand for solar power creates more opportunities for companies to reduce production costs by improving solar-cell designs and manufacturing processes, to introduce new solar technologies, and to obtain lower prices from raw-material and component suppliers competing for market share.

When the mass market is ready and knowledge spillover effects become more widespread, what is the best way to encourage small or start-up firms to take the chance of participating and being profitable in this specific sector?

The obstacles facing photovoltaics manufacturing in the United States are many. They include:

- Inadequate scale: most US manufacturers are small and medium-sized enterprises unable to compete in many segments of the industry.

- Excess global capacity and international competition: the fast rise of solar module manufacturing in China and Taiwan (representing over 50% of global production) has pushed down prices for solar PV equipment.

- Dependence on subsidies: even if technical change is driving down the cost of solar PV, in 2011 only subsidized panels could be installed in the United States.

- Technical challenges: the industry is progressing very fast in terms of the efficiency of solar PV panels. In addition, the lack of technical standards makes the investment in this technology too risky for venture capital to invest. (Wessner and Wolff, 2012)

The policy implication is that if the United States wants to develop solar technologies for civilian markets, they should either give incentives to other government Departments to subsidize the development of this type of technology, or they should organize a Grand Challenge, such as the Human Genome or the Human Proteome Programs, and join entrepreneurial SMEs, large corporations, universities and other stakeholders in a consortium to define industry standards in product and process. The solar PV technology is on the threshold of achieving cost parity with fossil fuels. The country which meets the future standards and acquires the market for this technology will obtain major returns on its investment. Small SBIR subsidies will not give back the United States the leadership lost in this technology.

7.6. Conclusion

It is found that only the factor of targeting the military market can make the small business obtain more SBIR grants among the seven general-evaluated factors. The innovation capabilities and the technological diffusion effects of small businesses are thus restricted. This can partly answer the question "Why is small business in the solar

PV industry still quite weak in spite of a similar governmental support program as that in other industries?"

The study samples only the small businesses which are awarded SBIR grants, which might be the most innovative groups, but does not paint a full picture of small business in the solar PV industry in US. Other studies should be conducted to explore further the factors for success in the solar PV although there are quite a few successful specialized manufacturers in the US, so that a comparison can be made for suitable policy recommendations. Furthermore, by the time solar energy becomes more and more cost-effective, so as to be a good replacement for conventional electricity, the subsidy policies might be obsolete. In such circumstances, the question of what policies should be implemented to take advantage of the competitive advantages of the US requires further detailed comprehensive policy research.

CHAPTER VIII

A SECTOR WITH INNOVATIONS DRIVEN BY DEMAND

8.1. How to explain the distinctive features of the sector?

Based on the above research in the important aspects of the solar PV sector, some distinctive characteristics have been drawn:

- The majority of the innovators are the industrial user firm, but not the pure solar PV firms whose primary business is solar PV. Government subsidy policies to promote usage greatly influence industrial development and innovation behaviours.

- The different generations of technologies have been coexisting for a long time. Although the new technologies have been massively exploited in recent years, the technologies with the highest market penetration rate are not the most advanced.

- For the solar PV innovation, even the star scientists put just half their expertise in the sector, and another half in the other related areas. Their academic entrepreneurship is quite limited.

How to explain the above phenomenon, which is in some way different from the typical high-tech sector, has brought new questions. If taken as a high-tech sector, the solar PV sector is not such a classic high-tech sector that its innovation and the industrial development are driven by the scientific or technological progress. But if taken as a traditional sector, its technology developed so rapidly and the technological innovation that made cost-efficient improved so significantly that the solar energy has become more and more feasible to be used. How to understand the specific sector is the objective of the chapter.

8.2. Similarity with the semiconductor sector

The case of solar PV sector is not unique. The semiconductor sector, which is the important origin sector for the solar PV sector, also has the same characteristics as those of the solar PV sector in some points.

By examining patents, co-patents, R&D alliances and new ventures in semiconductors, Adams, Fontana and Malerba (2013) have drawn quite similar conclusions for the semiconductor sector:

1. The magnitude of innovation by user firms was quite high in both absolute and relative terms compared to firms in the sector over the entire period under examination,

and a broad range of intermediate users were a major source of patents in a product field (semiconductor devices) outside of their 'core' business.

2.The distribution of innovation among firms from different intermediate user industries was highly uneven; this finding points to differences across final demand groups in terms of the requirements, the intensity of use, and the strategic content of semiconductors.

3. Innovative users were highly heterogeneous in terms of size, diversification and vertical integration. Large user firms, most of which were vertically integrated, had substantial patent portfolios. Their main line of business is not semiconductors but they produce chips as vertically integrated user firms rather than as diversified semiconductor firms. There is also evidence of a vast number of smaller user firms that were able to patent this technology, albeit at lower rates.

8.3. User-innovation sector whose innovations are driven by demands?

According to Adams, Fontana, and Malerba (2013), the various streams of research have shown that user firms may contribute to innovation in a variety of ways. 'Active' users may simply provide knowledge and feedback to producers (Eurostat, 2004) while 'lead' users (von Hippel, 1986; Gault and von Hippel, 2009) will innovate on their own in order to develop solutions for their specific needs before the bulk of the marketplace even recognizes the same need. 'Experimental' users (Malerba et al., 2007) are willing to try emerging technologies and attribute intrinsic merit to a product simply because it embodies a new technology. 'User entrepreneurs' go further to take responsibility for the production and commercialization of products/services that they have first developed for their own use (Hienerth, 2006; Shah and Tripsas, 2007). 'Vertically integrated' user firms are designing and producing components for their in-house use and often sell their component solutions to the open market as well. For the semiconductor sector, "vertically integrated" user firms ("user firm" afterwards) are the important innovators.

Adams et al (2013) classify the actors of semiconductor sector into five categories: Semiconductor Firms, User Firms, Academics and Professionals, Linked Industries and Other Industries. The User Firms category consists of companies that sell products or services that use or incorporate semiconductors in six industries including Industrial Machinery, Consumer Electronics, Computer Equipment, Telecommunications, Automotive, Instrumentation and Aerospace/Defense.

By separating the related manufacturing firms into two groups, we can classify two categories for solar PV sector: one is composed of user firms and the other is made of specialized firms.

- User firms are companies whose main business are not solar PV products but they innovate in solar PV for serving their main business. Their main demand is from their specific usage (for example, to be used in extreme environments such as in space or offshore exploration), and the demand-driven innovations are mainly conducted inside the firms.

- Specialized firms are companies whose main business are the manufacturing and sale of solar PV products. Their main demand is from the daily electricity usage, in which the priority will be the low-cost for the front-up installation and adequate supply of the energy for daily use.

Specialized firms appeared around thirty years ago, which may seem very late compared to the sixty-year technology development history of user firms. Actually, user firms have pushed the technology innovation for the solar PV sector in the long run. Historically, the various applications of solar PV technologies evolved in the following order: its first application was in space, in the late 1950s and 1960s, with satellites requiring a reliable long-term source of electricity, even if the cost of this energy was high. A second major application, in the 1970s, was in sea buoys and sea oil and gas exploration and exploitation, far from conventional sources of electricity. At this time, large hydrocarbon companies such as ARCO, BP and Shell started investing in solar PV R&D. As the cost of solar PV energy started to decline, following technical advance, some companies such as Telecom Australia became interested in the sector to provide telephone connections to a country with close to 8 million square km, lots of sunshine, but only 12 million population in the early 1970s. At the same time Japanese companies such as Sharp, and then Sanyo, invested in solar technology to equip their hand calculators and similar devices.

The number of patents owned by the top ten user firms and the top ten specialized firms are respectively listed in Table 3.11 and 3.12. Top ten user firms hold nearly 20% of total USPTO patents in solar PV while top ten specialized firms just hold nearly 5%.

By separating the firms into user firms and specialized firms, we can draw almost the same conclusion as that in the semiconductor sector: the solar PV sector is a user-innovation sector whose innovations are driven by demand.

Considering the characteristic of user-innovation, the distinctive features defined at the beginning of the chapter can be explained well here:

1. Distinct academic innovation behaviours:

- Nearly half of the publications of star scientists in the solar PV sector are in the other related domains;
- Academic entrepreneurship is quite limited;
- It is unusual that the star scientists who have a great number of publications do not

have many patents, and the inventors who have large numbers of patents do not have many publications, while the star scientists always have the numbers of publications and patents in the same time for bio-industries;

Considering the fact that the intermediate user firms are dominating the sector, the majority of the innovation is made inside big user firms, the diversified research direction well be made inside the firms and the research budget will be dispersed among the different user firms, the attractiveness and support for the academic scientists are much less than that of other high-tech industries. This can well explain why there are different innovation behaviours in the sector.

2. The coexistence of the different generations of technologies while the first generation still holds the biggest market share.

There are three generations of technologies available now, but the technology with the highest marketing penetration rate is still the first generation, by which Chinese manufacturers can achieve the best performance in the world. Why did the new technology emerge so fast, but the dominating technologies are still of the first generation? The answer is that innovation is driven by demand. On the one side, the diversified demands from the user firms drive the continuous innovation; on the other side, the massive market demands of daily electricity usage have not been explored yet. As the more mature the technology is the less costly, the technology used massively drives few continuous investment for R&D. Nowadays, the technologies in the first generation still have the cost advantages, and it is still the best choice for the much bigger daily electricity usage market. Only on the condition that the more advanced technologies can be installed and operated in the same or less cost, the other generations of technology can achieve the higher market share.

3. The catching-up capability of developing countries is supported by the demand of the usage in the low cost; only countries with fast-moving integrating production capabilities can satisfy the demands of the market in the lower cost. This can explain why Chinese manufacturers can catch up on production and not on cutting-edge innovation and maintain the highest market share in the recent years.

8.4. Can the solar PV sector be taken as a new sub-category in the high-tech industries?

Based on the above studies, our conclusion is that the solar PV sector is not a traditional high-tech sector but a demand-driven one. Because of this significant feature, the sector has embodied a different academic innovation behaviour, in the evolution of the technologies, and in the comparative advantages among the different countries. So the question will be: can the solar PV sector be taken as a new sub-category in the high-tech sector? There are two concerns blurring the answers:

1. The sector is in such an early stage that it is not possible to draw any conclusions at the moment;

2. There indeed exists such sub-category in the high-tech industries whose innovation and the industrial development is mostly driven by the demand instead of by the technological progress itself.

If the second statement is confirmed, we have to establish a complete system to further explore the features, the rules and the problems of the sector to guide its development.

CHAPTER IX

CONCLUSION

9.1. Theoretical contributions

As the first study on the solar PV sector in the world with comparatively complete data, this study has contributed four points to the academic theories, and to the three levels of industrial practitioners.

9.1.1.Theoretical contributions

By using the methodology of SSI, this study gives more flesh to the concept of innovation cascade. Solar PV is not as classic as some other high-tech sectors, whose technology transfer pattern is quite clear in terms of location of innovation centers. The innovation cascade is well described and suggested by drawing the s vividly showing that the different publications peaks appeared successively in the different regions.

The uneven development and the organizational diversity of the clusters in the same sector are proven. It was found that more diverse clusters, hosting research universities, large multi-technology corporations, public laboratories, SMEs and venture capital, such as Silicon Valley, could be more resilient than clusters based on one or two large firms. In this kind of (more uncommon) clusters, the exit of the anchor tenants will not lead to the decline of the clusters. The factors influencing the resilience of the clusters in the specific sector were defined.

The criteria for defining the star scientists in the different sectors should be examined one by one, and the features of the sectors determine the contribution of academic star scientists to the development of the sector. So special attention should be paid regarding the generality of the concept and the usage of the star scientist notion.

The idea that innovation is driven by demand was explored, which can be the reason for several differences between the solar PV sector and other classic high-tech industries. This sheds light on exploring whether there is a distinctive sub-category of high-tech sector.

9.1.2.Contributions for industrial practitioners

By employing the methodology of SSI, the study firstly depicted the complete development and innovation picture at the country and regional level, which can be applied to the different levels of industrial practitioners.

At the country level, the evolution of the sector has showed the competitiveness of individual countries in the past and in the present, and the competitive advantages and disadvantages of the different countries. It provided a solid base for policy-makers to design the industrial arrangement and formulate viable industrial policies.

At the regional level, clusters in the world and inside major countries were found and analyzed. By understanding the differences among the clusters and the reasons for the uneven development of the clusters, policy-makers can take the experience and lessons from other clusters as well as the ideas on how to improve or launch the clusters.

At the firm level, it is very important to understand the macro-environments in which the firms are positioned. The marketing classification and the consuming demands were stated, the competition and innovation status were defined, the academic contributions were highlighted, all of which will be the context for drawing the development strategies for the firms either as users or directly as product or service providers.

9.2. Policy implication of the study

As there are policy implications in the previous individual chapters, here we focus on the key principle to formulate the sector policies.

According to Adams et al (2013), instead of adopting the general policies with the objective of stimulating "demand for innovation" including public procurement to regulate the solar PV sector, public policy should pay attention more on "innovation by demand", which is to valorize the application and technological knowledge that user firms possess and to stimulate them to introduce innovations and new technologies for wider markets. It is thought that the shift in perspective from supporting demand for innovation to supporting innovation by demand could be significant, and may add an important policy input for the growth and dynamics of an economy.

The policy implications of "innovation by demand" can be directed in the following aspects:

- In order to push the development of the solar PV sector, firms, experts and scientists in related industries should be encouraged to put their available capabilities and resources to solve the demand problems of wide markets. Only with all this integrated expertise, innovation can be made efficiently. At the same time, large companies with related capabilities should be promoted. For example, apart from the Feed-in-Tariff, other promoting policies including subsiding the innovation in solving the existing problems with the solar PV technologies, funding the invention of the new applications, awarding the priority to the solar PV related academic research, can be deployed.

- The demands of daily electricity use should be addressed for innovation: compared to the application in extreme environments and niche markets, daily electricity users have their own requirements, for example, they are more sensitive to installation and usage costs, more preferable to more dispersed locations, and more demanding on the storage of the surplus during the periods of insufficient sunshine.. For this part of demand, apart from solar PV manufacturers, the related industrial users should be encouraged to transfer their comparatively more advanced technologies into the construction-energy usage.

- The diversification of the actors in the clusters: it has been proved that the clusters with diverse actors are more resilient than those constituted just by just a few agents. Along with the idea of "innovation by demand", solar PV clusters should attract users with different applications to establish a diversified ecosystem, which will bring the sector into a healthy development cycle. As the solar PV sector is moving towards grid parity, well-understood and targeted subsidies will be critical to build the confidence of investors and attract capital. In addition, as the academic scientists are not so active in technological innovations, the priority of the research funds can be used to promote research and innovation in this specific domain.

- Phase out subsidies carefully. Since solar power could eventually be cost-competitive with the other conventional sources, regulators must adjust incentive structures over time and phase them out when grid parity is reached.

9.3. Limits and orientation for further research

Established in the theoretical framework of SSI, the study has reviewed the several elements including the technologies and the related innovation behaviour, firm and non-firm organizations, evolution processes and some of its economic performance such as the geographic agglomeration. But as a comprehensive system, the understanding of the sector is far away from the degree in which it is fully understood both in terms of depth and scale.

For the aspects we have focused on during the research, we have to deepen the understanding:

- In terms of the evolution of the sector, can technology transfer rules in the world be generalized for the other high-tech industries? The drivers of technology transfer should be explored further.

- In terms of innovation clusters, what is the contribution of the different factors to the rise and fall of the clusters? Comparative studies with different clusters should be made.

- In terms of innovation behaviour, what are the other domains of the star scientists defined in the field? Does their academic research tend to converge to or diverge from the solar PV? Can the complementary expertise from the firms help them focus more on solar PV innovation?

- In terms of entrepreneurship, as the academic entrepreneurship is limited, what features do successful entrepreneurs have? What factors influence the longevity of start-ups?

- In terms of catch-up, the review of Chinese solar PV sector is just concentrated in the early development before 2011. Whether China can maintain the advantages at a later stage will be in the core part of the real catch-up ,so we have to keep track of the sector to formulate an objective answer.

For the aspects that we have not yet explored, more research on their distinctive features and their corresponding industrial performances should be made.

APPENDIX A

THE EVOLUTION OF SOLAR CELL TECHNOLOGIES[20]

- 1767, First Solar Collector (Switzerland)

In the year 1767, a Swiss scientist named Horace-Benedict de Saussure created the first solar collector — an insulated box covered with three layers of glass to absorb heat energy. Saussure's box became widely known as the first solar oven, reaching temperatures of 230 degrees Fahrenheit.

- 1839, Photovoltaic Effect Defined(France)

In 1839, a major milestone in the evolution of solar energy happened with the defining of the photovoltaic effect. A French scientist by the name of Edmond Becquerel discovered this using two electrodes placed in an electrolyte. After exposing it to the light, electricity increased.

- 1873, Photo Conductivity of Selenium(UK)

In 1873, Willoughby Smith discovered photoconductivity of a material known as selenium. The discovery was to be further extended in 1876 when the same man discovered that selenium produces solar energy. Attempts were made to construct solar cells using selenium. The cell did not work out well but an important lesson was learned

[20] http://exploringgreentechnology.com/solar-energy/history-of-solar-energy/

— that solid could convert light into electricity without heat or moving parts. The discovery laid a strong base for future developments in the history of solar power.

- 1883-1891 Light Discoveries and Solar Cells(Germany)

During this time several inventions were made that contributed to the evolution of solar energy use. First in 1893 the first solar cell was introduced. The cell was to be wrapped with selenium wafers. Later in 1887 there was the discovery of the ultraviolet ray capacity to cause a spark jump between two electrodes. This was done by Heinrich Hertz. Later, in 1891 the first solar heater was created.

- 1908, Copper Collector(US)

In 1908 William J. Baileys invented a copper collector, which was constructed using copper coils and boxes. The copper collector was an improvement of the earlier done collector but the only difference was the use of copper insulation. The improvements of the invention are being used to manufacture today's equipments.

- 1915, Photoelectric Effect (US)

In 1915, Robert Millikan first experimentally showed Einstein's prediction about the photoelectric effect was correct.

- 1958, Solar Energy in Space (US)

Solar power was used to power space exploration equipment such as satellites and space stations. This was the first commercial use of solar energy.

- 1959-1970, Efficiency of Solar Cells and Cost (US)

During the period between 1959 and 1970, there was major discussion about the efficiency of solar cells and reduction of costs. Up to that time the efficiency of the solar cells was only 14% and was not comparable to the high cost of producing cells. However in the 1970s, Exxon Corporation designed an efficient solar panel, which was less costly to manufacture. This was a major milestone in the history of solar energy.

- 1977, Governments Embrace Solar Energy(US)

In 1977, the US government embraced the use of solar energy by launching the Solar Energy Research Institute. Other governments across the world soon followed.

- 1981, Solar Powered Aircraft (US)

In 1981, Paul Macready produced the first solar powered aircraft. The aircraft used more than 1600 cells, placed on its wings. The aircraft flew from France to England.

- 1982, Solar Powered Cars (Australia)

In the year 1982, there was the development of the first solar powered cars in Australia.

- 1986-1999 Solar Power Plants (US)

Evolution of large-scale solar energy plants with advancement being made in each phase. By the year 1999, the largest plant was developed producing more than 20 kilowatts.

- 1999, Breakthroughs in Solar Cell Efficiency (US)

The most efficient solar cell was developed, with a photovoltaic efficiency of 36 percent.

- 2008, Subsidy Reduction in Spain (Spain)

Due to the global financial crisis in the year 2008, the Spanish government reduced subsidies on ongoing solar power production in the country. This had a negative effect on the sector across the world.

- 2010, Evergreen Solar and Solyndra Fail (US)

Two leading solar companies failed. This was due to lack of market for their high technology produced products.

- 2012, Record Breaking Solar Plants (China)

The past few years have seen enormous investment in utility-scale solar plants, with records for the largest frequently being broken. As of 2012, the history's largest solar energy plant is the Golmud Solar Park in China, with an installed capacity of 200 megawatts. This is arguably surpassed by India's Gujarat Solar Park, a collection of solar farms scattered around the Gujarat region, boasting a combined installed capacity of 605 megawatts.

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