1. Introduction

1.1 THE ORIGIN OF THE STUDY

Since the late 1970s the Chinese economy has been fast catching up in many industries, including information and communication technologies, vehicles, and other sectors. The solar photovoltaic industry is different from the other industries. It is the only sector in which the Chinese have claimed a large market share in the world economy. How was this accomplished? What are the factors leading to the success of the Chinese solar PV companies?

In the study of the solar PV sector we found that Chinese domestic factors alone cannot explain their success. The sector needs to be studied in a systematic way and at the global level, because its dynamics are global.

Therefore the topics we decided to study in the solar PV sector with the theories of sectoral system of innovation are as follows:

- How is the sector evolving in both technological and economic perspectives? Does the evolution help the global diffusion of the technologies? How does the technological diffusion promote the development of the sector in developing countries like China?
- What are the respective functions of the innovation-active components in the sectoral system of innovation, including scientists and small businesses? What are their innovation performances and their contributions to the development of the sector?
- Is there a developmental imbalance in the different regions of the world? And if this is the case, what are the factors leading to those imbalances?

All these questions are to be explored in the theoretical framework of sectoral system of innovation.
1.2 STARTING POINT

In order to explore the new understanding of the industry and maintain the academic value of the study, several aspects have been reviewed. We found that the solar PV sector has not been extensively studied:

- When searching the keywords ‘sectoral system of innovation’ and ‘solar photovoltaic’, we found just four publications in Scopus. Only one of them is really about reviewing the solar photovoltaic sector with the theories and methodologies of the sectoral system of innovation, and the case study is about just three countries. When the keywords ‘sectoral system of innovation’ and ‘solar photovoltaic’ are used to search Google Scholar, there is no other paper on the same subject. A few papers have been written on the global development of the sector 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, another is about Norway, one is about China, and the last 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 the two phrases is searched in Google Scholar, there are no papers about the same subject.

After the complete literature review was done, we found that these important aspects of the industries have not yet been studied. This virgin and fast-growing sector is waiting to be explored to formulate new findings for similar high-tech industries. Perhaps the sector is too new for economists and management scientists alike to have invested major efforts in its understanding as a sector.

1.3 THEORETICAL FRAMEWORK

Our theoretical background is based on evolutionary economics, one that includes non-linearity and inflexion points. We argue that the solar technological system has been improving its performance over the decades since the late 1950s, and recently crossed a landmark point where the performance of the technical system is now speeding up, as seen in Figure 1.1.
1.3.1 The Sectoral System of Innovation

In order to formulate an integrated view of the main dimensions of the sectors and what may account for the differences across sectors, the sectoral system of innovation (SSI) concept is useful. It was put forward by Franco Malerba (2002; 2004; Malerba et al., 1999), 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). The SSI approach highlights a particular set of points: knowledge and structure are key elements; the role of non-firm organizations such as universities, government organizations, local authorities and institutions, and rules of the game such as standards, regulations, labour markets; the dynamics and transformation of sectoral systems are also emphasized.

According to Niosi and Zhegu (2010), 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 systems, how sectoral policies are to be understood in the light of national policies and why some countries pull ahead while others fall behind.

The sectoral system of innovation includes the following components:
The revolution in energy technology

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 evolution.

The institutions: factors including organizations, 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 chapters to follow (see Figure 1.2).

1.3.2 The Evolution of the Sector

According to the literature review produced by Malerba (2007), there are two basic models to study sector evolution: sector life cycle models (Industry Life Cycle: ILC), based on the product life cycle (PLC) on one side, and history-friendly models on the other. Since the late 1970s, several studies using the PLC–ILC model have highlighted 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 products is followed by demand growth, a greater emphasis on process innovations

**Figure 1.2 The study reasoning route**

- 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 evolution.
- The institutions: factors including organizations, 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 chapters to follow (see Figure 1.2).
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 shown that the dynamic sequences differ 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 prominent after the PLC had adopted its canonical form in the 1960s and 1970s. In the meantime, some case studies have been developed using history-friendly models, for example in the computer sector (Malerba et al., 1999; 2001), the pharmaceutical sector (Malerba and Orsenigo, 2002), as well as in other industries such as software and chemicals.

In this research quantitative analysis and the cases 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 and industrial scientists have been in short supply and, in addition, existing companies are usually employing them. Those companies that are able to hire and retain this qualified human capital will have a sustained advantage over those who are 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 the competencies 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 competencies: the capacity to successfully combine those resources, incorporate new technical and scientific knowledge, and 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
The revolution in energy technology
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 speak about competencies, they are referring to technical work experience; however, 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 founders with strong backgrounds in science and technology became more and more important in the high-tech firm’s development, 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 of connecting academic research with 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 work 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 and Darby, 1996). These stars were often the founders and advisors of biotech companies.

In terms of the ways in which star scientists can contribute to the development of the firms, it is necessary to examine 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 university spin-offs (USO), getting listed on the board of directors of start-ups, acting as chief scientists and so on. 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 levels of performance. More entrepreneurial universi-
ties 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) 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 are related to the biotechnology and health sciences. Mowery et al. (2001) calculate that some 75 per cent 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 highlight 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 they are not as prominent as in the USA. None of the studies mentioned the academic entrepreneurship of the solar PV sector. So we will focus on the star scientists and their academic entrepreneurship in our specific sector.

1.3.4 Regional Systems of Innovation: Clusters

‘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 and Zhegu (2010) concluded that external economies, regional knowledge spillovers, cluster absorptive capacity and the existence of anchor tenants are among the reasons why clusters are established. The failure of some clusters while other clusters thrive has been well studied, and the resilience of some clusters is understood.

Like most other high-tech sectors, the solar PV sector has also experienced a marked geographic agglomeration. Vidican et al. (2009) found that the solar photovoltaic sector in the US has been concentrated in the two states of California and Massachusetts, with California hosting the largest share of companies over the years. Mathews et al. (2011) found that in Taiwan, the Fast-Follower Strategy (FFS), a strategy which aims at spanning as many steps in the value chain as possible and as quickly as possible, was adopted to promote the solar PV sector by capturing agglomeration and cluster effects for solar PV technology.
The development of the solar PV sector shows a financial imbalance in recent years. With the withdrawal of government subsidies, 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 have been acquired by competitors under suboptimal conditions since 2009. But at the same time, the solar PV sector grew well in China and Japan. According to Businessinsider.com, China and Japan were the top two countries with the biggest added capacities in 2016.

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

It is to be noted that, because of the EU economic crisis, European countries drastically reduced their additional solar PV facilities in 2016, while China and the United States have taken the lead. India has implemented a plan to produce 20 GW of solar power in 2020. In Latin America Chile (700 MW in 2016) has taken the lead, as has South Africa in that continent.

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 defined. We searched the academic databases and reviewed the related literature, and only then were our hypotheses 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 seen in Figure 1.3.

1.4.2 Data Collection

In order to obtain a complete analysis of solar PV innovation all over the world, data on both patents and publications were employed. In addition, case study and secondary data collection were used for the analysis at the different levels to explore the reasons behind the significance.

1.4.2.1 Patents

Patents are good indicators for assessing technological capability. The 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 flows through innovation systems or regional clusters of firms. Also, a growing number of researchers use patent citations as indicators of the R&D output of firms, or as determinants of innovation performance that

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**Figure 1.3  Research route of the study**

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could impact on their growth. Unlike a simple counting of patents, which is purely quantitative, patent citations also allow 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 United States Patent and Trademark Office (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 can 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 (Dynamic Random Access Memory) industry, Lee and Yoon (2010) investigated patterns of catch-up by Taiwan and Korea, and then they extended the net to include China. Analysing the patents from the USPTO by Korea 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 Taiwanese 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 flat panel displays (FPD); Hu (2008) used US patents registered by the 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 from the 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 the latecomers (Korea and Taiwan) leveraged significant knowledge flows from the technological leaders (US and Japan). But in contrast with earlier studies, Jang et al. (2009) had found that Japan dominates knowledge flows for Korean firms in the FPD industry (Japan accounting for 56 per cent of total citations by Korean firms at the USPTO between 1976 and 2005, compared with only 20 per cent for the US); likewise Taiwan
firms’ patenting favoured Japanese patents. Japan has used the US as a knowledge source, but with less divergence (39 per cent for Japan vs. 34 per cent 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 (2012) then turned their attention to the mobile telephone industry, covering patents taken out at the USPTO by Korean, Taiwanese 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 proof of the innovation capabilities. As the focus is on the solar PV sector, the keywords selected are ‘solar cell’, ‘solar cells’, ‘photovoltaic cell’ and ‘photovoltaic cells’. After studying the patent data in the USPTO and in the European Patent Office (EPO), we found that the data in the USPTO is more applicable than that in the EPO for the following reasons:

1. There are many more patents in the EPO and Chinese Patent Bureau database than in the USPTO, but the above keywords in the EPO and Chinese Patent Bureau database do not produce results that are as exact as in the USPTO, which means that by reviewing the patents randomly selected from the EPO database, some with the keywords in the abstract are not in the solar PV domain. And when the patents issued in the USPTO in the databank of the EPO are compared with the patents directly from the USPTO, there is a big difference in terms of quantity and quality. In order to find more comprehensive data to analyse the sector, the USPTO database is selected for the patent analysis.

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

3. As the most prolific inventing country, the United States assignees own nearly 50 per cent of the solar PV patents. In addition, competitors in Japan, Germany, Taiwan or the People’s Republic of China also patent their inventions in the United States in order to protect them from potential infringers.

Therefore the patent data in the USPTO has been selected as the basis for our patent analysis. Apart from the chapters covering the introduction, characteristics of the sector and conclusion, the different issues in the individual patents are taken as samples in the other five chapters (Table 1.1).
1.4.2.2 Publications
After reviewing several publication databases, we selected Scopus to analyse 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 keywords ‘solar cell’, ‘solar cells’, ‘photovoltaic cell’ and ‘photovoltaic cells’, and then all the publications obtained from these keywords were taken as the new database for analysis. As it was found that nearly all the authors have publications in the other domains, their publications in the other domains were also searched and analysed to explore their academic behaviour and knowledge transfer.

In order to see the relationship between the academic behaviour and 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 answers to how the SSI evolved, the differences among the clusters and why academic entrepreneurship is limited in the solar PV sector, case studies using interviews with some key persons were employed.

1.4.2.4 Secondary data collection
For some key case studies where there was no response to the survey request, secondary data collections were conducted to obtain 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 ascertain the

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Table 1.1 The dimensions of patents employed in the different chapters

<table>
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<tr>
<th>Issues</th>
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<th>Chapter 3</th>
<th>Chapter 4</th>
<th>Chapter 5</th>
<th>Chapter 6</th>
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influence of venture capital in academic entrepreneurship, annual studies from the venture capital association were employed.

1.5 STRUCTURE OF THE VOLUME

There are nine chapters in the volume and they are organized as follows:

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 volume is included.

Chapter 2 introduces the various key points of the solar PV sector in terms of industrial performance, technologies and regulations. This chapter serves as the foundation for understanding further specific studies.

Chapter 3 is about the innovation cascade of the sector. By comparing Industry Life Cycle (ILC) and Product Life Cycle (PLC) models, the innovation cascade is outlined for the solar photovoltaic sector.

Chapter 4 analyses the catch-up of the Chinese solar PV sector. The new techno-economic paradigm, government support, the human resource context, and integrative production capabilities are extracted to formulate the answers.

Chapter 5 analyses some 4400 US patents on solar photovoltaic (PV) technologies, protecting inventions made in the United States, Japan, Germany, Taiwan, South Korea and other OECD and emerging countries, in order to find out the spatial distribution of inventors. It is found that there are clusters of solar PV sectors in different countries. With the exception of the Silicon Valley, a special cluster with a unique ‘bottom up’ region in the solar PV sector, and government laboratories anchoring PV clusters in Taiwan, a major multinational corporation anchors all other clusters. The clusters are growing in Asia, resilient in the US, and declining in Europe.

Chapter 6 analyses the contribution of star scientists to the development of solar photovoltaic technology. It is found that the technology has been launched and keeps moving forward with major investments from large user companies and individual efforts from universities and academic stars. In contrast with biotechnology, star scientists, whatever their contribution, are comparatively minor players in solar photovoltaic technology.

Chapter 7 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 is detected. By comparing it with the semiconductor
Table 1.2 Description for each chapter

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Themes</th>
<th>Research questions</th>
<th>Theories</th>
<th>Methods</th>
<th>Theoretical and empirical contributions</th>
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<tr>
<td>1</td>
<td>Introduction</td>
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<td>2</td>
<td>Key points of the sector</td>
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<td>3</td>
<td>Evolution and innovation cascade</td>
<td>1. What is the evolution of the solar PV sector? 2. What are the characteristics of the technological trajectory?</td>
<td>Sectoral system of innovation, Product Life Cycle and Industrial Life Cycle</td>
<td>Quantitative and case studies</td>
<td>Redefinition of term 'innovation cascade', the debate of PLC–ILC theories</td>
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<td>4</td>
<td>China catch-up</td>
<td>How can the Chinese solar PV sector complete its catch-up?</td>
<td></td>
<td>Case studies and secondary data</td>
<td>Horizontal technological policies, the key entrepreneurs and the integrative production capabilities are the important factors</td>
</tr>
<tr>
<td>5</td>
<td>Cluster</td>
<td>1. Are there solar PV innovation clusters? 2. If yes, where do the clusters locate? 3. What are the differences among different clusters?</td>
<td>Cluster</td>
<td>Quantitative analysis and case studies</td>
<td>There are 23 clusters in the world, yet there are imbalances in the cluster development in Europe, North America and Asia</td>
</tr>
<tr>
<td>6</td>
<td>Star scientist</td>
<td>1. What is the definition of the star scientists for the solar photovoltaic sector? 2. How much academic entrepreneurship is in the solar PV sector? 3. What are the roles of venture capital, universities and technology transfer offices?</td>
<td>Star scientists</td>
<td>Quantitative analysis, case studies and secondary data</td>
<td>The definition of star scientists; academic entrepreneurship and venture capital are limited; famous universities and their technology offices do not play an important role in the academic entrepreneurship</td>
</tr>
<tr>
<td>7</td>
<td>Demand-driven</td>
<td>What are the characteristics of the solar PV sector?</td>
<td>Evolution of the sector</td>
<td>Comparison study</td>
<td>The solar PV sector is a demand-driven sector</td>
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<tr>
<td>8</td>
<td>Grand challenge policy</td>
<td>What is the relationship between innovation cascade and the grand challenge policies?</td>
<td>Grand challenge policy</td>
<td>History study</td>
<td>Grand challenge policy partly explains the innovation cascade</td>
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<td>9</td>
<td>Conclusion</td>
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sector, it is found that the solar PV sector is one whose innovation is mostly driven by demand, but so far not pushed by science and technology progress. Three special aspects are put forward. Further study is called for about whether its distinctiveness is significant enough to be a sub-category of the high-tech sector.

Chapter 8 links two recent concepts about innovation: those of grand challenges and innovation cascades. In addition, the evolution of the innovation policy is discussed.

Chapter 9 is the conclusion. The contributions of the studies are highlighted, the policy implications are made, the limitations of this enquiry are noted, and further research directions are suggested.

The themes, research questions, theories, methodologies, theoretical or empirical contributions of each chapter are outlined in Table 1.2.

NOTES